République Algérienne Démocratique et Populaire

Ministère de l'Enseignement Supérieur et de la Recherche Scientifique

Université Ibn Khaldoun de Tiaret

Faculté des Sciences Appliquées

Département de Génie Mécanique

Laboratoire de Recherche des Technologies Industrielles

THÈSE

Pour l'obtention de diplôme de
Doctorat 3éme cycle LMD

Domaine : Sciences et Technologies
Filière : Génie mécanique
Spécialité : Installations Énergétiques et Turbomachines

Thème

Étude et analyse du procédé thermohydraulique pour la production de la puissance mécanique

Présenté par :

GUELIB Asmaà

Soutenue le: 08/12/2025 **Devant le Jury composé de:**

MM.

SAD CHEMLOUL Nord Eddine	Prof. (Université de Tiaret)	Président
ZEBBAR Djallel	Prof. (Université de Tissemsilt)	Encadrant
MEKROUSSI Said	Prof. (Université de Tiaret)	Co-encadrant
HABIBI Samir	Prof. (Université de Sidi Bel Abbés)	Examinateur
KARAS Aek	Prof (Université de Tiaret)	Examinateur
CHAIB Khaled	Prof. (Université de Tiaret)	Examinateur

Année universitaire : 2024-2025

People's Democratic Republic of Algeria
Ministry of Higher Education and Scientific Research
Ibn Khaldun University of Tiaret
Faculty of Applied Sciences
Department of Mechanical Engineering
Research Laboratory of Industrial Technologies

THESIS

As a requirement to aim for the degree of
Doctorate 3rd Cycle LMD

Domain: Sciences and Technology
Major: Mechanical Engineering
Specialty: Energy Installations and Turbomachinery

Theme

Study and analysis of thermohydraulic process for the production of mechanical power

Presented by:

GUELIB Asmaa

Defended on:08/12/2025 **Members of Jury:**

Mrs.

SAD CHEMLOUL Nord Eddine	Professor (University of Tiaret)	President
ZEBBAR Djallel	Professor (University of Tissemsilt)	Supervisor
MEKROUSSI Said	Professor (University of Tiaret)	Co-supervisor
HABIBI Samir	Professor (University of Sidi Bel Abbes)	Examiner
KARAS Aek	Professor (University of Tiaret)	Examiner
CHAIB Khaled	Professor (University of Tiaret)	Examiner

Année universitaire : 2024-2025

Dedication

I would like to dedicate my thesis

To my parents,

whose continuous

efforts and encouragement

To my family members

To my friends

and all who are proud of my achievements

GUELIB Asmaa

Acknowledgements

First and foremost, praise and thanks be to Allah, for giving me strength and endurance to finish this dissertation.

I extend my deepest gratitude to my supervisor, Professor Zebbar Djallel, for his invaluable advice and his exceptional guidance, unwavering support and insightful critiques throughout my research journey. His immense knowledge and encouragement helped me to complete this research and write this thesis.

I would also like to thank my Co-supervisor, Said Mekroussi, for his advice and comments.

I would also like to thank the jury members for their time spent evaluating this work and for their kindness to me in accepting the discussion of this dissertation.

Finally, I would like to express my gratitude to everyone who contributed in any way to the completion of this thesis

Table of contents

List of figures IV
List of tables V
Nomenclature VI
General introduction 1

Chapter 1: Environmental impact of different energy sources, sustainable energy solutions, and second law applications

1.1. Introduction 4
1.2. Energy consumption 4
1.3. Electricity consumption in Algeria 6
1.3.1 Renewable energy sources for residential applications 7
1.3.1.1 Solar energy 7
1.4 The Sustainable Development Goals 8
1.5. Second law of thermodynamics 11
1.5.1 Statements of the second law of thermodynamics 12
1.5.1.1 The Kelvin-Planck statement 12
1.5.1.2 Clausius statement of the second law 13
1.5.2 Thermal energy reservoirs 13
1.5.3 Heat engines, heat pump and refrigerators 14
1.5.3.1 Thermal efficiency of heat engine 15
1.5.3.2 The coefficients of performance 17
1.5.4 Reversibility and irreversibility 18
1.5.5 The Carnot engine 19
1.5.6 Entropy 21
1.5.6.1 The Clausius inequality 21
1.5.7 Second-law efficiency 26
1.6. Conclusion 26

Chapter 2: Bibliographic research of energy efficiency concepts: cogeneration, trigeneration, and thermohydraulic processes

2.1. Introduction 28
2.2. Concepts of cogeneration and trigeneration 28
2.2.1 Cogeneration system 28
2.2.1.1 Technical options for micro-cogeneration 29
2.2.1.1.1 Steam-cycle-based micro-cogeneration systems 29
2.2.1.1.2 Gas-cycle-based micro-cogeneration systems (Stirling) 29
2.2.2 Trigeneration 29
2.2.2.1 Trigeneration technology 30
2.2.2.1.1 The technologies of trigeneration with thermal coupling. 30
2.2.2.1.2 Mass-coupling trigeneration technologies 31
2.2.2.1.3 Hydraulic coupling trigeneration technologies 32
2.2.2.1.4 Mechanical coupling trigeneration technologies 33
2.3. Thermohydraulic process 34
2.3.1 CAPILI concept (Carnot's machine with Piston Liquid) 35
2.3.1.1 Fundamentals of thermo-hydraulic conversion 36
2.3.1.2 Variants of the CAPILI engine process 36

2.3.1.3 Literature review of CAPILI engine 38
2.3.1.4 Working fluid selection 39
2.4. Conclusion 41

Chapter 3: Thermodynamic analysis of the novel concept of the organic Rankine thermo-hydraulic machine with liquid piston

3.1. Introduction 43
3.2. Description of the novel concept of the organic Rankine thermo-hydraulic machine with liquid piston 44
3.2.1 Principle of operation 44
3.3. Description of the thermodynamic cycle 46
3.3.1 Working principles 46
3.3.1.1 System equations and theoretical analysis 47
3.3.2 CoolProp: thermophysical properties library details (CoolProp_Microsoft Excel) 49
3.4. Results and discussion of the thermodynamic analysis 50
3.4.1 Choice of the best working fluid 50
3.4.1.1 Effect of the temperature of evaporation of the suitable working fluid (R1233zd) on the efficiencies 51
3.5. Conclusion 54

Chapter 4: Development of an analytical model of the hydraulic system of the ORPILI machine

4.1. Introduction 56
4.2. Hydraulic system description of ORPILI plant 56
4.2.1 Parameters of the mathematical model of the hydraulic system 57
4.2.1.1 Definition of the hydraulic power 57
4.2.1.1.1 Definition of the minor losses total resistance coefficient 57
4.2.1.2 Definition of the available mechanical power 57
4.2.1.3 Definition of the admissible power 58
4.2.1.4 Definition of the admissible Reynolds number 59
4.2.1.4.1 Selection of hydraulic oil kinematic viscosity 59
4.2.1.5 Determination of the flow rate 60
4.3. Results and discussions of the hydraulic analysis 61
4.3.1 Evolution of powers 62
4.3.2 Effect of the total height corresponding to the height between the transfer liquid levels in transfer cylinders ΔH 64
4.3.3 Definition of the allowable flow rate range corresponding to the pressure drop 65
4.3.4 Variations of admissible and available mechanical powers and Reynold numbers according to diameters 65
4.4. Conclusion 67
General conclusion and perspectives 68
References 71
Appendix 78
Appendix A: INAPI Patent 79
Appendix B: Results of thermodynamic calculations for various working fluids 80
Abstract 97
Résumé 98
الملخص 99

List of figures

Fig.1.1. Global primary energy consumption, 1990-2023 [22]. 6
Fig.1.2. The Kelvin-Planck statement [34]. 12
Fig.1.3. The Clausius statement [34]. 13
Fig.1.4. Bodies with relatively large thermal masses can be modeled as thermal energy reservoirs[35]. 14
Fig.1.5. A source supplies energy in the form of heat, and a sink absorbs it [35] 14
Fig.1.6. A heat engine with two heat reservoirs [35]. 15
Fig.1.7. Reversed heat engine (heat pump or refrigerator) [35]. 17
Fig.1.8. Two familiar reversible processes [35]. 18
Fig.1.9. The Carnot cycle (P-v diamgram) [36]. 20
Fig.1.10. The system considered in the development of the Clausius inequality [33]. 22
Fig.1.11. The entropy change between states 1 and 2 [35]. 24
Fig.1.12. The Carnot cycle on T-S diagram [36]. 24

Fig.2.1. Principle of thermal coupling for a trigeneration system using biomass as the primary energy source[47]. 31
Fig.2.2. Mass coupling for a solar trigeneration system [48]. 32
Fig.2.3. Hydraulic coupling for the CHV3T process [49]. 33
Fig.2.4. The principle of mechanical coupling for a trigeneration system (CAPILI process) [50]. 34
Fig.2.5. A thermo-hydraulic transformer implementing work transfer via a liquid piston [53]. 35
Fig.2.6. Fundamental schema of the CAPILI motor and the working fluid cycle in Mollier's diagram: a) for the 1st type, b) for the 2nd type [53]. 37

Fig.3.1 a) ORPILI plant schematic, b) View of the test bench of the novel thermo-hydraulic machine ORPILI. 44
Fig.3.2. ORPILI Cycle on a P-h diagram. 46

Fig.4.1. Hydrostatic scheme of the hydraulic part of the power plant [24]. 56
Fig.4.2. Variation of the kinematic viscosity of the oil according to temperatures [83], [84], [85]. 60
Fig.4.3. The variation of the hydraulic power according to the volume flow rate: (a) case 1: Δp = 1416.4 kPa and η_{th_max} = 17.5%, (b) case 2 : Δp = 235.3 kPa and η_{II_max} = 90.3%. 64
Fig. 4.4. Variation of the hydraulic power with the flow rate and the total height ΔH for d = 0.02 m: (a) case 1: Δp = 1416.4 kPa and η_{th_max} = 17.5%, (b) case 2 : Δp = 235.3 kPa and η_{II_max} = 90.3%. 64
Fig. 4.5. Comparison of the allowed flow rates according to the pressure drop for d = 0.03 m in transfer cylinders obtained for both studied cases with those obtained by Semmari et al. [38] . 65

List of tables

Table 2.1 Date of ban on working fluids according to the type of fluid 41

Table 3.1. Thermodynamic performances of the ORPILI cycle of different working fluids as a function of the superheated temperature 51

Table 3.2. Effect of variation of evaporator temperature on efficiencies 52

Table 4.1 Input parameters for the hydraulic system 62

Table 4.2. Variations of admissible and available mechanical powers and Reynolds numbers according to diameters 66

Nomenclature

d	diameter of the hydraulic pipe, m
D	diameter of the transfer cylinder, m
f	frequency, Hz (or s^{-1})
g	acceleration of gravity, m/s^2
h	specific enthalpy, J/kg
K	flow rate coefficient, m^3/s
P	power, W
p	pressure, Pa
Q	specific heat exchanged during transformation, J/kg
Re	Reynolds number, $Re = Dv\rho / \mu$
S	entropy J/K
T	temperature, K
V	velocity, m/s
V_vol	volume (m^3)
$\dot{V}$	flow rate, m^3/s
W	specific work, J/kg
y	extraction ratio

Greek symbols

ΔU	the change in internal energy
ΔH	height difference, m
$\boldsymbol{v}$_vol	specific volume, m^3/kg
η	efficiency
ρ	density of the fluid, kg/m^3
μ	dynamic viscosity, $N.s/m^2$
$\boldsymbol{v}_f$	kinematic viscosity, m^2/s
τ	the duration of a thermodynamic cycle, s

Subscripts and Superscripts

ad	admissible
av	available
cond	condenser
evap	evaporator
exp	expansion

H	high
hyd	hydraulic
in	inlet
max	maximal
min	minimal
L	low
LT	the work transfer liquid
out	outlet
R	refrigerator
sc	superheated
t	total
th	thermal
vs	valves

Abbreviations and Acronyms

CT, CT’	Transfer cylinders
CAPILI	Carnot with piston liquid
CCHP	combined cooling, heating, and power generation
CHP	Combined Heat and Power
CHV3T	Trithermal Hydraulic Steam Compression
CFCs	chlorofluorocarbons
COP	the coefficient of performance
EKC	Environmental Kuznets Curve
FLP	the pressurized fluid from the liquid piston
GWP	Global Warming Potential
HCCs	carbon tetrachloride and hydro chlorocarbons
HCFCs	Hydrochlorofluorocarbons
HCFOs	hydrochlorofluoro-olefins
HFOs	hydrofluoro-olefins
HMEC	Hydro-Mechanic-Electric-Conversion
HP	Heat pump
INDC	Intended Nationally Determined Contribution
irrev	irreversible
ODP	Ozone Depletion Potential
ORPILI	Organic Rankine Cycle with Liquid Piston
OTEC	Ocean Thermal Energy Conversion

R	reservoir
RE	Renewable energy
rev	reversible
RLMEMS	Research Laboratory in Mechanical Engineering, Materials and Structures
SE	Stirling engine
SDGs	Sustainable Development Goals
TES	Thermodynamics, Energy and Reactive Systems

General introduction

General introduction

Over the last few decades, Earth has experienced significant climate change due to global warming. The Intergovernmental Panel on Climate Change (IPCC) identifies carbon dioxide (CO_2) as the primary greenhouse gas responsible for this warming, due to human activities such as burning fossil fuel for energy production and transportation, deforestation, and industrial processes. In response, various international agreements have been established to combat climate change and mitigate the impacts of global warming. The Kyoto Protocol was the first international agreement that required countries to reduce their annual carbon emissions. It was initially signed by almost all nations at the 1992 Earth summit and later finalized in Kyoto, Japan, in 1997 [1]. The 28th COP summit ended in Dubai, UAE on December 13, 2023. COP summits allow countries to discuss and decide on actions to meet the UN Framework Convention on Climate Change goals. Leaders and organizations focus on strategies to achieve targets set by previous COP summits, especially the Paris Agreement. The Paris Agreement, adopted at COP21 and accepted by 196 countries, aims to limit global warming of well below 2°C, while pursing efforts to keep it under 1.5°C, and to reduce greenhouse gas emissions to net zero by 2050 [2].

In 2011, Algeria chose the path of building sustainable energy. As one of Africa's three largest energy consumers and CO_2 emitter, Algeria was particularly interested in signing the Paris Climate Agreement. Moreover, the country is becoming increasingly susceptible to the impacts of climate change, including desertification, land degradation, and drought. In Intended Nationally Determined Contribution (INDC), Algeria has pledged to reduce greenhouse gas emissions by at least of 7 % by 2030 [1].

Algeria can reduce its carbon footprint and contribute to the fight against climate change. Additionally, heavy reliance on non-renewable energy sources makes the Algerian economy vulnerable to the volatility of global hydrocarbon prices. A transition from conventional to cleaner energy sources is essential to achieve environmental sustainability. Algeria can move toward a more sustainable and stable future by investing in renewable energy and improving energy efficiency [3].

In this context, the main objective of this thesis is to valorize solar energy, specifically by improving the thermodynamic conversion cycle. This involves developing a novel thermohydraulic process. Previous studies on thermohydraulic concept have examined two fields:

CHV3T, for the production of cold, and CAPILI, for the production of electricity. This thesis focused on the CAPILI process, highlighting its problems and developing a novel concept to overcome these drawbacks.

This novel thermohydraulic process, ORPILI, is the subject of RLMEMS patent [4] (Appendix). The objective of this concept is to achieve higher energy efficiency than the CAPILI cycle.

The first chapter of this manuscript explores the environmental impact of various energy sources, followed by a discussion on sustainable development goals and the application of the second law of thermodynamics.

The second chapter presents the principles of cogeneration and trigeneration concepts, followed by a state-of-the-art of the thermohydraulic process CAPILI.

Chapter three is devoted to the main objective of this study, which is the novel configuration of the thermohydraulic machine ORPILI. First, this novel thermohydraulic process's operational principle is outlined, followed by a thermodynamic analysis of this proposed variant to evaluate the most suitable working fluid from those considered in this study. This chapter also details the extraction of thermophysical properties, including specified enthalpy and entropy of the working fluids at various phases of the ORPILI cycle using CoolProp software.

The last chapter highlights the proposed process's originality. It presents the hydraulic modeling of the ORPILI system, which contains different mathematical models and analyses.

The thesis concludes with a summary of the key findings and suggestions for future research.

Chapter 1

Environmental impact of different energy sources, sustainable energy solutions and second law applications

1.1 Introduction

Energy is a crucial economic infrastructure element intricately linked to human history and development. The amount of energy a community consumes often reflects its level progress. As a significant factor in economic, political, social, and environmental domains, energy has become one of the most widely debated topics globally[5]. This chapter discusses the environmental impact, various energy needs and technologies, followed by the presentation of sustainable development goals along with the principles of the second law of thermodynamics.

1.2 Energy consumption

The consumption of energy is increasing day by day. According to the 73rd edition of the Statistical Review of World Energy [6], total primary energy consumption reached a record 620 Exajoules (EJ), up 2% from the previous year and 0.6% above its ten-year average. Fossil fuel consumption, as a percentage of primary energy, dropped by 0.4% to 81.5% (Fig.1.1).

Historically, fossil fuels (e.g. coal, oil, and natural gas) have played a central role in developing and maintaining the global energy infrastructure. They have driven much of economic growth and facilitated technological advancements in the modern world. However, their extensive use has come at a significant environmental cost. Burning fossil fuels is an major contributor to increasing levels of carbon dioxide emissions, a key driver of global climate change [7]. This is supported by the findings of several studies. For instance, Ref [8] found that higher FFE in Malaysia is associated with increased environmental emissions. Likewise, another study [9] identified that FFE significantly contributes to CO2 emissions in the European Union. Similar outcomes were reported in Ref [10], which studied 27 developed countries, demonstrated a positive relationship between conventional energy consumption and CO2 emissions in SAARC nations. Additionally, bekun et al. [11] discovered that increasing FFE is associated with higher CO2 emissions. Turning to studies focused on Algeria, Pablo-Romero et al. [12] tested the validity of the EKC (Environmental Kuznets Curve) hypothesis in the country. The results of ARDL model show that energy use and electricity consumption significantly influence CO2 emission in the long run [13] reached a similar conclusion in their study. Chekouri et al. [1] used the STIRPAT model to study the relationship between CO2 emissions, income, FFE, and RE in Algeria and found that FFE is a major contributor to CO2 emissions.

The extraction and consumption of fossil fuels have led to significant biodiversity loss and extensive contamination, posing a fundamental risk to the health and stability of our planet's ecosystems[7]. To adress these environmental threats and safeguard the Earth, sustainable and pollutant-free technologies, known as renewable energy technologies, have been introduced [14].

Environmental sustainability necessitates transitioning from conventional to cleaner energy sources (renewable energy sources), as this can improve environmental quality without compromising economic growth. By making energy more affordable, accessible, and efficient for people across all income levels, this transition can promote economic development while providing energy free of air pollutants and greenhouse gas emissions, thereby helping to mitigate climate change [15].

Renewable energy sources can be used to produce energy again and again i.e. solar energy, wind energy, geothermal energy, marine energy, biomass energy, biofuels, and many more [16].

The transition to renewable energy (RE) has been the subject of multiple studies examining the relationship between RE and CO2 emissions. Samuel et al [17] investigated the impact of RE on CO2 emission in the context of South Africa and that found that a 1 % increase in renewable energy sources decrease CO2 emissions by 2855 kt . According to Refs [18], [19], the impact of renewable energy on ecological footprints in Turkey was re-examined, with findings indicating that RE improves environmental quality. In Algeria, only a few studies have investigated the influence of renewable energy on CO2 emissions. Belaïd et al. [13] found that RE can help improve overall environmental quality. A study published by Sahnoune et al. [20] demonstrated that developing RE sources and implementing energy efficiency measures can significantly reduce CO2 emissions and help preserve fossil resources. Furthermore, a study conducted by Hassoun et al. [21] indicated that the use of RE sources can effectively reduce CO2 emissions.

From the estimation of the 73rd edition of the Statistical Review of World Energy [6], Renewables' share of total primary energy consumption reached 14.6%, an increase of 0.4% over the previous year (Fig.1.1) [22].

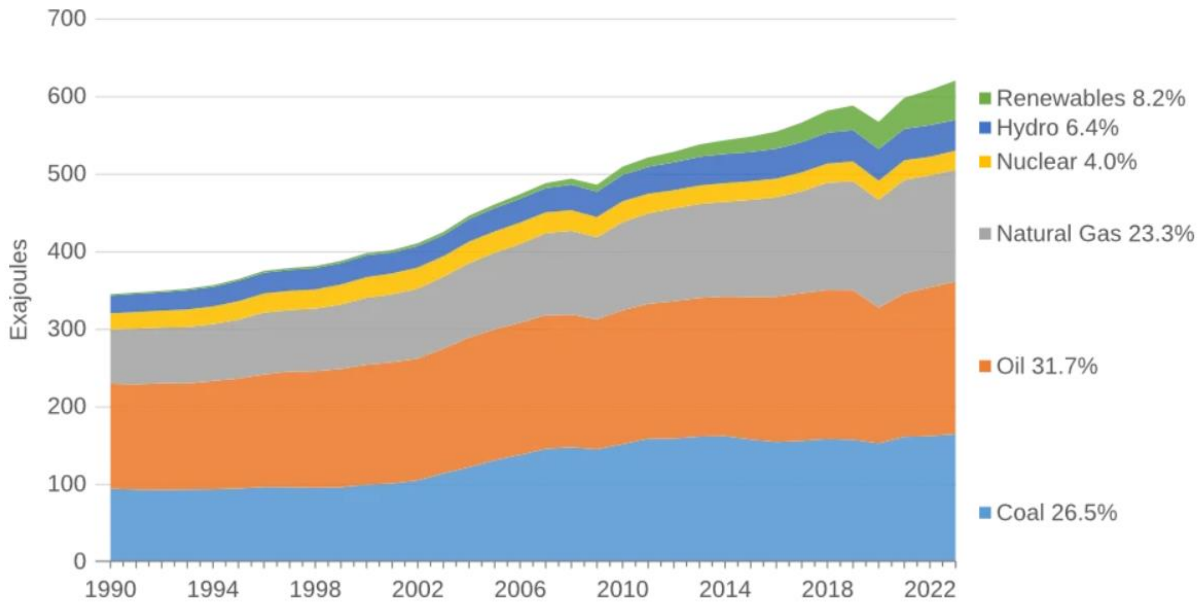


Fig.1.1. Global primary energy consumption, 1990-2023 [22].

1.3 Electricity consumption in Algeria

Electricity consumption in Algeria is projected to rise significantly. Total energy consumption has increased rapidly since 2020, reaching approximately 85.7 TWh in 2023 and expected to reach 130–150 TWh in 2030. From 1999 to 2009, electricity consumption surged across three main sectors, as categorized in the national energy balance of 2009: industry construction, and public works; transport; residential, and others including agriculture. For the residential sector, electricity consumption increased rapidly, rising from 3.134 ktoe in 1999 to 5.524 ktoe in 2008, an increase of 76.26%. In 2009, this growth experienced a slight decline of 1.60%, possibly due to climatic variations. For the industry, construction, and public works sector, the record shows a more modest increase, from 1.950 ktoe in 1999 to 2.721 ktoe in 2000, a growth rate of 39.60%. Electricity consumption in the transport sector showed irregular growth patterns [13]. Overall, the residential sector remains the greatest consumer of electricity in Algeria, much like in other developing countries where energy demand is highest in this sector. Even with advancements in low-energy consumption equipment, the residential sector continues to consume more than 40% of total electricity in Algeria [23].

1.3.1 Renewable energy sources for residential applications

To meet the increasing electricity demand, reduce greenhouse gas emissions, improve energy efficiency, and increase the share of renewable energy, the residential sector must adopt various renewable energy sources. Solar thermal, photovoltaic energy, biomass, and geothermal energy are among the most suitable renewable resources for residential applications [24].

1.3.1.1 Solar energy

Solar energy can be harnessed through photovoltaic panels for electricity generation or solar thermal collectors for heating purposes[25].

In Algeria, the potential of renewable electricity is predominantly driven by solar electricity due to the country's high solar radiation levels. Thanks to its geographical location, Algeria has one of the world's highest solar potentials, with an annual estimate of 13.9 TWh. The country receives annual sunshine exposure equivalent to 2.500 KWh/m^2 [13]. It is estimated that the size of the Algerian Sahara could capture enough solar energy to meet the entire world's electricity demand [26]. Algeria's covers an area of 2.381.741 km^2, with the Sahara alone constituting 84% of its territory. The solar energy potential of Algeria represents over 60 times the current electrical consumption of the European Union [13].

With Algeria's new (ENR) program, renewable energies and energy efficiency are set to become central to the country's energy and economic strategies. By 2030, 37% of its energy capacity and 27% of its national electricity production will come from renewable sources. Algeria's renewable energy program aims to make the country a prominent player in solar and wind energy while also incorporating biomass, cogeneration, and geothermal energy to drive sustainable economic growth [27].

In the residential sector, where there need for heating, cooling, and electicity, cogeneration and trigeneration technologies are gaining attention as effective solutions to meet these needs while minimizing environmental impact [25]. By adopting these systems, can further its sustainability goals and support economic development with cleaner, more efficient energy solutions for homes.

1.4 The sustainable development goals

In 2015, the United Nations introduced and ratified the Sustainable Development Goals (SDGs) within the framework of Agenda 2030 to address various global challenges. The SDGs consist of 17 goals, outlined in the references [28], [29], [30].

Goal 1 aims to end poverty and ensure equal rights for the poor and vulnerable. It also focuses on implementing social protection of vulnerable people and building resilience to economic and environmental challenges.

Goal 2 focuses on eliminating hunger and ensuring safe, nutritious, and sufficient food for all people, especially the poor and vulnerable. This goal promotes sustainable farming practices and aims to double the agricultural productivity and incomes of small-scale food producers. It also emphasizes environmental protection for future food needs.

Goal 3 promotes good health and well-being. It works to reduce the maternal and child mortality ratio, minimizes diseases, and ensures universal access to sexual and reproductive healthcare services. It supports achieving universal health coverage by encouraging vaccination, access to safe medicines, and quality healthcare for everyone. It also aims to decrease deaths and health risks caused by pollution and harmful chemicals.

Goal 4 ensures quality education for everyone. It aims to provide inclusive and quality education for children, youth, and adults, and supports equal access to affordable education, for all men and women, including the university level.

Goal 5 focuses on achieving gender equality and eliminating all forms of discrimination, violence, and harmful practices against women and girls. It promotes equal rights in education and work and supports women's full participation in leadership in decision-making roles.

Goal 6 aims to provide clean water and sanitation for all people. It ensures universal access to adequate and equitable sanitation and hygiene. This goal also enhances water quality, reduce water pollution, increase water-use efficiency across all sectors, and promote the sustainable management of water resources. Furthermore, it emphasizes protecting and restoring ecosystems connected to water to ensure a clean and healthy environment for future generations.

Goal 7 ensures access to affordable, reliable and modern energy services for all. It aims to substantially increase the proportion of renewable energy in the global energy mix such as solar, wind, and hydropower, which are environmentally friendly and help reduce pollution. It also works to double the global rate of improvement in energy efficiency and encourage new technologies that save energy. Goal 7 supports enhanced international cooperation to facilitate access to clean energy research and technology and promotes the expansion of energy infrastructure and upgrading of technology for supplying sustainable energy services, especially in rural and underdeveloped areas where millions of people still live without electricity.

Goal 8 focuses on promoting decent work and sustainable economic growth. It works to create more jobs, foster entrepreneurship, and support creativity and innovation through access to financial services. This goal ensures full, and productive employment and decent work for all, while working to reduce unemployment. It also aims to eradicate forced labour, protect workers' rights, and eliminate child labour. Additionally, it supports developing and implementing policies that promote sustainable tourism, which generates jobs and promotes local culture and products.

Goal 9 aims to build high-quality, reliable, sustainable, and resilient infrastructure, promote sustainable industrialization, and encourage innovation. This goal focuses on improving infrastructure to support sustainable industries by increasing resource efficiency and adopting cleaner, environmentally friendly technologies and industrial processes, with each country acting in line with its abilities.

Goal 10 of the SDGs aims to reduce inequality and promote the social, economic, and political inclusion of everyone, regardless of age, gender, disability, race, religion, or background. This goal focuses on adopting fiscal, wage, and social protection policies that progressively achieve greater equality. It also supports safe, regular, and responsible migration and mobility of people.

For goal 11, a key target is provide everyone with access to adequate, safe, affordable housing and basic services, while improving living conditions in slums. It also works to ensure more affordable, accessible, and sustainable transportation. This goal aims to protect cultural heritage, and ensure safety during disasters, and promote green and public spaces for all.

Goal 12 promotes responsible consumption and production. It aims to ensure the sustainable management and efficient use of natural resources, reduces global food waste, and manage chemicals and waste responsibly to protect health and the environment. The goal supports sustainable practices in businesses and everyday life, encourages eco-friendly choices, reduces pollution, and promotes recycling and reuse to decrease waste generation. It also emphasizes the importance of raising awareness and providing information for sustainable living.

Goal 13 of the SDGs aims to enhance resilience and the ability to adapt to climate change and its impacts. It encourages strengthening education, raising awareness, and building the capacity of individuals and institutions to mitigate climate change, adapt to its effects, reduce its impacts, and improve early warning systems.

Goal 14 focuses on reducing all types of marine pollution, protecting ecosystems, establishing effective harvesting regulations, and end overfishing, illegal, unreported, unregulated fishing, and harmful fishing practices. It also aims to increase the economic gains for small island developing states and least developed countries by promoting sustainable management of marine resources, particularly through fisheries, aquaculture, and tourism.

The essential objective of Goal 15 is to protect, restore, and sustainably use terrestrial and inland freshwater ecosystems and their services. It aims to enhance all kinds of forests by implementing sustainable management and combating deforestation. This goal supports the restoration of degraded land, takes immediate and significant action to reduce natural habitat degradation, stops biodiversity loss, and conserves and protects threatened species from extinction. It also works to incorporate ecosystem and biodiversity values into national and local planning, development initiatives, poverty reduction strategies, and accounting systems.

Goal 16 focuses on promoting peace,providinf access to justice, and building effective, accountable, and inclusive institutions. It aims to reduce all formes of violence and related deaths worldwide, and to eliminate abuse and exploitation. This goal also targets the reduction of illegal financial and arms flows, enhances the recovery and return of stolen assets, and combats organized crime.

The final goal, goal 17, is strengthening global partnerships to support sustainable development. It aims to generate additional financial resources for developing countries from various sources and support them in achieving long-term debt sustainability. This goal also emphasizes strengthening North-South, South-South, and triangular regional and international cooperation to improve access to science, technology and innovation and promote knowledge sharing on mutually agreed terms.

This thesis's objective is closely aligned with multiple SDGs goals, especially goal 7: affordable and clean energy, as it promotes a potential energy conversion that utilizes a sustainable thermodynamic cycle, by improving efficiency, and the supporting of the transition toward more sustainable energy systems using renewable heat sources, particularly solar energy which offers potential for low-cost application especially regions with abundant solar resources. Furthermore, this thesis aims to provide an efficient and environmentally friendly approach to energy conversion. It supports sustainable industrial practices and infrastructure development by reducing reliance on fossil fuels, minimizing carbon emissions, and encouraging clean technology-core aspects. All this can achieve goal 9. In addition, it can contribute to attaining goal 13: climate action.

1.5 Second law of thermodynamics

The first law of thermodynamics asserts that an energy balance is maintained during a state change or thermodynamic process inside a system. However, it does not provide any information regarding the feasibility of that change of state or process. For example, the first law does not determine whether a metallic bar of uniform temperature can spontaneously develop a temperature gradient, becoming warmer at one end and cooler at the other. It merely stipulates that if such a process were to occur, the energy gained by one end would be exactly equal to the energy lost by the other. The second law of thermodynamics, on the other hand, establishes the criterion for determining likelihood or spontaneity of diverse processes[31].

Spontaneous processes in nature occur exclusively in one direction. Heat consistently transfers from a body at a higher temperature to one at a lower temperature; water invariably flows downward; time perpetually moves forward. The reverse of these occurrences never transpires spontaneously. The process's spontaneity arises from a finite driving potential, often referred to as the 'force' or 'cause,' while the resulting phenomenon is termed the 'flux,' 'current,' or 'effect.' Standard forces such as temperature gradient, concentration gradient, and electric potential gradient correspond to their respective conjugate fluxes: heat transfer, mass transfer, and electric current flow. These transfer processes cannot proceed spontaneously from a lower to a higher potential. This directional law constrains energy transformation beyond that established by the first law [31].

The second law outlines the theoretical performance limitations of cycles, engines, and other energy conversion mechanisms, limitations that go beyond those dictated by energy conservation, and offers a quantitative framework for comparing actual devices with these theoretical benchmarks[32].

1.5.1 Statements of the second law of thermodynamics

Unlike the first principle, which is expressed in a single statement, the second principle is expressed through several statements. Two classical statements of the second law are the Kelvin-Planck statement and the Clausius statement.

1.5.1.1 The Kelvin-Planck statement:

It is impossible to construct a device that produces work while interacting with a single heat reservoir [33] (Fig.1.2).

It asserts that constructing a cyclic heat engine that extracts a specified quantity of heat from a high-temperature reservoir and converts it entirely into work is unfeasible. The only alternative is that heat must be transported from the working fluid at a lower temperature to a low-temperature reservoir. Consequently, work can be accomplished through heat transfer only when two temperature levels exist, with heat being transported from the high-temperature body to the heat engine, and then from the heat engine to the low-temperature sink. This indicates that constructing a heat engine with a 100% of thermal efficiency is impossible[34].

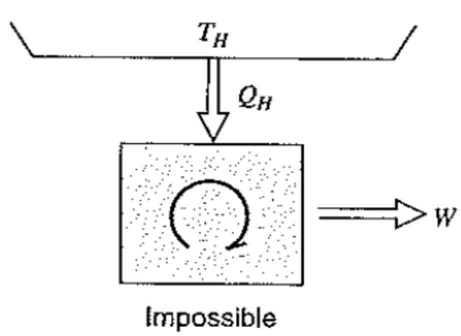


Fig.1.2. The Kelvin-Planck statement [34].

1.5.1.2 Clausius statement of the second law:

It is impossible to devise a process whose sole effect is to deliver heat from a reservoir of lower temperature to a reservoir of higher temperature [33] (Fig.1.3).

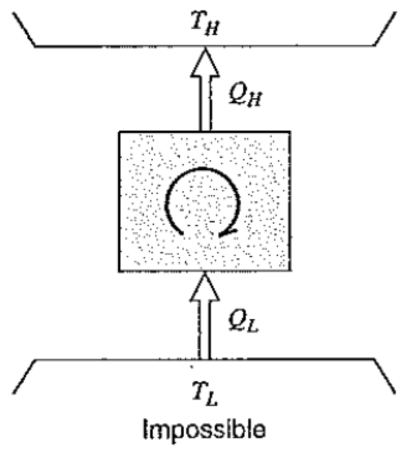


Fig.1.3. The Clausius statement [34].

To investigate the deeper implications and significance of the second law, as expressed in the two statements mentioned above, it is essential to clearly define the concepts of heat reservoirs, heat engines, thermal efficiency, and reversibility[32].

1.5.2 Thermal energy reservoirs

In developing the second law of thermodynamics, it is very convenient to consider a hypothetical body with a substantial thermal energy capacity (mass specific heat) that can provide or absorb finite quantities of heat without experiencing any temperature variation. A body of this nature is called a thermal energy reservoir, or simply a reservoir. For most practical purposes, the Earth's atmosphere, oceans, lakes, and rivers can be considered thermal reservoirs (Fig.1.4). For example, the atmosphere does not warm significantly due to heat losses from residential buildings during winter. Similarly, megajoules of waste energy discharged into large rivers by power plants do not result in any substantial change in water temperature [35].

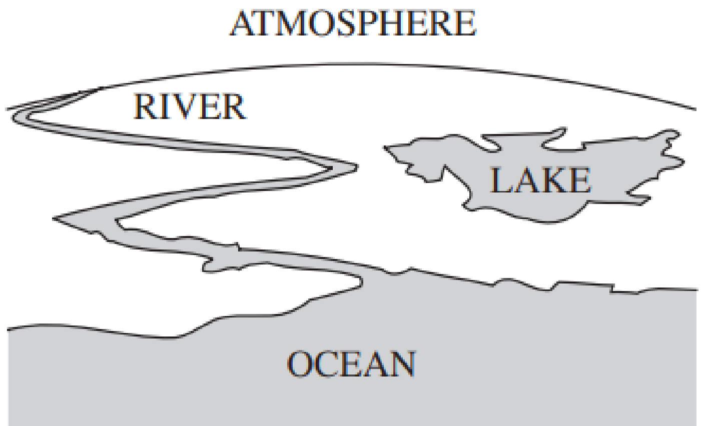


Fig.1.4. Bodies with relatively large thermal masses can be modeled as thermal energy reservoirs [35].

A reservoir at high temperature which supplies heat to the system is called a source, while one at low temperature that receives heat from the system is called a sink (Fig.1.5) [35].

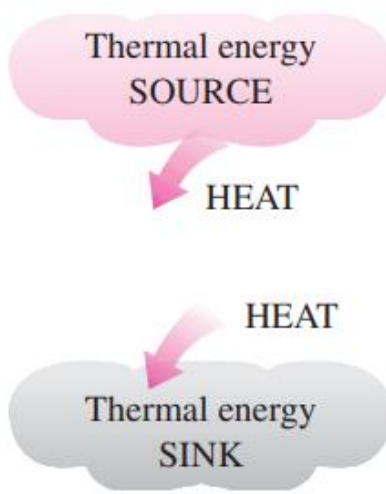


Fig.1.5. A source supplies energy in the form of heat, and a sink absorbs it [35].

1.5.3 Heat engines, heat pump and refrigerators

The Kelvin-Planck statement specifically refers to a cyclically functioning apparatus, which can be interpreted as a heat engine. Many implications of the diverse statements of the second law apply to heat engines. Fig.1.6 depicts the concept wherein energy is transferred as heat from a high-temperature reservoir to the engine. The engine converts a fraction of this thermal energy into work and discharges the remainder to a low-temperature reservoir. The engine operates within a thermodynamic cycle, where the working fluid consistently returns to its initial state, allowing the device to function continuously[32].

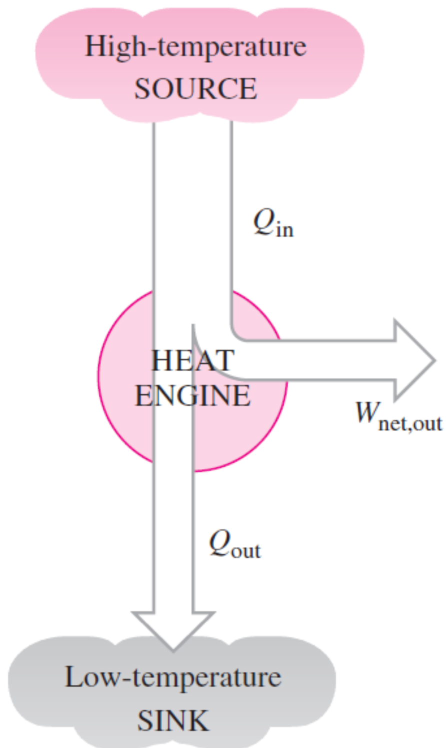


Fig.1.6. A heat engine with two heat reservoirs [35].

Fig.1.6 shows schematically a heat engine that utilises two heat reservoirs for heating and cooling, respectively, while executing work[33].

Recall that the change in internal energy ΔU is zero for a closed system undergoing a cycle. Therefore, the net work of the cycle, as given in equation (1.1), is equal to the net heat transfer to the system[33]:

$$\oint \delta Q = \oint \delta W \quad (1.1)$$

$$W_{net} = Q_{in} - Q_{out} = Q_H - Q_L \quad (1.2)$$

1.5.3.1 Thermal efficiency of heat engine

In Eq.1.2, Q_{out} denotes the amount of the energy wasted to complete the cycle. However, Q_{out} is never zero; hence, the net work output of a heat engine is invariably less than the magnitude of heat input. Only a portion of the heat delivered to the heat engine is transformed to work. The ratio of net work to net heat of a cycle is a measure of the performance of a heat engine and is called the thermal efficiency η_{th} [35]. The thermal efficiency of a heat engine can be expressed as:

$$\eta_{th} = \frac{W_{net}}{Q_{in}} \tag{1.3}$$

Substituting W_{net} from Equation 1.2, the efficiency may be defined in terms of heat input and heat rejected:

$$\eta_{th} = 1 - \frac{Q_{out}}{Q_{in}} \tag{1.4}$$

A heat engine can be reversed by providing an input of work from the surroundings, as shown in Fig.1.7. This reversed engine consumes work to transfer heat from a cold region to a hotter region. These devices are commonly used for heating or cooling purposes and are categorized into two main types: heat pumps, refrigerators, or air conditioners, depending on their application. A heat pump is a device that extracts energy from the atmosphere, the ground, or a body of water and transfers it to provide residential heating. The objective of a heat pump is to provide energy to a high-temperature reservoir, such as the inside of a building. The purpose of a refrigerator or air conditioner is to extract energy from the low-temperature reservoir. In a household refrigerator, energy is extracted from the interior, where food items are preserved, and energy is rejected by the environment, usually via a heat exchanger positioned at the appliance's rear. The heat rejection from a refrigerator contributes to heating a home in winter and adds cooling load for summer air conditioning. An air conditioner extracts heat from the cool inside of a structure and expels heat to the outside[32].

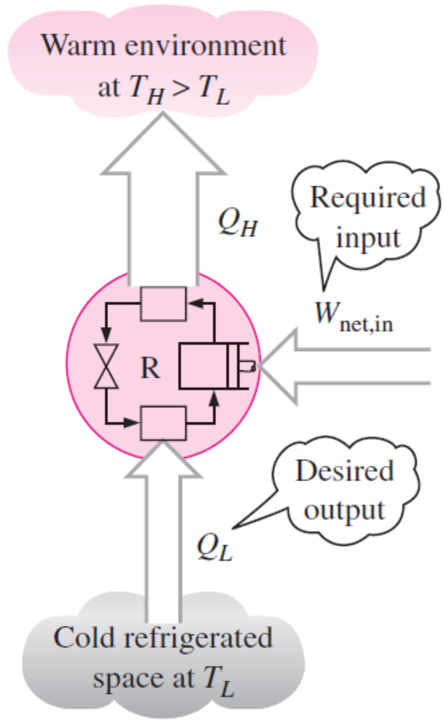


Fig.1.7. Reversed heat engine (heat pump or refrigerator) [35].

1.5.3.2 The coefficients of performance

The efficiency of a refrigerator is expressed in terms of the coefficient of performance, denoted by COP_{Re}. The desired outcome in this case is removing heat Q_L (Q_{out}) from a cold reservoir at a temperature T_L, and the expense is the work input $W_{net,in}$. The removed heat Q_L, together with the work W, is transferred to the hotter environment as Q_H (Q_{in})at a temperature T_H ($T_H > T_L$) [33].The COP of a refrigerator can then be expressed as:

$$COP_{Re} = \frac{\text{Desired output}}{\text{Required input}} = \frac{Q_L}{W_{net,in}} \tag{1.5}$$

Substitution of Equation 1.2 into Equation 1.5 renders the expression for the COP_{Re} of a refrigerator in terms of heat interactions.

$$COP_{Re} = \frac{Q_L}{Q_H - Q_L} \tag{1.6}$$

For the heat pump, the performance is defined as the ratio of the heat-delivered Q_H (the desired product) to the work consumed (the expense) [33]. Therefore, the coefficient performance (COP_{HP}) for a heat pump is given by :

$$COP_{HP} = \frac{\text{Desired product}}{Expense} = \frac{Q_H}{W_{net,in}} \tag{1.7}$$

Which can also be expressed as

$$COP_{HP} = \frac{Q_H}{Q_H - Q_L} \tag{1.8}$$

1.5.4 Reversibility and irreversibility

The second law of thermodynamics enables us to divide all processes into two classes:

(a) Reversible or ideal process.

(b) Irreversible or natural process.

A reversible process is carried out in such a way that, open completion, both the system and its surroundings can be returned to their initial states (Fig.1.8).This process is conducted infinitely slowly, with an infinitesimal gradient, ensuring that every state traversed through by the system is an equilibrium state. A reversible process coincides with a quasi-static process [31].

Processes that are not reversible are called irreversible processes, which is carried out with a finite gradient. A reversible process, characterized by a series of equilibrium phases, is an idealized hypothetical process attainable that can only be attained as a limit. It is described as an asymptote to reality. All spontaneous processes are irreversible[31].

a) Frictionless pendulum

b) Quasi-equilibrium expansion and compression of a gas

Fig.1.8. Two familiar reversible processes [35].

1.5.5 The Carnot engine

The Carnot engine is the most efficient heat engine operating between a high-temperature reservoir and a low-temperature reservoir. It is an optimal engine that employs reversible processes to establish its operational cycle; hence, it is referred to as a reversible engine. The Carnot engine is highly significant, as its efficiency defines the upper limit of efficiency for any real engine. If the efficiency of a real engine is markedly inferior to that of a Carnot engine operating under the same conditions, improvements may be possible[36].

The Carnot cycle, using an ideal gas as the working substance, consists of four reversible processes that form a complete thermodynamic cycle: two adiabatic and two isothermal (Fig.1.9) which are as follows [36]:

Process 1→2: Isothermal expansion (heat absorption at T_H)

Initially, heat is transmitted reversibly from the high-temperature reservoir at the constant temperature T_H. The piston in the cylinder is retracted, increasing in volume.

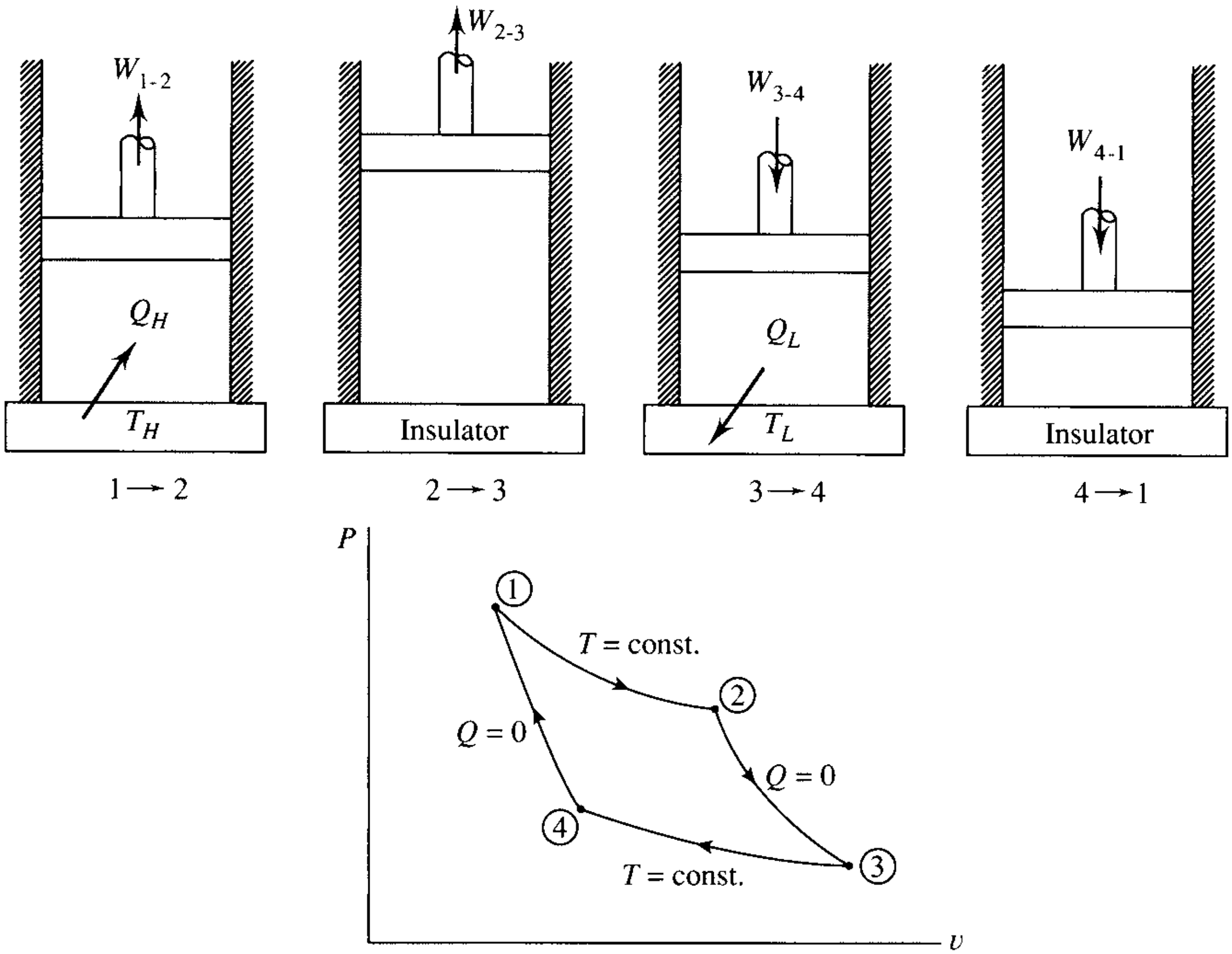


Fig.1.9. The Carnot cycle (P-v diagram) [36].

Process 2 → 3: Adiabatic reversible expansion (No heat exchange).

The cylinder is well insulated during this process, preventing heat transfer throughout this reversible operation. The piston is being retracted, and volume is increasing.

Process 3 → 4: Isothermal compression (heat rejection at T_L).

After the adiabatic expansion process, heat is transferred reversibly to the low-temperature reservoir at the constant temperature T_L. During this process, the piston compresses the working substance, decreasing its volume.

Process 4 → 1: Adiabatic reversible compression.

The cylinder is again completely insulated, preventing heat transfer during this reversible process. The piston continues compressing the working substance until the initial volume, temperature, and pressure are attained, thus completing the cycle.

The thermal efficiency of Carnot cycle is expressed by equation (1.9) by substituting of the equation 1.2 of W_{net}.

$$\eta = \frac{Q_H - Q_L}{Q_H} = 1 - \frac{Q_L}{Q_H} \tag{1.9}$$

Carnot's postulate is the old version of the second law of thermodynamics, and it is fully equivalent to the modern version that refers to entropy [37].

1.5.6 Entropy

If the first law is referred to as the law of internal energy, then the second law might be articulated as the law of entropy. Thermodynamics can be described as the science of three fundamental concepts: energy, equilibrium, and entropy[31].

1.5.6.1 The Clausius inequality

The second law of thermodynamics often leads to formulations involving inequalities. Another significant inequality with substantial implications in thermodynamics is the Clausius inequality. This concept was first introduced by the German physicist R. J. E. Clausius (1822–1888), a pioneer in fields of thermodynamics[35], which is expressed in [33] as:

$$\oint \frac{\delta Q}{T} \leq 0 \tag{1.10}$$

The demonstration of Equation 1.10 is predicated on the principle that the work performed by a system undergoing a cyclic process while engaging with a singular heat reservoir is invariably non-positive [33], that is:

$$\oint \delta W = \left(\oint \delta Q \right) \leq 0 \text{ (single reservoir)} \tag{1.11}$$

Consider a system A connected to a thermal energy reservoir at T_R through a Carnot engine (Fig.1.10). The reversible engine R receives heat δQ_R from the reservoir and rejects heat δQ to system A at temperature T. From the efficiency of a reversible engine, it can be deduced that[33]

$$\frac{\delta Q_R}{\delta Q} = \frac{T_R}{T} \tag{1.12}$$

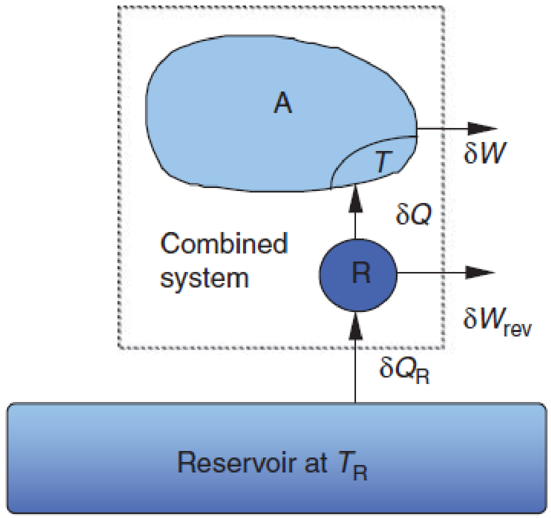


Fig.1.10. The system considered in the development of the Clausius inequality [33].

The cyclic device absorbs heat δQ_R from the reservoir and delivers heat δQ to the system at a boundary temperature T (a variable), while generating reversible work δW_{rev}. The system, in turn, generates work δW due to this heat transfer[35].

The work of a complete cycle of the combined system (Fig.1.10), which is equal to the heat in the cycle [33], is given by:

$$\oint(\delta W + \delta W_{rev}) = \oint \delta Q_R \tag{1.13}$$

The combined system, in contrast to the Carnot engine, engages with a single reservoir. Thus, based on the Kelvin–Planck statement of the second law, which asserts that no system can generate a net amount of work while functioning in a cycle and exchanging heat with a single thermal energy reservoir, it follows that the work of a cycle of the combined system $\delta W+\delta W_{rev}$ cannot be a work output, and therefore, cannot be a positive quantity. However, it can be negative or zero [33].

$$\oint(\delta W + \delta W_{rev}) = \oint \delta Q_R \leq 0 \tag{1.14}$$

By substituting δQ_R from equation 1.12 the relation 1.14 becomes:

$$T_R \oint\left(\frac{\delta Q}{T}\right) \leq 0 \tag{1.15}$$

Since T_R is consistently positive, it follows that:

$$\oint\left(\frac{\delta Q}{T}\right)\leq 0 \tag{1.16}$$

This is the Clausius inequality that applies to all cyclic processes, whether reversible or irreversible. For irreversible processes the integral is less than zero.

$$\oint\left(\frac{\delta Q}{T}\right)_{irrev}\prec 0 \tag{1.17}$$

For reversible cycles the integral must be zero.

$$\oint\left(\frac{\delta Q}{T}\right)_{rev}=0 \tag{1.18}$$

Clausius recognized in 1865 that he had discovered a new thermodynamic property, which he named entropy[35]. It is denoted as S and is given by [36]

$$dS=\left(\frac{\delta Q}{T}\right)_{rev} \tag{1.19}$$

Integrating eq.1.19 for any process involving the change in entropy between two states

$$\Delta S=\int_1^2\left(\frac{\delta Q}{T}\right)_{rev} \tag{1.20}$$

The entropy variation between two processes (Fig.1.11) is the same, whether the process is reversible or irreversible [35].

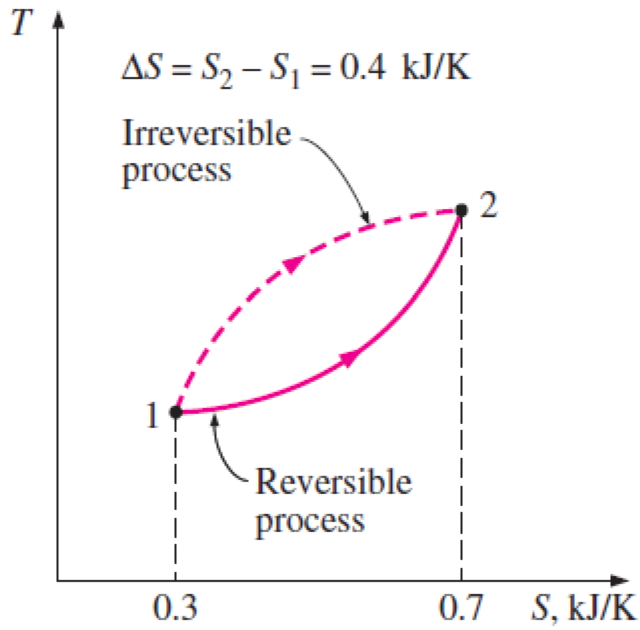


Fig.1.11. The entropy change between states 1 and 2 [35].

Temperature-entropy diagrams are frequently used to represent significant cycles or processes of. The Carnot cycle provide a clear representation when plotting temperature against entropy [36], as illustrate in Fig.1.12.

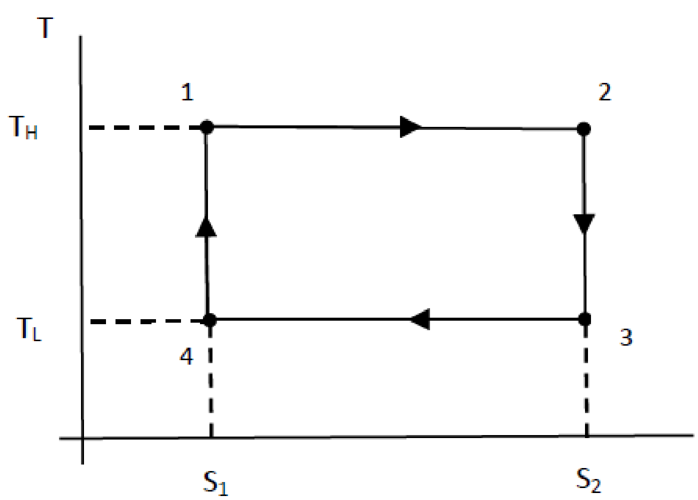


Fig.1.12. The Carnot cycle on T-S diagram [36].

The change in entropy for the initial isothermal process from state 1 to state 2 is [36].

$$S_2 - S_1 = \int_1^2 \frac{\delta Q}{T} = \frac{Q_H}{T_H} \tag{1.21}$$

Entropy remains constant during the reversible adiabatic process from state 2 to state 3 (ΔS=0). The entropy change for the isothermal process from state 3 to state 4 is less than that of the first process from state 1 to state 2 (eq.1.22).

$$\Delta S = -\frac{Q_L}{T_L} \tag{1.22}$$

The process from state 4 to state 1 is also reversible adiabatic, and the entropy change remains constant (ΔS=0).

For a simple system undergoing a reversible process, the heat transfer can be defined in differential form [see Eq. (1.19)] [36] as:

$$\delta Q = TdS \text{ or } Q = \int_1^2 TdS \tag{1.23}$$

And

$$\delta W = pdV_{\_vol} \tag{1.24}$$

Thus, the first law of thermodynamics for a reversible process may be written as:

$$TdS - pdV_{\_vol} = dU \tag{1.25}$$

Equation 1.25 applies to all processes, whether reversible or irreversible. When divided by the mass, this equation is expressed in terms of specific properties as:

$$Tds - pdv_{\_vol} = du \tag{1.26}$$

The change of enthalpy is given by:

$$dh = du + pdv_{\_vol} + v_{\_vol}dp \tag{1.27}$$

Substituting du from Eq. 1.27 gives the following:

$$Tds = dh - v_{\_vol}dp \tag{1.28}$$

1.5.7 Second-law efficiency

Evaluating the performance of engineering systems solely through first law efficiency can be insufficient or unrealistic. A more comprehensive measure, known as exergy efficiency (or second law efficiency), is introduced to mitigate this limitation. This efficiency is defined as the ratio of the thermal efficiency of an actual system to the maximum possible (reversible) thermal efficiency between the same thermodynamic states[38]:

$$\eta_{II} = \frac{\eta_{th}}{\eta_{th,rev}} \tag{1.29}$$

1.6 Conclusion

Investigating alternative energy sources underscores the critical importance of transitioning to renewable energy as a key strategy for ensuring a sustainable, secure, and environmentally responsible future. This shift is especially vital within the residential sector, which significantly contributes to energy consumption through heating, cooling, and electricity demands. Addressing these challenges requires innovative solutions that effectively balance efficiency, sustainability, and economic feasibility. By embracing these approaches and adhering to the second law of thermodynamics principles, sustainable energy systems can achieve enhanced efficiency, driving transition toward a greener and more sustainable energy future.

Chapter 2

Bibliographic research of energy efficiency concepts: cogeneration, trigeneration, and thermohydraulic processes

2.1 Introduction

The context of the energy crisis has given rise to new concepts that can contribute to reducing of primary energy consumption and greenhouse gas emissions in the residential and tertiary sectors [39], particularly the concepts of cogeneration and trigeneration, which will be discussed in this chapter. Subsequently, the thermohydraulic CAPILI processes are presented to provide a comprehensive global understanding of the work that will be explored in the following chapters.

2.2 Concepts of cogeneration and trigeneration

2.2.1 Cogeneration system

Cogeneration, also known as CHP (Combined Heat and Power), is defined as the sequential production of two forms of useful final energy from a single primary energy input. These forms of energy typically involve converting thermal energy from a primary source, which can be either renewable or fossil-based (e.g., natural gas, biomass, solar, etc.), into mechanical work and heat. The mechanical work is often converted into electricity[40].

Cogeneration is recognized as one of the most energy-efficient methods, often achieving overall efficiencies greater than 80%. This efficiency is primarily due to its ability to capture and utilize energy that would typically be wasted, like heat. Consequently, cogeneration can significantly reduce primary energy consumption, saving between 15% and 30% compared to the separate production of heat and electricity[25].

In general, CHP has the potential to significantly decrease greenhouse gas emissions in the residential, industrial, and tertiary sectors by reducing fuel consumption and minimizing energy losses during transmission. The latter occurs because it generates energy closer to the consumer[41].

Cogeneration is typically employed in large generating units, such as combined heat and power plants. However, there is a growing trend toward its use in smaller systems, particularly for local and distributed applications. According to the EU Cogeneration Directive, a micro-cogeneration unit is defined as having a maximum power output of less than 50 kWe [42].

2.2.1.1 Technical options for micro-cogeneration

Micro-cogeneration utilizes various technologies, including small steam turbines, small gas turbines, organic Rankine cycle systems, Stirling engines, and fuel cells [42].Among the most advanced and widely available on the market, the most promising for meeting the needs of homes using low-temperature solar resources, there are two main types: those based on steam or gas cycles[24].

2.2.1.1.1 Steam-cycle-based micro-cogeneration systems

A micro-cogeneration system using steam or an organic working fluid operates based on the Rankine thermodynamic cycle. It is predominantly used in high-power cogenerations applications. By using an organic working fluid instead of water, the system can recover heat from low-temperature sources, which are typically associated with waste heat recovery processes. However, the electric efficiency of the Rankine cycle in micro-cogeneration is low, resulting in limited primary energy savings, as it generates less electricity than other technologies. Despite this, these systems offer advantages due to their lower costs than competing technologies. Furthermore, due to the low mechanical stresses, they are expected to have a long lifespan[43].

2.2.1.1.2 Gas-cycle-based micro-cogeneration systems (Stirling)

A Stirling engine is an external combustion engine that operates on a closed thermodynamic cycle (the Stirling cycle). The working fluid absorbs heat through a heat exchanger with unmixed fluids, allowing the use of various heat sources, such as fuel combustion or devices like solar collectors [44].

SE micro-CHP systems are similar in shape and size to domestic gas boilers. However, they not only supply heat for hot water and space heating but also generate electricity [45].

2.2.2 Trigeneration

A trigeneration concept, also known as combined cooling, heating, and power generation (CCHP), goes beyond cogeneration by simultaneously producing electricity, heat, and cooling from a single energy source. The trigeneration plant is composed of the prime mover, a heat recovery unit, and an absorption or an adsorption chiller [39].

CCHP systems can achieve greater overall efficiencies than traditional power plants or cogeneration systems. Depending on the requirements and system design, the heating and cooling outputs can function simultaneously or alternately. This adaptability allows CCHP systems to optimize energy use according to immediate demand, making them more effective and sustainable compared to conventional systems, which typically produce electricity and heat separately[46].

2.2.2.1 Trigeneration technology

There are types of trigeneration processes, mainly cogeneration processes described above, coupled with one of the cold production processes. This coupling can be carried out in different ways.

2.2.2.1.1 The technologies of trigeneration with thermal coupling.

Cooling production utilizing this coupling approach is typically achieved through a liquid/gas absorption, commonly involving LiBr/H2O. Fig.2.1 depicts a diagram of a trigeneration process with thermal coupling. This process comprises capturing the heat generated by the engine cycle utilized for electricity generation (3-4) and heating (4-5) and transferring it to the absorption cycle to generate cooling. A trigeneration system utilizing biomass combustion can attain an efficiency of 90% [24].

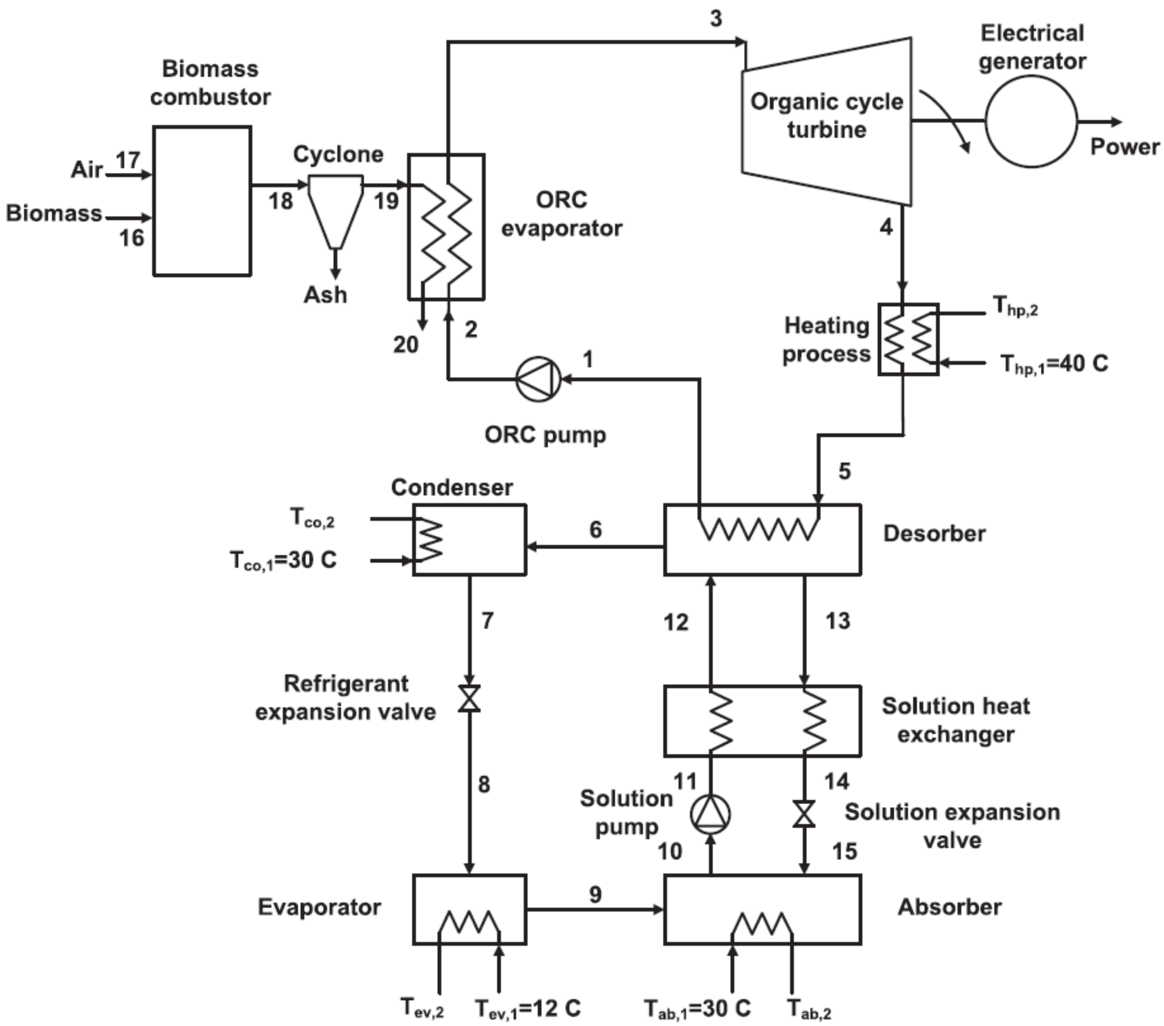


Fig.2.1. Principle of thermal coupling for a trigeneration system using biomass as the primary energy source[47].

2.2.2.1.2 Mass-coupling trigeneration technologies:

In the coupling configuration depicted in Fig.2.2 of the solar collectors, the solar thermal energy generated by the parabolic cylindrical collectors is transferred to the working fluid (1-2). The high-pressure steam generated expands in the turbine, generating electricity (2-13). During the expansion process, steam is taken from the turbine. A fraction of this steam is utilized for heating purposes, typically ranging from 3% to 10%, while remaining amount is sent towards the ejector. The primary steam flow in the mixing chamber of the ejector generates a vacuum due to its acceleration. This vacuum device extracts a supplementary stream of steam from the second evaporator (8-9). The two steam streams are then combined. The steam mixture accelerates within the converging-diverging section of the ejector, forming a shock wave. This shock wave causes compression near the outlet of the ejector (3-4).

The steam discharged from the turbine (13-14) is subsequently combined with the steam mixture entering the ejector before undergoing condensation (14-5) [24].

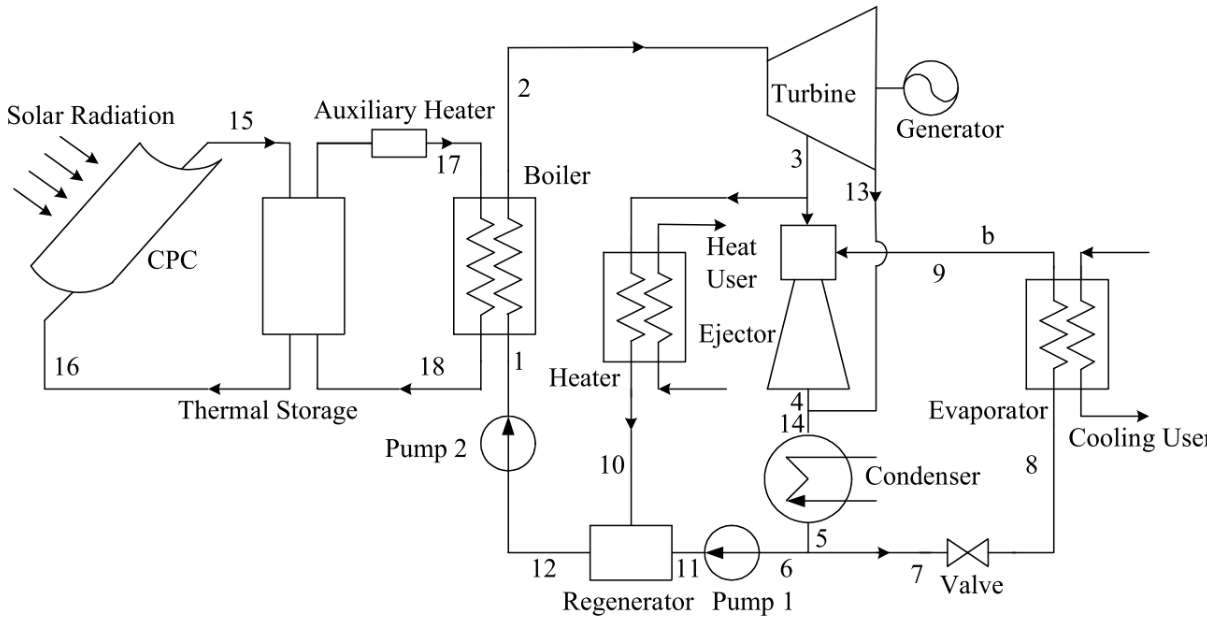


Fig.2.2. Mass coupling for a solar trigeneration system [48].

2.2.2.1.3 Hydraulic coupling trigeneration technologies:

The thermohydraulic process studied by Martin et al. [49] is one of the hydraulic coupling trigeneration processes with work recovery. In this process, work is transferred from the engine cycle to the receiving cycle through a secondary fluid called the transfer fluid, to improve the conversion chain. This process is used exclusively for solar cooling and does not allow for electricity production (Fig.2.3).

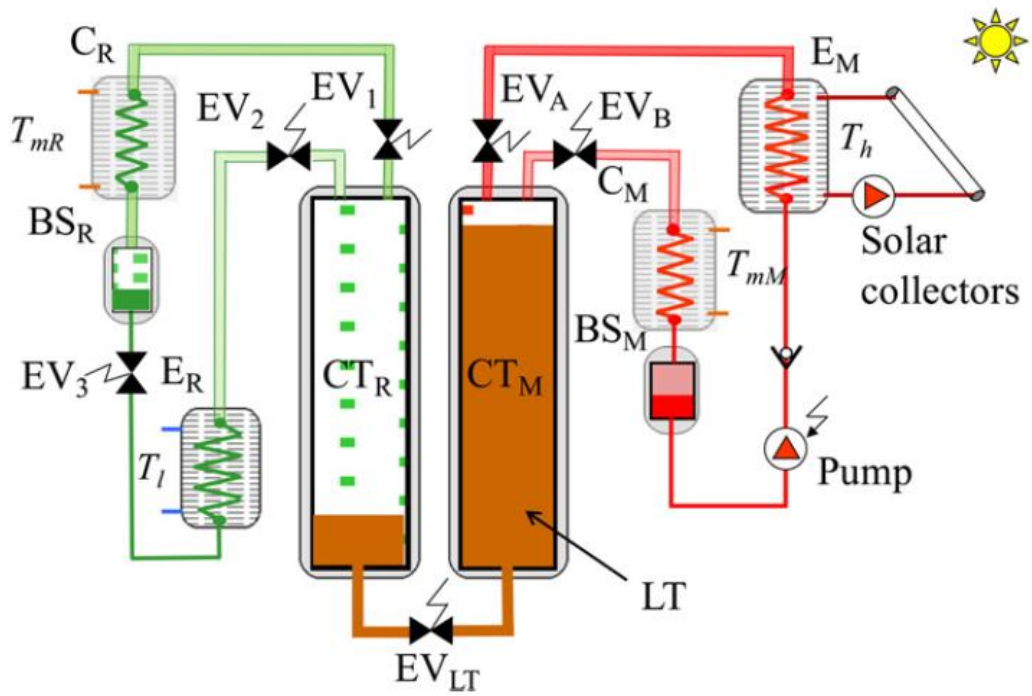


Fig.2.3. Hydraulic coupling for the CHV3T process [49].

2.2.2.1.4 Mechanical coupling trigeneration technologies:

This coupling mode is used in the CAPILI process (Fig.2.4), which combines a driving machine with a receiving machine to achieve trigeneration [50]. The following section will provide a detailed literature review on CAPILI thermohydraulic processes.

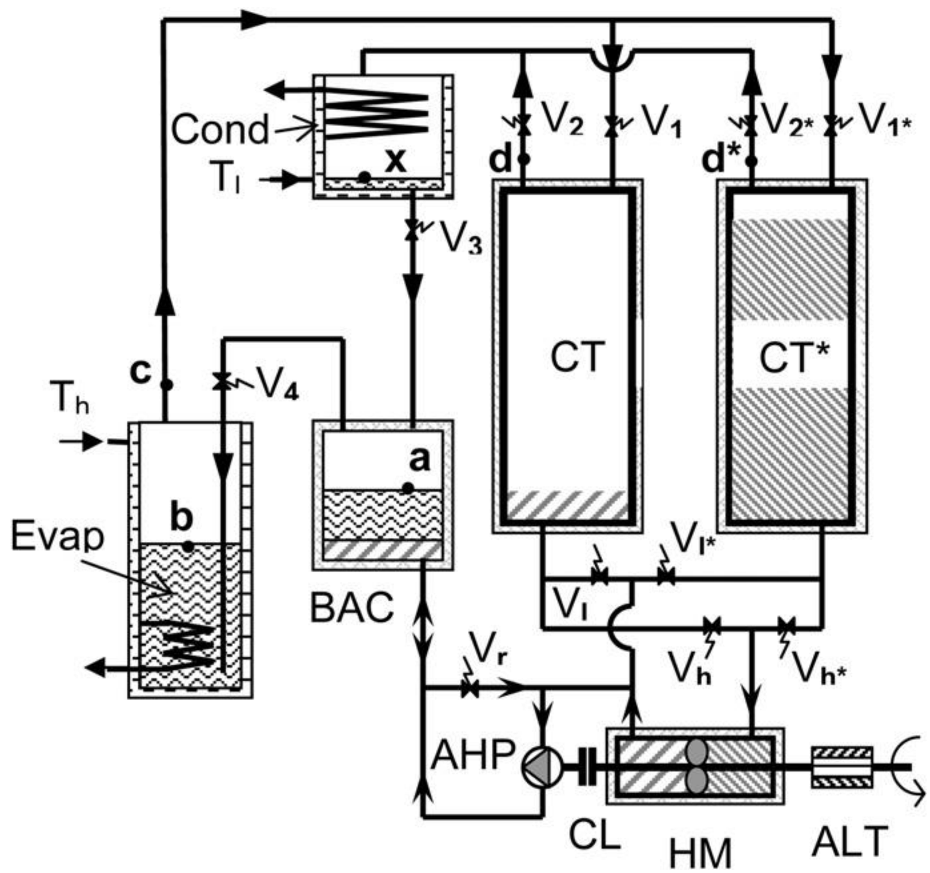


Fig.2.4. The principle of mechanical coupling for a trigeneration system (CAPILI process) [50].

2.3 Thermohydraulic process

Since 2007, the TES team (Thermodynamics, Energy and Reactive Systems) of the Promes laboratory has been conducting original research on thermo-hydraulic processes[51].

The term "thermo-hydraulics" refers to a process involving an incompressible liquid used as an intermediate medium to hydraulically transfer work between different components or thermal subsystems, thereby improving the efficiency of the energy conversion chain[25].

Thermo-hydraulic processes involve machines operating either in motor or receiver mode, or combinations of both. Work is produced by the alternating motion of an inert liquid, which acts as a liquid piston moving alternately between two cylinders (CT) [52]. These processes utilize liquid/gas (L/G) equilibrium during condensation and evaporation, offering numerous potential functions, such as the production of useful heat and/or cooling, with the possibility of generating work [53].

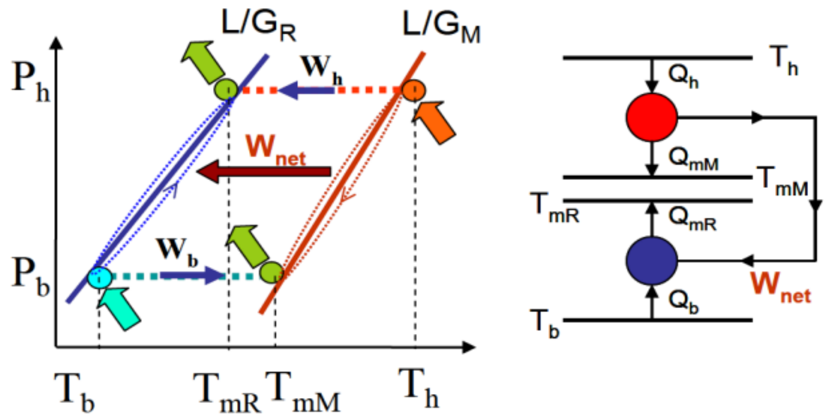


Fig.2.5. A thermo-hydraulic transformer implementing work transfer via a liquid piston [53].

Thermohydraulic processes, powered by renewable energy sources, can meet the different energy needs of the habitat. These processes are based on two thermo-hydraulic fields, named CAPILI and CHV3T. CAPILI addresses electrical needs and has been implemented for both residential [50] and Ocean Thermal Energy Conversion (OTEC) power production [54]. CHV3T, on the other hand, meets heating and air conditioning needs by utilizing "low temperature" heat, particularly solar energy, as its main energy source [25].

2.3.1 CAPILI concept (Carnot's machine with Piston Liquid)

The thermohydraulic process CAPILI is the inverse of the Rankine cycle, uses the liquid piston concept, which can address issues encountered in the Rankine cycle. The liquid piston is undoubtedly not a new concept, it has been known for a long time in thermal engines. Its first known application dates back to 1909, when Humphrey [55] developed an internal combustion engine operating on the Atkinson cycle, which is used in pumping stations and irrigation systems. Since then, interest in the implementation of a liquid piston in energy conversion processes has grown, and various patents describing Stirling engine and Stirling heat pump concepts have been issued [56],[57],[58],[59].

Klüppel and Gurgel [60] presented the operating principles, theoretical analysis, and experimental results of a liquid piston pumping device in which the liquid acts as a displacement piston.

Van de Ven et al. [61] proposed the liquid piston concept as a solution to the difficulties encountered on Stirling engines. Additionally, Van de Ven James [62] proposed a Stirling engine operating in liquid piston heat pump mode.

Research on this concept has been continued to the present day. Motamedi et al. [63] presented a mathematical model, along with its simulation and subsequent validation of the dynamic equations developed for a Stirling pressurizable liquid piston engine. The model developed after that is the subject of an optimization study by Ahmadi R. et al. [64] to have a stable limit cycle dynamic behavior and improved system performance. Samuel Langdon-Arms et al. [65] developed a model of a Stirling solar-powered liquid-piston refrigerator for lower capacity applications, with refrigerator power up to 5 kW.

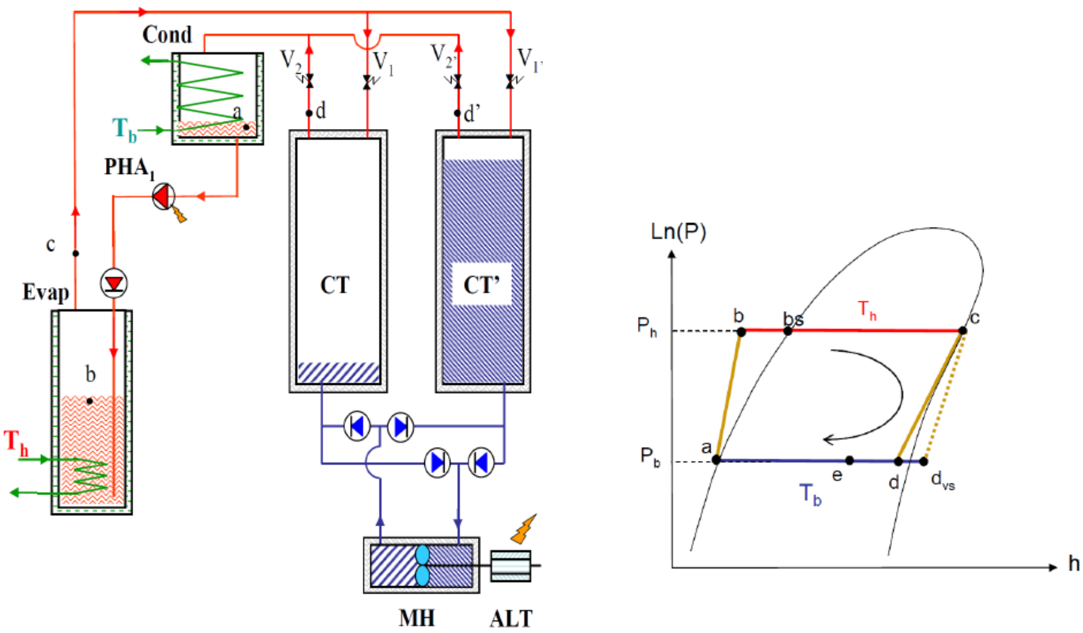
2.3.1.1 Fundamentals of thermo-hydraulic conversion

The dithermal machine CAPILI is a concept that involves converting thermal energy into work through a liquid that play a role of liquid piston. The CAPILI engine typically consists of two cylinders, each connected to a different heat exchanger (an evaporator and a condenser), and operating at various pressures. The liquid moves between these cylinders. The exchange of work between the machine and the environment is accomplished through a hydraulic/mechanical converter, which is traversed by the liquid during the isothermal phases of the cycle. This thermodynamic process can operate either in motor mode when $T_{evap}>T_{cond}$ (for cogeneration or electricity production), or in receiver mode when $T_{evap}<T_{cond}$ (for heat pump or refrigeration) [53]. The work-transfer liquid (LT) in the CAPILI machine must have a very low saturation pressure (such as oil) at the operating temperatures of the process. It must also be immiscible with the working fluid and preferably denser than it[50].

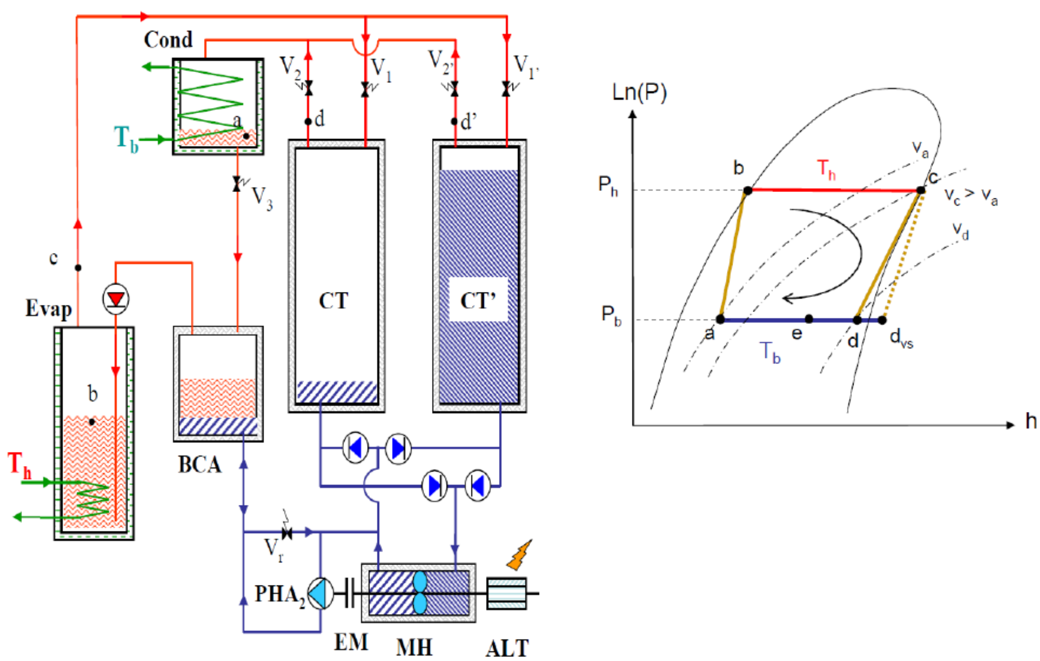
2.3.1.2 Variants of the CAPILI engine process

The CAPILI machine operating in engine mode represents two main configurations, called the 1st or 2nd type. The 2nd type, which is more complex, aligns perfectly with Carnot's cycles, whereas the 1st type CAPILI machine being simpler and less efficient shows a slight deviation [50].

Fig.2.6 represents the schematic and the P-h diagram (Mollier's diagram) of the CAPILI engine of the 1st and the 2nd type, which are presented in detail in the ref. [53]



a)



b)

Fig.2.6. Fundamental schema of the CAPILI motor and the cycle of the working fluid in Mollier's diagram: a) for 1st type, b) for the 2nd type [53].

2.3.1.3 Literature review of CAPILI engine

The CAPILI process has been the subject of several research. [25], [50], [53], [54], [66], [67]. Previous work on the CAPILI thermo-hydraulic machine must be examined to gain a comprehensive understanding of the section discussed in the following chapters.

Mauran et al. in [50] presented the CAPILI process as a significant advancement in thermohydraulic conversion for heat pumps and heat engines, with the potential to achieve near-Carnot efficiencies by minimizing system irreversibilities. This study [50] demonstrates that the CAPILI process offers high exergy efficiencies. While the second type engine is more efficient, the first type provides a simpler and more cost-effective solution. The same reference [50] also indicated that the multipurpose design of the CAPILI process allows it to function flexibly as either an engine or a heat pump, enhancing its utility in residential applications for combined cooling, heating, and power generation. The process presented by Mauran et al [50] shows significant potential to enhance energy efficiency and reduce greenhouse gas emissions in residential settings, supporting sustainable development objectives.

In ref. [54], Semmari et al. introduced the CAPILI process for Ocean Thermal Energy Conversion (OTEC). They emphasize dynamic models using the equivalent Gibbs system concept to optimize the cycle's performance and components. In a subsequent study [54], the same author concluded that the CAPILI cycle can achieve an ideal efficiency of 3.82 % by selecting working fluid R134a, and that the dynamic modeling demonstrated stable performances after one cycle. Furthermore, Semmari et al. [54] suggested that a hydraulic accumulator or implementing a flywheel could enhance the efficiency and stability of the CAPILI OTEC plant.

Driss stitou [53] provided a comprehensive overview of CAPILI technology and presented thermodynamic analysis tools for designing, optimizing, and evaluating the thermal energy transformation process. The overarching goal of this study is to better address the challenges of rational management while minimizing the environmental associated with its transformation.

In another study, Semmari et al [66] developed an analytical model for a hydraulic motor using the concept of hydraulic resistance for the CAPILI system. This model integrates the entire Hydro-Mechanic-Electric-Conversion (HMEC) line, significantly impacting the overall efficiency of hydraulic energy conversion systems operating under variable flow rates or pressure heads. To validate the model, an experimental bench in this study [66] was constructed and tested under varying conditions. The results demonstrated a linear relationship between the hydraulic motor's operating pressure and flow rate, establishing that hydraulic resistance is inversely related to the electrical load. Furthermore, parametric studies identified key efficiency parameters of the HMEC line, showing good agreement between the analytical model and experimental data. The authors [66] concluded that the findings highlight the model's relevance for optimizing and regulating power output in thermo-hydraulic energy conversion systems.

Borgogno et al. [25] aim to achieve trigeneration by integrating two thermohydraulic process pathways (CHV3T and CAPILI) to meet all the needs of the residential sector and advance technological maturity by designing a demonstrator capable of operating in a significant environment.

Zebbar et al. [67] investigated the use of thermohydraulic processes for power generation from low-potential heat sources, such as solar and geothermal energy. The study focused on a thermodynamic analysis of CAPILI concept, particularly the first type. The authors concluded that n-butane (R600) was the suitable working fluid for the thermohydraulic process CAPILI, as it exhibited the highest efficiencies, achieving thermal, Carnot, and second law efficiencies of 20.3%, 23%, and 88%, respectively, at condenser and evaporator temperatures of 30°C and 120°C.

2.3.1.4 Working fluid selection

The selection of the working fluid has been extensively discussed in numerous papers and scientific articles [68], [69], [70], [71]. Most of the studies are based on theoretical investigations of working fluids through the utilization of simulations of thermodynamic models. Scientific papers primarily focuses on the thermo-physical properties of working fluids, with particular emphasis on thermal efficiency, second law efficiency, and net work output. The choice of working fluid requires careful consideration of various thermodynamic, safety, environmental, and economic factors to ensure optimal performance. A suitable fluid should exhibit favorable physical and chemical properties, including low specific volume and viscosity, while also minimizing safety risks such as toxicity and flammability. Additionally, the fluid's environmental impact must be minimal, with low ozone depletion potential (ODP) and global warming potential (GWP). From an economic perspective, cost-effectiveness is essential, along with ensuring high thermal and exergetic efficiency to enhance the overall cycle performance. Therefore, balancing these factors is crucial in determining the most suitable fluid candidates [72].

Under the period (1830-1930), some familiar solvents and volatile fluids had been used. Some common refrigerants were ethers, carbon dioxide, ammonia, sulfur dioxide, methyl formate, HCs, water, carbon tetrachloride and hydro chlorocarbons HCCs. Today, many of these refrigerants are considered "natural refrigerants". For the period (1931-1990), refrigerants such as chlorofluorocarbons CFCs, HCFCs, ammonia and water were commonly used. Between 1990 and 2010, the protection of the stratospheric ozone layer became a significant focus of international environmental policy [72]. During this period, the most widespread working fluids were Chlorofluorocarbons (CFCs). These fluorinated working fluids had a very high ozone depletion potential (ODP) as well as a high global warming potential (GWP). Following the discovery of a hole in the ozone layer, the Montreal Protocol in 1987 aimed to ban fluids with a high ozone depletion potential (ODP) by 1996. Hydrochlorofluorocarbons (HCFCs), which have a non-zero but near-zero ODP, were also subject to these regulations [73].

Since 2011, typical refrigerants are expected to have very low or no ozone depletion potential ODP, low global warming potential GWP and high efficiency. Potential candidates are include low-GWP HFCs, natural refrigerants such as ammonia, carbon dioxide, hydrocarbons and water, as well as unsaturated hydrofluorochemicals like hydrochlorofluoro-olefins (HCFOs) and hydrofluoro-olefins (HFOs) [72]. HFO gases such as R1234yf, R1234ze, R1233zd, etc. are considered as a new generation of refrigerants (4^{th} generation). They are intended to replace older refrigerants like freons (e.g.,R134a and R32) in various refrigeration engineering applications (refrigeration, heat pumps, air conditioning, automotive air conditioning, etc.) [74].

The Kyoto Protocol in 1995 and the Paris Agreement in 2015 aimed to limit the production and use of fluids with high global warming potential (GWP). The Kigali Amendment in 2016, an amendment to the Montreal Protocol, further provides for the gradual phase-out of HFCs [73]. These regulations on working fluids can be summarized in table 2.1 [73].

Table 2.1 Date of ban on working fluids according to the type of fluid

Type of fluid	ODP value	GWP value	Prohibition date
CFC	High	Low - Medium - High	1995
HCFC	Low	Low	2015
HFC	None	Medium - High	2030
HFE	None	Low - Medium	-
HFO	Nulle	Low	-
HC	None	Low	-

2.4 Conclusion

First, cogeneration and trigeneration for energy efficiency are described as energy effecient solutions aimed at reducing primary energy consumption, mitigation greenhouse gas emissions, and achieving sustainable cost savings. In addition, it detailes the thermohydraulic processes, with a particular focus on the CAPILI concept and its different variants. These processes offer a comprehensive framework for evaluating energy systems from technical and economic perspectives. These discussions establish a solid foundation for the in-depth analyses and evaluations presented in the following chapters.

Chapter 3

Thermodynamic analysis of the novel configuration of the thermohydraulic machine ORPILI

3.1 Introduction

The thermo-hydraulic processes CAPILI mentioned in the first chapter have several disadvantages. Firstly, a critical issue is the positioning of the expansion phase under the equilibrium dome. This placement keeps the maximum temperature in the cycle significantly above the critical temperature of the working fluid, which in turn limits the maximum output work or mechanical power per unit mass of the working fluid. Secondly, the CAPILI machine relies on a complex control system composed of various solenoid valves and sensors to reverse the flow direction in the hydraulic motor. Finally, the current thermo-hydraulic CAPILI machine includes a condensate transfer pump driven by an electric motor, which is not the most practical solution. To address these issues, the present study proposes the development of a new concept that retains the advantages of the CAPILI cycle while aiming to eliminate its respective disadvantages. The proposed advancements include: first, the introduction of steam superheating, which raises the average temperature of heat input into the cycle, effectively transforming it into a variant of the Organic Rankine cycle known as ORPILI (Organic Rankine with PIston LIquid). Second, an innovative design of the ORPILI thermo-hydraulic machine reduces the number of solenoid valves by incorporating a mechanical transmission. Third, a steam turbine has been added to power the transfer pump, thereby improving the system's efficiency and overall performance.

This chapter describes the operating principle of the new ORPILI thermo-hydraulic process configuration. Based on a thermodynamic analysis conducted for this concept, an initial estimation of the cycle’s energy and exergy efficiencies is provided for different working fluids, considering three temperature levels: condensation temperature, evaporation temperature, and superheat temperature.

The different working fluids used in the process will be studied, and their performances compared to determine which working fluid is most suitable for our application. This will provide an initial assessment of the potential of the thermo-hydraulic process ORPILI.

3.2 Description of the novel concept of the organic Rankine thermo-hydraulic machine with liquid piston

3.2.1 Principle of operation

The ORPILI system is designed to efficiently convert thermal energy into mechanical power through a series of components. An evaporator (3), connected to a heat source, operating at an evaporator temperature T_{evap}, while a condenser, linked to a heat sink, operates at a lower temperature T_{cond}. Two insulated work-transfer cylinders (1 and 19) facilitate efficient energy transfer, and a steam turbine (5) converts thermal energy into mechanical work. A superheated steam-driven transfer pump (6) ensures the condensate is transferred to the evaporator (3) and maintains the necessary pressure differential between the evaporator and condenser. Additional components include a superheater (2) for further heating the steam, hydraulic motors (7 and 8) coupled through gears (9 and 11) to convert fluid energy into mechanical work, and a generator (10) to produce electrical energy. The system also incorporates two-way solenoid valves (12 and 13) for steam flow control, an extraction steam valve (14), non-return valves (15-18) to prevent backflow, and level sensors (20 and 21) to monitor fluid levels. A solar panel (23) provides an auxiliary renewable energy source to enhance sustainability, and the panel board (22) houses the control mechanisms and circuitry for managing the entire system's operations.

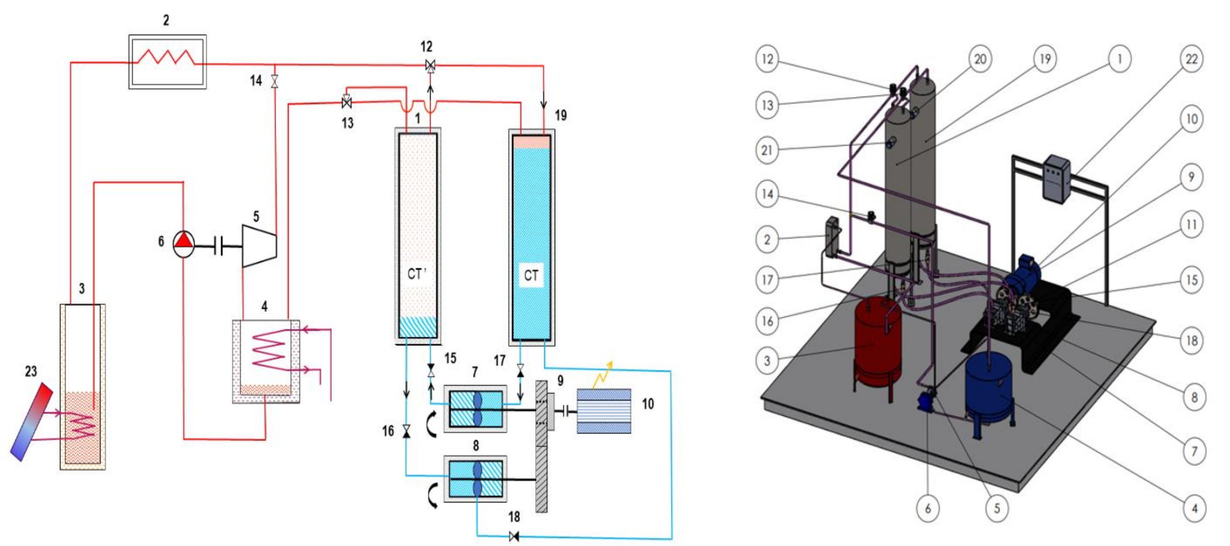


Fig.3.1 a) ORPILI plant schematic, b) View of the test bench of the novel thermo-hydraulic machine ORPILI.

1- work-transfer cylinder CT’

11-gear

2- superheater
3- evaporator
4- condenser
5- steam turbine
6- transfer pump
7 and 8- hydraulic motors
9-gear
10- generator
12,13 -2-way solenoid valve
14- extraction steam valve
15,16,17 and 18- non-return valves
19-work-transfer cylinder CT
20 and 21-level sensor
22- panel board
23- solar collector

The proposed ORPILI system, represented in this study (Fig.3.1), is a novel and sophisticated approach to energy conversion. By integrating several components, it efficiently converts thermal energy into mechanical and electrical power. The system features an evaporator (3), which absorbs heat initiates phase change of the working fluid from liquid to vapor, connected to a high-temperature heat source. This vapor is then further heated in the superheater (2) to reach the optimal temperature before entering the turbine. The superheated steam passes through a two-way solenoid valve (12), and enters a work-transfer cylinder (19), where it exerts pressure on the surface of the liquid acting as a liquid piston. The pressure beneath this piston matches that in the evaporator, denoted as p_{evap}. A diaphragm may be inserted to prevent direct contact between the steam and liquid. This pressure drives a hydraulic motor connected to a generator via a freewheel, converting mechanical energy into electrical energy.

Additionally, the pressurized fluid from the liquid piston (FLP) is directed into a hydraulic motor (7), which is coupled to a generator (10) via a freewheel. Afterward, the FLP flows to another work-transfer cylinder (1) through a non-return valve (16). During this phase, the solenoid valve (13) connects the steam space in the work-transfer cylinder (1) to the condenser (4) at a pressure p_{cond}, where the condensate is pumped back to the evaporator (3) by a transfer pump (6). This pump is driven by a steam turbine (5), which is supplied from the superheater (2) via the extraction valve (14). The pump maintains the required pressure drop between the evaporator and the condenser ($\Delta p = p_{evap} - p_{cond}$).

When the FLP level reaches a designated level n2, as detected by a level sensor (20), the non-return valves (16) and (18) are activated to change the direction of the flows. Superheated steam then enters the initial work-transfer cylinder (1), creating pressure that forces the hydraulic oil toward another hydraulic motor (8) through the non-return valve (16). This hydraulic motor (8) is connected to a generator (10) via a pair of gears mechanism (9) and (11), along with a freewheel.

The cycle continues as the hydraulic oil exits the hydraulic motor (8), passes through another non-return valve (18), and re-enters the work-transfer cylinder (19), pushing the working fluid steam toward the condenser (4) via the solenoid valve (13). Once the FLP level reached the designated level n1, detected by level sensor (21), solenoid valves (12) and (13) are activated, and the cycle begins again

3.3 Description of the thermodynamics cycle

This section discusses the theory and mathematics of ORPILI power plants and presents the relevant equations. First, the cycle's thermodynamic parameters are outlined, followed by the equations governing each process. Finally, the equations are introduced to estimate the efficiencies of different working fluids in the proposed thermohydraulic system.

3.3.1 Working principles

The operation of this process is based on the thermodynamic cycle followed by the working fluid, characterized by an alternation of half-cycles consisting of two main phases. These phases follow one another throughout the operation of the process, during which the roles of the work-transfer cylinders are reversed.

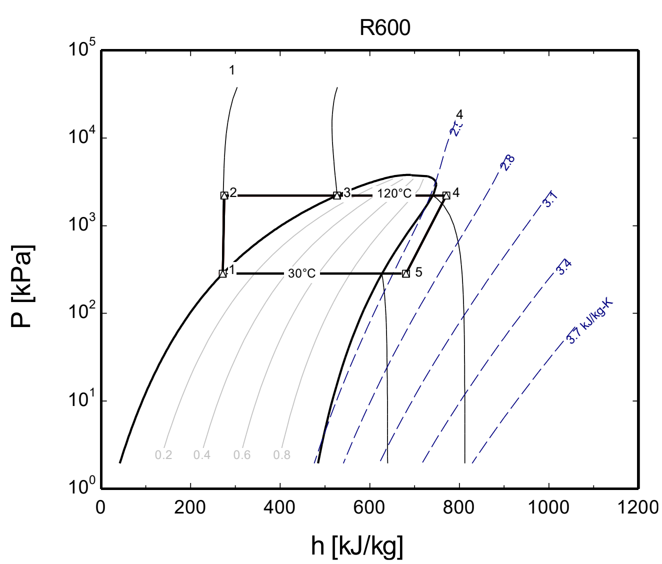


Fig.3.2. ORPILI Cycle on a p-h diagram.

The working fluid undergoes a thermodynamic cycle, represented as (12345), which is depicted schematically on the Mollier diagram (p-h) diagram (pressure vs. enthalpy) in Fig. 3.2. The diagram illustrates the essential processes and heat transfer of the system. The cycle of this innovative machine is a Rankine type, utilizing superheated steam with a steam generator operating at high pressure and temperature (T_{evap}, p_{evap}), and a condenser functioning at low pressure and temperature (T_{cond}, p_{cond}).

3.3.1.1 System equations and theoretical analysis

These equations describe the theoretical thermodynamic process at each point in the cycle. As demonstrated in Fig.3.2 the working fluid passes through four main processes to complete one cycle.

Process (1-2) compression in the pump

The working fluid leaves the condenser as saturated liquid at low-pressure p_l and then is pumped to the evaporator pressure (p_H) at constant entropy. As shown in Fig.3.2, point 1 indicates the state of the working fluid at pump inlet, and point 2 represents the state at pump outlet. The specific work input to the pump is calculated using the following equation:

$$W_{pump} = (h_2 - h_1) = v_{\_vol1} \times (p_2 - p_1) \tag{3.1}$$

Where W_{pump} is the work input of pump (J/kg), h_1: is the enthalpy at the pump inlet (J/kg), h_2: is the enthalpy at the pump exit (J/kg), $\boldsymbol{v}_{\_vol1}$: is the specific volume (m^3/kg), p_1: pressure in the pump inlet, p_2: pressure in the pump outlet.

Process 2-4 heat addition in the evaporator

Heat is added to the working fluid during this procedure, causing it to evaporate in the evaporator. The evaporator is connected to the CT cylinder, resulting in the superheating of steam, and the process can be considered isobaric. Vapor production in the evaporator at high-pressure (p_H) then displaces the transfer liquid (LT) towards the CT' cylinder until it reaches the high level

$$Q_{in} = (h_4 - h_2) \tag{3.2}$$

Q_{in} refers to the specific heat added to the working fluid (kJ/kg) and h_4 is the vapor enthalpy at the evaporator's exit (kJ/kg).

Process 4-5 Expansion

The process involves an isentropic expansion of vapor contained within the CT cylinder (see figure 3.1, case a), where the energy absorbed in the evaporator is converted into useful mechanical energy. Point 5 indicates the expander exit, where the work is done and can be calculated as:

$$W_{\exp} = (1-y)\times(h_4 - h_5) \tag{3.3}$$

Where W_{exp} is the work input of the expander (J/kg) and h_5 is the vapor enthalpy at the expander exit (J/kg).

The following equation expresses the work of turbine:

$$W_{turbine} = y\times(h_4 - h_5) \tag{3.4}$$

From energy balance (Fig.3.1.a)

$$W_{turbine} = W_{pump} \tag{3.5}$$

$$y\times(h_4 - h_5) = (h_2 - h_1) \tag{3.6}$$

The net work developed by the cycle

$$W_{cycle} = W_{\exp} - W_{pump} \tag{3.7}$$

Process (5-1) Heat rejection

Heat is rejected during this process, and the working fluid, in vapor form from cylinder CT'(Fig.3.1.a), is condensed as it moves towards the condenser. In this phase, it is recycled back into the system. The working fluid becomes saturated after it leaves the condenser. The state of the working fluid indicated as Point 1 in Fig.3.2, which represents the condenser exit and the pump inlet. The amount of heat rejected can be calculated as:

$$Q_{out} = (h_5 - h_1) \tag{3.8}$$

Where Q_{out} is the specific heat rejected in the condenser (J/kg).

The net thermal efficiency for the entire process can be calculated from the following equation:

$$\eta_{th} = \frac{W_{cycle}}{Q_{in}} = \frac{((1-y)\times(h_4 - h_5)) - (h_2 - h_1)}{h_4 - h_2} \tag{3.9}$$

Thermal efficiency is the ratio of the network output to heat absorbed in the evaporator.

For the 2nd law efficiency, it can be calculated as:

$$\eta_{II} = \frac{\eta_{th}}{\eta_C} \tag{3.10}$$

Where the Carnot efficiency is expressed by the following equation:

$$\eta_{Carnot} = \frac{T_{cond}}{T_{evap}} \tag{3.11}$$

The input parameters for the ORPILI cycle operation are as follows: the superheated temperature ranges from 65°C to 130°C, and the evaporator temperature ranges from 60°C to 120°. The condenser temperature is held constant at 30°C. Based on these conditions, and taking into account the arguments mentioned above, the working fluids adopted and evaluated for the present ORPILI cycle include R600a, R600, R1234yf, R1234ZE, R1233ZD, and SES36.

Several databases of thermophysical properties for pure fluids and fluid mixtures are available. In this chapter, the thermophysical properties of the working fluids of the various points in the ORPILI cycle such as specified enthalpy and entropy can be extracted using CoolProp software [75],[76]. The high and low temperatures of the working fluid must be defined by users as well. Some thermodynamic models have been created in Excel and linked to the NIST CoolProp working fluids database. These thermodynamic models are created in Excel in order to run numerical calculations and to compare the working fluids from a thermo-physical perspective. Safety and environmental criteria were also taken into consideration to complete the selection process.

3.3.2 CoolProp: thermophysical properties library details (CoolProp_Microsoft Excel)

CoolProp [77] is a free open-source licensing, cross-platform fluid properties database based C++. It provides thermophysical properties for pure fluids, pseudo-pure fluids, and moist air. In this study, the ORPILI cycle will be modeled in Microsoft Excel by calling the Coolprop library. The working fluids mentioned above will be evaluated using this model. The process diagram of the ORPILI cycle and the P-h diagram are shown in Fig.3.2. According to the diagram, the working fluid leaves the evaporator at a temperature of 60°C and enters the transfer cylinder (CT) at a superheated temperature of 65°C (point 4).

At point 1, it is necessary to determine the pressure. With the condenser temperature set at 30°C, we can utilise the CoolProp function in Microsoft Excel to find the pressure. Following the isobaric line (Fig.3.2), the pressure at point 5 equals that at point 1 ($p_1=p_5$). The evaporator pressure can be determined from the evaporator temperature, which is 60°C at point 3. The pressures at points 2 and 4 on the constant pressure line are equal to the pressure at point 3 ($p_2=p_3=p_4$). We will determine the properties of the fluid at points 1, 2, 3, 4, and 5. we just go through all the knows to calculate our unknowns. All the units are specified. We know our temperature, our pressure, and we can calculate the enthalpy and entropy (see Appendix).

3.4 Results and discussion of the thermodynamic analysis

3.4.1 Choice of the best working fluid

A computational model is developed to carry out the exegetic analysis of the system. Under similar temperature conditions, the comparative performance of the six working fluids mentioned above is evaluated.

Table 3.1 shows the thermodynamic performances (thermal and second-law efficiencies) of the ORPILI cycle of the six fluids. The results indicate that the refrigerants R1234yf and R1234ze exhibit considerably lower thermal efficiency compared to the other fluids, specifically 11.6% and 13.9%, respectively. This indicates that these working fluids are unsuitable for this particular type of machine.

Furthermore, the machine attains optimal efficiency when operating with refrigerants R-600a, R-600, R1233zd, and SES36 within the temperature range of 65 to 130°C. The highest thermal efficiencies observed are 16.1%, 16.9%, 17.5%, and 15.6% correspondingly.

For the working fluid R1233zd, the results show that this refrigerant has the highest thermal efficiency (η_{th}), which is 17.5 % at a superheat temperature (T_{sc}) of 130°C, corresponding to a second-law efficiency of 76.6 %. The corresponding Carnot efficiency and pressure drop are about 22.4 % and 1416.4 kPa, respectively. According to the previously mentioned selection criteria, the results indicate that the fluid R1233zd is suitable.

The HFO gas R1233zd is identified as the optimal working fluid for CAPILI applications, replacing the formerly widely used R123 in ORC applications. Furthermore, R1233zd has minimal environmental impact, is completely non-flammable, , and is non-toxic[25].

Table 3.1. Thermodynamic performances of the ORPILI cycle of different working fluids as function as the superheated temperature

Tsc (°C)	***R600a***		***R600***		***SES36***		***R1233ZD***		***R1234ZE***		***R1234yf***	
	η_{th}	η_{II}	η_{th}	η_{II}	η_{th}	η_{II}	η_{th}	η_{II}	η_{th}	η_{II}	η_{th}	η_{II}
65	0.078	0.871	0.080	0.888	0.072	0.799	0.081	0.903	0.077	0.852	0.073	0.817
70	0.089	0.855	0.090	0.873	0.082	0.789	0.092	0.889	0.086	0.833	0.082	0.795
75	0.098	0.839	0.100	0.859	0.091	0.779	0.102	0.877	0.095	0.815	0.090	0.773
80	0.107	0.824	0.109	0.846	0.099	0.769	0.112	0.864	0.103	0.797	0.097	0.752
85	0.115	0.809	0.118	0.832	0.107	0.759	0.121	0.852	0.110	0.779	0.103	0.729
90	0.122	0.7941	0.126	0.819	0.115	0.748	0.129	0.840	0.117	0.760	0.109	0.707
95	0.129	0.780	0.133	0.807	0.122	0.739	0.137	0.829	0.123	0.743	0.113	0.683
100	0.135	0.767	0.140	0.794	0.129	0.728	0.144	0.817	0.127	0.724	0.116	0.699
105	0.141	0.752	0.147	0.782	0.135	0.718	0.151	0.806	0.132	0.704	--	--
110	0.147	0.739	0.153	0.770	0.141	0.709	0.158	0.796	0.136	0.683	--	--
115	0.152	0.725	0.158	0.758	0.146	0.699	0.164	0.785	0.139	0.698	--	--
120	0.156	0.711	0.164	0.746	0.151	0.689	0.170	0.774	--	--	--	--
125	0.159	0.698	0.164	0.747	0.156	0.679	0.175	0.764	--	--	--	--
130	0.161	0.702	0.169	0.736	0.155	0.676	0.175	0.766	--	--	--	--

3.4.1.1 Effect of the temperature of evaporation of the suitable working fluid (R1233zd) on the efficiencies

Table 3.2 shows the variation of thermal efficiency (η_{th}) and the second law efficiency (η_{II}) of a system for the selected working fluid R1233ZD at different evaporator temperatures (T_{evap}), ranging from 60°C to 120°C, while keeping the condenser temperature constant at (T_{cond}=30°C). The Carnot efficiency (η_{Carnot}) corresponding to each evaporator temperature is also provided. As the evaporator temperature T_{evap} increases, the thermal efficiency (η_{th}) also increases, indicating that raising the evaporator temperature enhances the thermal performance of the system. However, the second law efficiency (η_{II}) generally decreases with increasing of T_{evap}.

Table 3.2. Effect of variation of evaporator temperature in efficiencies											
T_{evap}=60°C, T_{cond}=30°C, η_{Carnot}=0.09			**T_{evap}=65°C, T_{cond}=30°C, η_{Carnot}=0.10355**			**T_{evap}=70°C, T_{cond}=30°C, η_{Carnot}=0.116618**			**T_{evap}=75°C, T_{cond}=30°C, η_{Carnot}=0.12931**		
T_{sc}(°C)	**η_{th}**	**η_{II}**	**T_{sc} (°C)**	**η_{th}**	**η_{II}**	**T_{sc} (°C)**	**η_{th}**	**η_{II}**	**T_{sc}(°C)**	**η_{th}**	**η_{II}**
65	0.081314	0.90259	70	0.0921	0.889425	75	0.102232	0.876641	80	0.111751	0.864211
70	0.081232	0.901676	75	0.092024	0.888685	80	0.102167	0.876078	85	0.111702	0.863827
75	0.081128	0.900521	80	0.091921	0.887696	85	0.102071	0.875256	90	0.111617	0.863175
80	0.081005	0.899156	85	0.091796	0.886491	90	0.101949	0.87421	95	0.111503	0.862288
85	0.080866	0.897607	90	0.091652	0.885096	95	0.10299	0.88314	100	0.111362	0.861198
90	0.080711	0.895897	95	0.09149	0.883533	100	0.101639	0.871552	105	0.111198	0.859929
95	0.080545	0.894046	100	0.091313	0.881825	105	0.101456	0.869987	110	0.111014	0.858505
100	0.080367	0.89207	105	0.091123	0.879989	110	0.101258	0.868289	115	0.110812	0.856944
105	0.080179	0.889987	110	0.090922	0.878042	115	0.101047	0.866476	120	0.110594	0.855263
110	0.079983	0.887808	115	0.09071	0.875997	120	0.100823	0.864561	125	0.110363	0.853477
115	0.079779	0.885546	120	0.090489	0.873865	125	0.100589	0.862557	130	0.11012	0.851598
120	0.079569	0.883212	125	0.09026	0.871658	130	0.100347	0.860474			
125	0.079353	0.880815	130	0.090025	0.86939						
130	0.079132	0.878363									
T_{evap}=80°C, T_{cond}=30°C, η_{Carnot}=0.141643			**T_{evap}=85°C, T_{cond}=30°C, η_{Carnot}=0.153631**			**T_{evap}=90°C, T_{cond}=30°C, η_{Carnot}=0.165289**			**T_{evap}=95°C, T_{cond}=30°C, η_{Carnot}=0.17663**		
T_{sc}(°C)	**η_{th}**	**η_{II}**	**T_{sc}(°C)**	**η_{th}**	**η_{II}**	**T_{sc}(°C)**	**η_{th}**	**η_{II}**	**T_{sc}(°C)**	**η_{th}**	**η_{II}**
85	0.120695	0.852107	90	0.129097	0.840303	95	0.136987	0.828772	100	0.144394	0.817491
90	0.120667	0.851907	95	0.129095	0.840292	100	0.137018	0.828959	105	0.144463	0.817884
95	0.120599	0.851426	100	0.129048	0.839987	105	0.136997	0.828834	110	0.144474	0.817946
100	0.120496	0.850701	105	0.128962	0.839426	110	0.136932	0.82844	115	0.144435	0.817724
105	0.120363	0.849764	110	0.128842	0.838644	115	0.136829	0.827815	120	0.144353	0.817259
110	0.120204	0.848642	115	0.128692	0.837669	120	0.136692	0.826989	125	0.144233	0.816583
115	0.120022	0.847358	120	0.128516	0.836525	125	0.136527	0.825987	130	0.144082	0.815723
120	0.119821	0.845933	125	0.128318	0.835235	130	0.136336	0.824831			
125	0.119601	0.844383	130	0.1281	0.833815						
130	0.119366	0.842724									

Table 3.2 (Continue) Effect of variation of evaporator temperature in efficiencies

T_{evap}=100°C, T_{cond}=30°C, η_{Carnot}=0.187668			T_{evap}=105°C, T_{cond}=30°C, η_{Carnot}=0.198413			T_{evap}=110°C, T_{cond}=30°C, η_{Carnot}=0.208877			T_{evap}=115°C, T_{cond}=30°C, η_{Carnot}=0.219072		
T_{sc}(°C)	η_{th}	η_{II}	T_{sc}(°C)	η_{th}	η_{II}	T_{sc}(°C)	η_{th}	η_{II}	T_{sc}(°C)	η_{th}	η_{II}
105	0.151341	0.806433	110	0.157852	0.795574	115	0.163945	0.784886	120	0.169637	0.774342
110	0.151456	0.807044	115	0.158019	0.796418	120	0.164174	0.785981	125	0.169937	0.775711
115	0.151504	0.807301	120	0.158111	0.79688	125	0.164316	0.786662	130	0.170137	0.776627
120	0.151496	0.807258	125	0.158139	0.797022	130	0.164386	0.786998			
125	0.151439	0.806957	130	0.158113	0.79689						
130	0.151341	0.806434									

T_{evap}=120°C, T_{cond}=30°C, η_{Carnot}=0.229008		
T_{sc}(°C)	η_{th}	η_{II}
125	0.174941	0.76391
130	0.175324	0.765583

3.5 Conclusion

In this chapter, a modified configuration of a thermohydraulic machine was proposed to enhance its performance. To achieve this, steam superheating, implementing a mechanical transmission, and a steam turbine were integrated into the basic CAPILI machine. These modifications led to the development of a new Organic Rankine cycle variant, known as ORPILI.

A parametric study was conducted to evaluate the effects of key operating parameters (i.e., superheated temperature, evaporator temperature, and condenser temperature) on the thermodynamic performances (thermal efficiency, second law efficiency, Carnot efficiency) of the ORPILI cycle. The study considered various working fluids, including R600a, R600, R1234yf, R1233ZD, R1234ZE and SES36. Among these, R1233zd considered working fluids for the developed cycle ORPILI, R1233zd has the highest performance, which makes this fluid suitable for the ORPILI system.

The results showed that increasing the evaporator, along with the superheated temperature, led to improved thermal efficiency. However, this also resulted in a decrease in second law efficiency. Additionally, increasing the condenser temperature decreased the thermal and second-law efficiencies.

Based on these findings and the selection of R1233ZD as the optimal working fluid, the following chapter presents a series of analyses aimed at investigating the behaviour of the hydraulic system within the new proposed ORPILI cycle.

Chapter 4

Development of an analytical model of the hydraulic system of the ORPILI machine

4.1 Introduction

In this chapter, a detailed examination of the hydraulic concept of ORPILI plant's system is conducted. Following the system's description, a series of mathematical models and analyses are employed to optimize the design of its components. This aspect of the study highlights the originality of the proposed concept.

4.2 Hydraulic system description of ORPILI plant

The hydraulic system for the ORPILI concept is envisaged according to the principle schematic shown in Fig.4.1. This figure illustrates the transfer process of the liquid LT between cylinders, highlighting the role of the hydraulic converter and valves in controlling the flow.

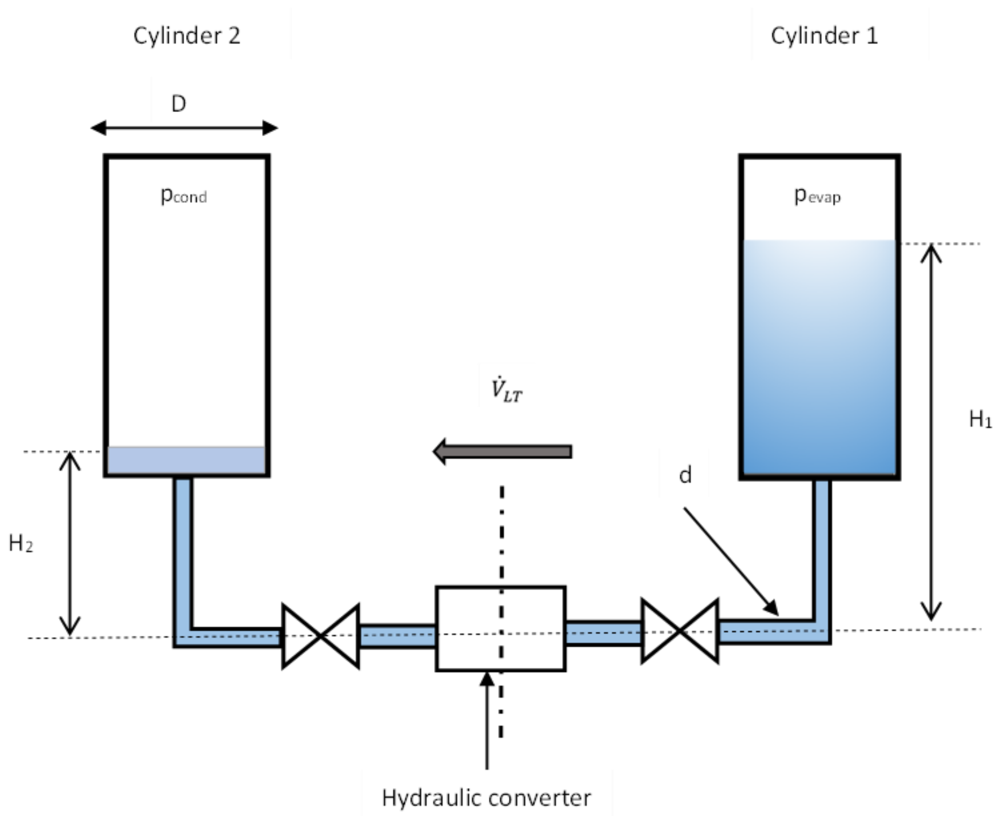


Fig.4.1. Hydrostatic scheme of the hydraulic part of the power plant [24].

4.2.1 Parameters of the mathematical model of the hydraulic system

The equations for the model (Fig.4.1), derived from Bernoulli's equation, include hydraulic power, available mechanical power, admissible power, admissible Reynolds number, volume flow rate.

4.2.1.1 Definition of the hydraulic power

Hydraulic power, denoted as P_{hyd} (eq.4.2), is the power consumed by the hydraulic converter. Bernoulli's equation (4.1) can be applied to the scheme shown in Fig.4.1, considering the minor losses characterized by their flow coefficient, to evaluate hydraulic power (eq.4.2).

$$p_{evap} + \frac{\rho V_1^2}{2} + \rho g H_1 = p_{cond} + \frac{\rho V_2^2}{2} + \rho g H_2 + \frac{P_{hyd}}{\dot{V}_{LT}} + \Delta P_{\text{Minor losses}} \tag{4.1}$$

$$P_{hyd} = -\frac{8 \times \rho \times K_{total} \times \dot{V}_{LT}^{3}}{\pi^2 \times d^4} + (\Delta p + \Delta H \times \rho \times g) \times \dot{V}_{LT} \tag{4.2}$$

4.2.1.1.1 Definition of the minor losses total resistance coefficient

Minor losses occur at change of section, such as pipe features: the entrance of the pipe, exit from a pipe, and fluid system components, including bends in a pipe, valves (Fig.4.1), and other fittings [78]. The values of loss coefficients K for each element contributing to minor losses such as the threaded elbow (K_{elbow}), the entry to a pipe from a cylinder ($K_{entrance}$), and the exit from a pipe into a cylinder (K_{exit}) can be determined from reference[79]. Additionally, the valve loss coefficient K_{vs}, which depends on the nominal diameter, is provided in this reference [80].

The total flow coefficient, K_{total}, is evaluated as the sum losses that occur in the hydraulic system shown in Fig.4.1

$$K_{total} = 2K_{vs}(d) + K_{entrance} + 2K_{elbow} + K_{exit} \tag{4.3}$$

4.2.1.2 Definition of the available mechanical power

The available mechanical power, P_{av}, represents the amount of mechanical power generated by the engine cycle and transferred to the transfer liquid. This power depends on factors such as the diameter of the transfer cylinder, the vertical distance covered by the transfer liquid, the pressure difference between the evaporator and the condenser (Δp), and the frequency of the thermodynamic cycle $f = \tau^{-1}$, where τ is the duration (in seconds) of a single thermodynamic cycle.

The power may be fully or partially delivered to the turbine, depending on the losses in the hydraulic circuit, such as those cause by bends and valves and other components, which are, in turn, influenced by the diameter of the transfer piping and the volumetric flow rate of the transfer liquid. However, a fraction of the mechanical power P_{av} accessible at the transfer cylinders is used to overcome the losses within the hydraulic circuit, as directly derived from equation (4.2). The remaining power is then converted into mechanical power by the hydraulic converter.

$$P_{av} = \Delta p \times \frac{\pi \times D^2}{4} \times \Delta H \times f = \Delta p \times \frac{\pi \times D^2}{4} \times \frac{\Delta H}{\tau} \tag{4.4}$$

4.2.1.3 Definition of the admissible power

One of the factors that must be considered is the maximum allowable flow velocity, which is crucial for preserving the system's integrity and performance. It has been established that the flow velocity, or admissible speed, can reach a maximum of 6m/s [81].This significantly enhances the admissible power and, in turn, increases the specific power (kW/kg) of the new power plant. In fact, it is advisable to maintain a specific flow velocity in hydraulic pipes to prevent the transition to a turbulent regime characterised by roughness. In this context, admissible power refers to the maximum power that a hydraulic system or component can handle without exceeding its design constraints or resulting harm. The admissible power, P_{ad} (eq.4.6), can be calculated by first substituting the admissible speed, V_{ad}, into the volume flow equation (4.5), and then substituting it into the hydraulic power equation (4.2) to obtain the admissible power (eq.4.6). This calculation takes into consideration various factors such as the design, materials, and operating conditions of the hydraulic components.

$$\dot{V}_{LT\,ad} = V_{ad} \times \pi \times \frac{d^2}{4} \tag{4.5}$$

$$P_{ad} = P_{hyd}\left(\dot{V}_{LT\,ad}\right) \tag{4.6}$$

4.2.1.4 Definition of the admissible Reynolds number

The admissible Reynolds number, denoted as Re_{ad} (eq.4.7) is obtained by substituting the admissible speed V_{ad} into the Reynolds number formula. This value depends not only on the admissible speed V_{ad} but also on the kinematic viscosity of the hydraulic fluid, ν_f.

$$\mathrm{Re}_{ad} = \frac{V_{ad} \times d}{\nu_f} \tag{4.7}$$

4.2.1.4.1 Selection of hydraulic oil kinematic viscosity

The hydraulic oil viscosity grade selection must be compatible with the typical operating temperature. Viscosity is a crucial factor in the flow of oil in hydraulic system, as it determines the oil's resistance to flow as essential aspect for both lubrication and energy transmission[82]. As stated by the same source [82], hydraulic systems typically utilize oil with a viscosity ranging from 32 to 68 cSt at a temperature of 40°C (Fig.4.2) [83],[84],[85]. However, in thermo-hydraulic machine where the hydraulic oil is exposed to superheated vapor, the selection of hydraulic oil is contingent upon vapor superheated temperature. For instance, if the temperature reaches 100°C, it is necessary to use a hydraulic oil with a viscosity of at least at 15 cSt, which corresponds to a hydraulic oil ISO VG 150. To meet the requirements of a temperature of 130°C, a ISO VG 460 hydraulic oil is necessary to maintain a viscosity of 15 cSt. In this scenario, the power plant should be started by heating the hydraulic oil above 40°C, ensuring the kinematic viscosity remains below 600 cSt.

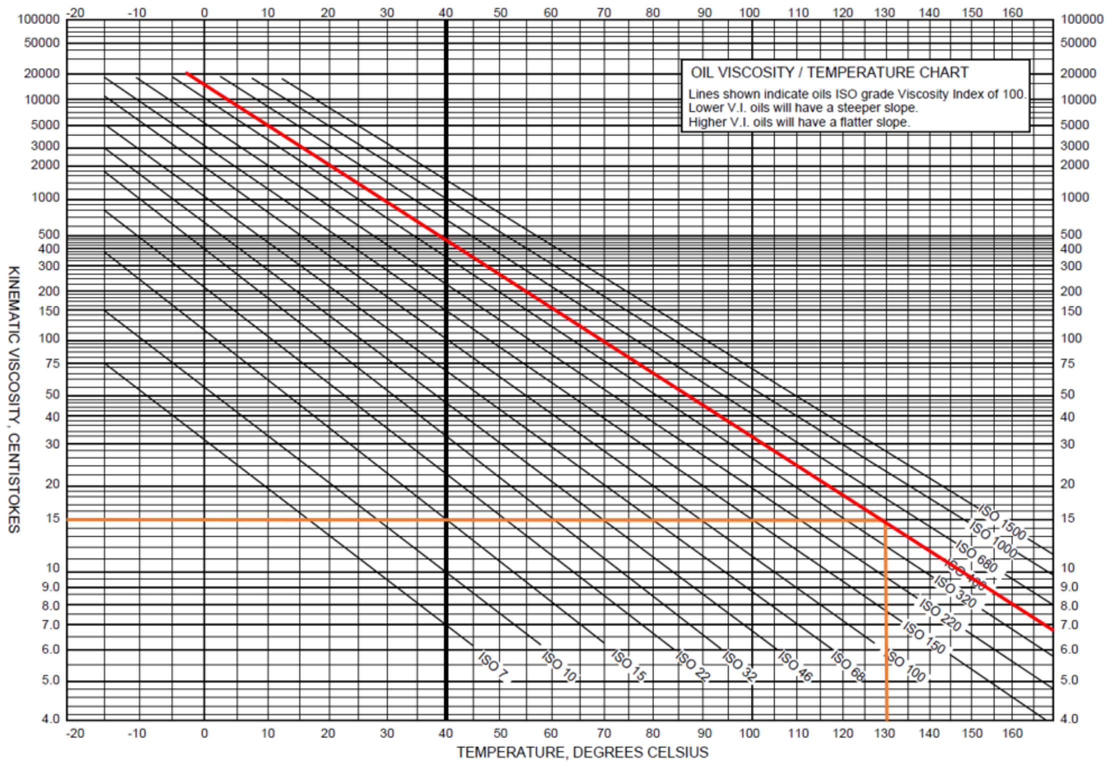


Fig.4.2. Variation of the kinematic viscosity of the oil according to temperatures [83], [84], [85].

4.2.1.5 Determination of the flow rate

The flow rate $\dot{V}_{LT}$ through the turbine can be determined by solving the cubic equation (eq.4.8), which can alternatively be expressed as eq.4.9. The constants C_1 and C_2 are defined in equations 4.10 and 4.11, respectively. For real solutions to exit, the discriminant Δ (eq.4.12) of this cubic equation must be negative[54].

With the resolution of equation 4.9, we obtained the inequality (eq.4.14) that may be utilized to find real solutions for the flow rate $\dot{V}_{LT}$. Equations 4.15 and 4.16 define a range for K_{total}, establishing its minimal limits for P_{av} and maximal limits of P_{ad}.

$$\frac{8\times K_{total}\times \dot{V}_{LT}^{3}}{g\times \pi^{2}\times d^{4}}-(\Delta p+\Delta H\times \rho\times g)\times \dot{V}_{LT}+P_{hyd}=0 \tag{4.8}$$

$$\dot{V}_{LT}^{3}-C_1\times \dot{V}_{LT}+C_2=0 \tag{4.9}$$

$$C_1=\frac{(\Delta p+\Delta H\times \rho\times g)\times g\times \pi^{2}\times d^{4}}{8\times K_{total}} \tag{4.10}$$

$$C_2 = \frac{P_{hyd} \times g \times \pi^2 \times d^4}{8 \times K_{total}} \tag{4.11}$$

$$\Delta \leq 0 \rightarrow \frac{C_2^2}{4} - \frac{C_1^3}{27} \leq 0 \text{ [54]} \tag{4.12}$$

$$\frac{\left(\frac{P_{hyd} \times g \times \pi^2 \times d^4}{8 \times K_{total}}\right)^2}{4} \leq \frac{\left(\frac{(\Delta p + \Delta H \times \rho \times g) \times g \times \pi^2 \times d^4}{8 \times K_{total}}\right)^3}{27} \tag{4.13}$$

$$K_{total} \leq \frac{\pi^2 \times d^4 \times (\Delta p + \Delta H \times \rho \times g)^3}{54 \times \rho \times P_{hyd}^2} \tag{4.14}$$

$$K_{\text{total min}} = K_{total}(P_{av}) = \frac{\pi^2 \times d^4 \times (\Delta p + \Delta H \times \rho \times g)^3}{54 \times \rho \times (P_{av})^2} \tag{4.15}$$

$$K_{\text{total max}} = K_{total}(P_{ad}) = \frac{\pi^2 \times d^4 \times (\Delta P_t)^3}{54 \times \rho \times (P_{ad})^2} \tag{4.16}$$

Finally, a condition underlies P_{hyd} >=0 of equation (4.2), which is necessary to ensure the turbine's proper functioning. This condition can be used to deduce the relation of flow rate (eq.4.17). By replacing the expressions for the minimum and maximum total flow coefficient (eqs 4.15 and 4.16) into equation 4.17, a condition on this flow rate is obtained, as expressed in equations 4.18 and 4.19.

$$\dot{V}_{LT} = \pi \times d^2 \sqrt{\frac{\Delta p_t}{8 \times \rho \times K_{total}}} \tag{4.17}$$

$$\dot{V}_{\text{LT min}} = \dot{V}_{LT}(K_{\text{total min}}) \tag{4.18}$$

$$\dot{V}_{\text{LT max}} = \dot{V}_{LT}(K_{\text{total max}}) \tag{4.19}$$

4.3 Results and discussions of the hydraulic analysis

Based on the previous results obtained in Chapter 3, two operating cases are highlighted and analyzed in this chapter, as presented in table 4.1. The first case involves an operating regime that achieves a maximum thermal efficiency with a pressure drop of Δp. While, the second case focuses on an operating regime that yield the maximum second-law efficiency with a different pressure drop. In both cases, the same total height ΔH, which is the vertical distance between the transfer liquid levels in transfer cylinders, is maintained. Ultimately, the transfer liquid is assigned a density of 900kg/m³. The acquired results are displayed in Figs. 4.3 e 4.5. and in the accompanying table 4.2.

Table 4.1 Input parameters for hydraulic system

Parameter		Value	Unit
Working fluid		R1233zd	
Case 1	η_{th_max}	17.5%	
	Δp	1416.4	kPa
Case 2	η_{II_max}	90.3%	
	Δp	235.3	kPa
ΔH		0.1	m
ρ		900	kg/m³

The global table of efficiencies and pressure drop is presented in the annex.

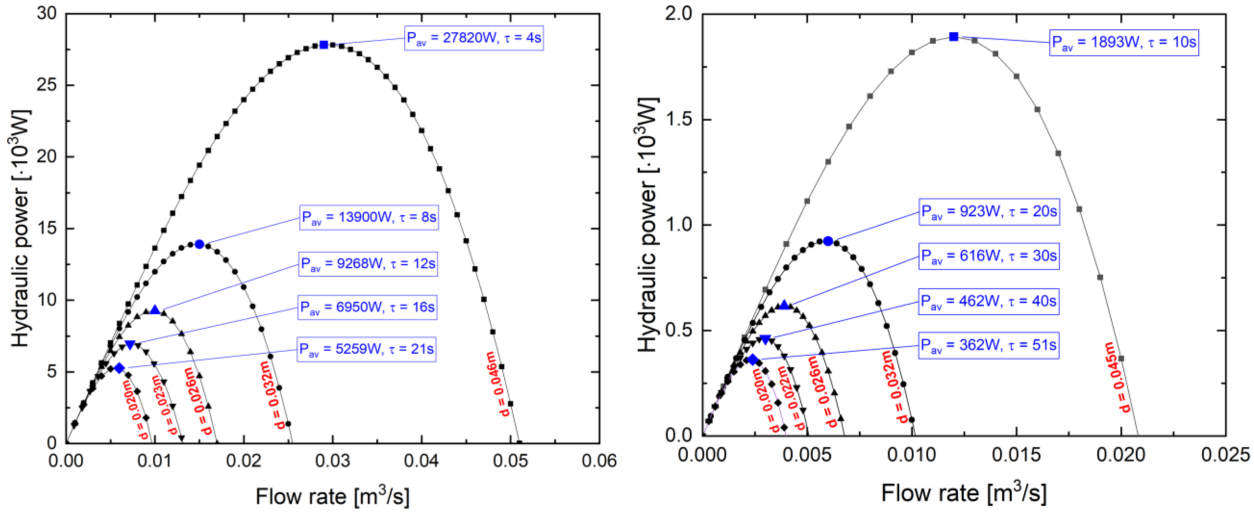
4.3.1 Evolution of powers

The variation of hydraulic power with volume flow rate for different pipe diameters is shown in Fig.4.3. The figure illustrates the highest hydraulic powers and the most efficient flow rates for each diameter. The hydraulic power curve exhibits a parabolic shape for a given pipe diameter. We can remark that:

- The power equals zero at the two spots where the curve crosses the x-axis. The first point represents the converter's idle condition with a volume flow rate of zero. The second point also reflects an idle state; however, at this point, the converter experiences a maximum volume flow rate and the most significant pressure losses in the hydraulic circuit. Hydraulic power reaches its maximum when the pressure losses are carefully examined, and the volumetric flow rate is accurately set. The pressure losses at this point can only be minimal. To clarify, from Fig.4.5, the pressure losses in the hydraulic circuit might range from a minimum value when the converter is not in motion to their maximum value when the converter is once again not in motion. This variation depends on the volumetric flow rate for a particular diameter. At a specific diameter of the hydraulic circuit, hydraulic power reaches its highest value, corresponding to an optimal volume flow rate, resulting in minimal pressure losses in the circuit.

- It is essential that the mechanical power available P_{av} at the transfer cylinder is equal to or greater than the hydraulic power to fully utilize the greatest hydraulic power achievable with a specific diameter. This implies that the available mechanical power at the transfer cylinder is influenced by the frequency of the thermodynamic cycle (*f*) or the duration of a thermodynamic cycle (τ) (eq.4.4). The latter is contingent upon the temperatures and/or pressures of the hot and cold reservoirs, the working fluid, and heat transfer parameters such as exchange surfaces, heat transfer coefficient, and temperature jumps. Given the lack of actual data, we can make an assumption to facilitate this analysis. We will assume a frequency (cycles per second) at which the mechanical power available at the transfer cylinder equals the hydraulic power. This hydraulic power is represented by the horizontal line that intersects with the maximum P_{hyd} for a given diameter, which is displayed as a peak in Fig. 4.5.
- It has been noted that the available mechanical power at the transfer cylinder grows as the frequency *f* of the thermodynamic cycle increases. Consequently, an increase in the number of cycles per second directly corresponds to a larger amount of available mechanical power that can be harnessed at the transfer cylinder (P_{av}).
- Fig.4.3 represents two study cases: the first case a) take into consideration two inputs parameters: the maximal value of thermal efficiency η_{th_max}= 17.5% and a pressure drop Δp = 1416.4 kPa, for this case the maximal hydraulic power achieved is 5259 W with a diameter of d=2 cm. While for the second case b) take into consideration other inputs which are the maximal value of second law efficiency η_{II_max} =90.3 % and a pressure drop Δp = 235.3 kPa, for this case the maximal hydraulic power is equal to 362 W for the same diameter. For the maximal diameters d=4.6 cm and 4.5 cm in cases a) and b), respectively, the peak hydraulic power rises to 27820 W and 1893 W, respectively.

These results indicate that choosing the appropriate type of converter depends on the specific case. In the first scenario, both the hydraulic turbine and piston converter are appropriate because of the relatively high-pressure differential and substantial hydraulic power. In the second scenario, however, only a hydraulic turbine is relevant due to the low-pressure differential between the transfer cylinders. It is important to note that achieving high mechanical power is possible only when operating in a mode that ensures high thermal efficiency. On the other hand, modes with high second-law efficiency do not generate significant mechanical power levels.

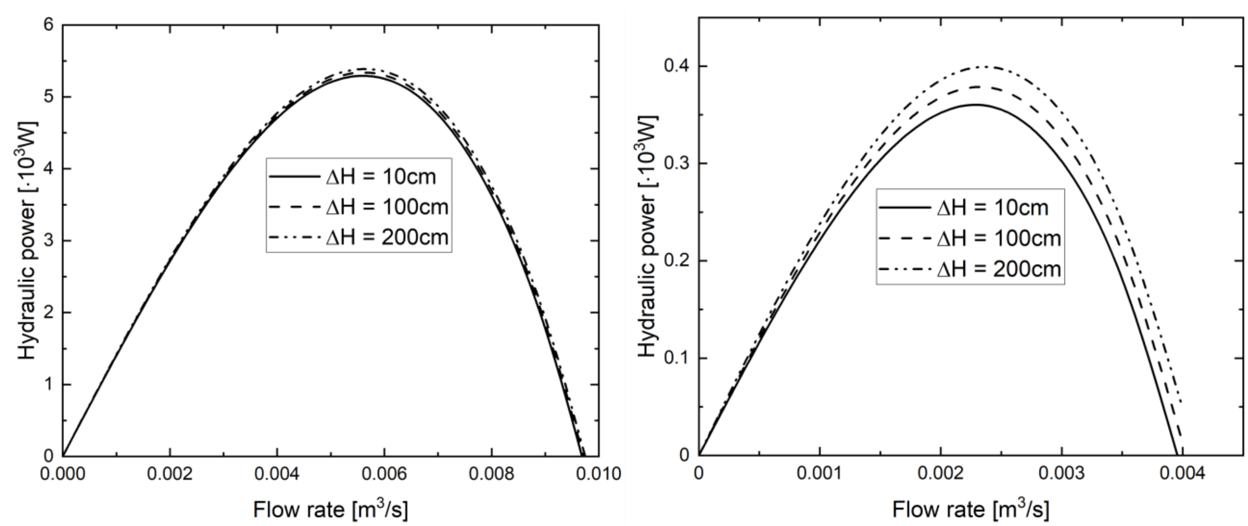


(a) (b)

Fig. 4.3. The variation of the hydraulic power according to the volume flow rate: (a) case 1: Δp = 1416.4 kPa and η_{th_max} = 17.5%, (b) case 2 : Δp = 235.3 kPa and η_{II_max} = 90.3%.

4.3.2 Effect of the total height corresponding to the height between the transfer liquid levels in transfer cylinders ΔH

The hydraulic power evolution as a function of volume flow rate at different ΔH shown in Fig.4.4. The limited impact of ΔH on hydraulic power can be deduced from this figure. The relationship between ΔH and the duration of the thermodynamic cycle τ, or the frequency f, is clearly evident.

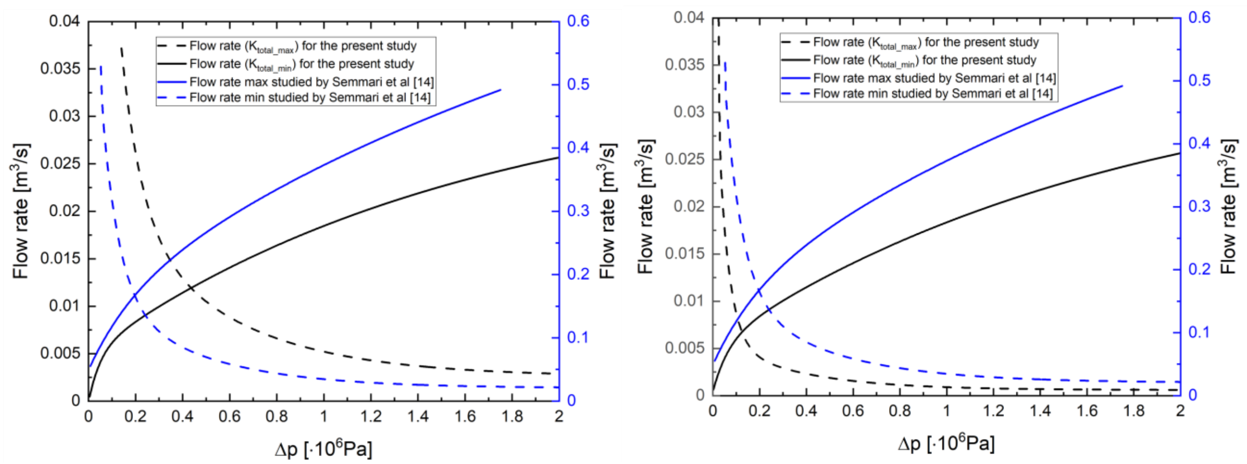


(a) (b)

Fig. 4.4. Variation of the hydraulic power with the flow rate and the total height ΔH for d = 0.02 m: (a) case 1: Δp = 1416.4 kPa and η_{th_max} = 17.5%, (b) case 2 : Δp = 235.3 kPa and η_{II_max} = 90.25%.

4.3.3 Definition of the allowable flow rate range corresponding to the pressure drop

Figure 4.5 illustre the permissible range of flow rates according to the pressure drop in transfer cylinders obtained for both studied cases a) and b). These results are compared to those reported by Semmari et al. [54]. Consequently, the working area is constructed based on the minimal and maximal total flow coefficients, which is exactly the same as the one achieved by Semmari et al. [54] for their thermohydraulic machine. However, in the work mentioned above, the flow rates appear to be rather overestimated. To address the differences in flow rates, the consistency of the hydraulic power equation proposed by Semmari et al [54] was examined using dimensional analysis. The term holding the loss coefficient seems to be expressed in m^3/s, although it should be in watts!



(a) (b)

Fig. 4.5. Comparison of the allowed flow rates according to the pressure drop for *d* = 0.03 m in transfer cylinders obtained for both studied cases with those obtained by Semmari et al. [38] .

4.3.4 Variations of admissible and available mechanical powers and Reynold numbers according to diameters

Table 4.2 presents the admissible power and admissible Reynolds number for cases (a) and (b) in relation to the diameter at the admissible speed V_{ad} of 6 m/s. In scenario (a), as the diameter grows, the admissible power rises significantly from 2570.7 W to 574501.9 W. Similarly, in scenario (b), the admissible power also increases from 344.4 W to 73581.4 W with the growth of diameter. This trends suggests that the hydraulic system can accommodate higher power levels with larger diameters, indicating improved fluid flow and the ability to meet higher power demands. However, it is crucial to ensure that the power levels do not exceed the system's admissible limits, as operating at excessive admissible power levels can lead to increased wear, pressure drops, and potential system failures.

Furthermore, the results in Table 4.2 show that the Reynolds number increases within the admissible speed range as the diameter grows. Specifically, in both cases (a) and (b), the Reynolds number ranges from 8000 to 120000. This rise in the Reynolds number at the admissible velocity indicates a shift from a state of a more turbulent flow regime, moving from smooth turbulence, typically defined by a Reynolds number between 2300 to 100,000, to potentially rougher turbulence [79]. Therefore, for pipe diameters less than 0.25 m, the flow regime in both scenarios remains well within the range of smooth turbulence, keeping it significantly distant from the rough turbulence regime.

Another careful reading of Table 4.2 reveals a well-established fact when comparing the available and admissible powers. In both cases, the available power surpasses the admissible power by an average of 51% and 4% respectively. This indicates that the operating condition with the highest value of second law efficiency, η_{II_max} = 90.3% (case 2), is capable of converting all the available power at the transfer cylinders more effectively than the one with the highest value of thermal efficiency, η_{th_max} = 17.5% (case 1). Nevertheless, the only disadvantage is that a power plant operating under scenario 2 conditions cannot deliver substantial amounts of mechanical powers and has a comparatively low specific power (kW/kg).

Table 4.2. Variations of admissible and available mechanical powers and Reynold numbers according to diameters

a)

Δp= 1416.4 kPa corresponding to η_{th_max}= 17.5%			
d [m]	P_{ad} [W]	Re_{ad}	P_{av}[W]
0.02	2570.7	8000	5297.5
0.03	5783.8	12000	11898
0.04	10281.6	16000	21230.3
0.05	16063.9	20000	33010.9
0.06	23129.5	24000	48368.1
0.07	31476.8	28000	64304.5
0.08	14187.7	32000	84277.8
0.1	64202.5	40000	130878.5
0.125	100280	50000	203748.5
0.15	144312.5	60000	292754.5
0.2	256148.5	80000	505666.8

b)

Δp=235.3 kPa corresponding to η_{II_max} = 90.3%			
d [m]	P_{ad}[W]	Re_{ad}	P_a [W]
0.02	344.4	8000	362.4
0.03	774.6	12000	810.7
0.04	1376.3	16000	1444
0.05	2149.4	20000	2254.1
0.06	3092.7	24000	3242.7
0.07	4204.5	28000	4400.9
0.08	5484.9	32000	5740.3
0.1	8544.7	40000	8886.4
0.125	13314.6	50000	13793.8
0.15	19082.4	60000	19874.9
0.2	33517.1	80000	34548.9

0.25	399595.8	100000	777949		0.25	51734.3	100000	52961.7
0.3	574501.9	120000	1101452.5		0.3	73581.4	120000	74832.5

4.4 Conclusion

This chapter presented modeling of hydraulic system of ORPILI power plant based on the thermodynamic results obtained in the previous chapter. Two cases a) and b) were studied concerning the input parameters of the suitable working fluid R1233zd which are: the maximal value of thermal efficiency η_{th_max}= 17.5% and a pressure drop Δp = 1416.4 kPa for the first case and the maximal value of second law efficiency η_{II_max} =90.3 % and a pressure drop Δp = 235.3 kPa for the second case. The following conclusions can be derived from the analysis:

1. High mechanical powers can only be generated in high thermal efficiencies working mode. Conversely, operating modes with high second low efficiencies cannot provide significant amounts of mechanical powers;
2. The hydraulic power curve takes a parabolic shape for a particular diameter of the hydraulic circuit piping. At its peak, hydraulic power is achieved when there are minimal pressure losses in the circuit, meaning that the volume flow rate is at its most efficient;
3. It has been demonstrated that a specific operational range exists in transfer cylinders where flow rate and pressure drop values are permissible. The minimum and maximum values of the total flow coefficients define the limits of this region;
4. A power plant with a high second-law efficiency cannot generate significant amounts of mechanical power and has a comparatively low specific power (kW/kg). In order to get a substantial power output, it is essential to select a power plant that operates with a high thermal efficiency, meaning it has a relatively high specific power.
5. The final finding is consistent with multiple postulates of the second law of thermodynamics. Nicolas Leonard Sadi Carnot made an initial observation during his examination of steam engines, where he a fundamental limit to the amount of work that can be produced from a specific quantity of heat.

General conclusion and perspectives

General conclusion and perspectives

The transition toward sustainable development, as outlined by the United Nations Sustainable Development Goals (SDGs), necessitates significant advancements in energy systems, particularly through integrating renewable sources and enhanced conversion efficiencies. This thesis has contributed to this broader objective by investigating thermohydraulic processes with a focus on improving specific mechanical work output of energy systems, specifically within the context of power production.

The research emphasized the critical role of entropy management in maximizing cycle efficiency through a structured exploration of the second law of thermodynamics and its implications for energy system design. Applying this principle to cogeneration and trigeneration systems demonstrated their potential in reducing primary energy consumption and greenhouse gas emissions.

A key outcome of the investigation was the thermodynamic assessment of the ORPILI system. The working fluid R1233zd emerged as the most suitable candidate due to its superior thermal performance, achieving a thermal efficiency of 17.5% and a second-law efficiency of 76.6% at a superheated temperature of 130°C. Subsequent hydraulic modeling further provided valuable insights into the performance of the ORPILI system, revealing a critical trade-off between thermal efficiency and second-law efficiency. High thermal efficiency facilitated increased mechanical power output, whereas high second-law efficiency, though indicative of low irreversibilities, was associated with reduced mechanical performance.

The findings underscore the necessity of optimizing pressure losses and flow conditions to achieve maximum mechanical power. They clarified that high second-law efficiencies indicate minimal irreversibilities but often correspond to lower mechanical outputs. In contrast, high thermal efficiencies are conducive to greater power generation. This dynamic aligns with the theoretical constraints imposed by Carnot's second law, reinforcing the fundamental limits of energy conversion processes.

In conclusion, the findings affirm the viability and relevance of advanced thermohydraulic cycles for sustainable power generation. However, to fully exploit the potential of these systems, further research is required particularly in refining the design of transfer cylinders and optimizing the mechanical gearbox, including the integration of a freewheel mechanism. These next steps will be essential for advancing the practical implementation of efficient and resilient energy systems aligned with global sustainability goals.

References

References

[1] S. M. Chekouri, A. Chibi, and M. Benbouziane, “Examining the driving factors of CO_2 emissions using the STIRPAT model: the case of Algeria,” *International Journal of Sustainable Energy*, vol. 39, no. 10, pp. 927–940, Nov. 2020, doi: 10.1080/14786451.2020.1770758.

[2] P. Arora, “COP28: ambitions, realities, and future,” *Environmental Sustainability*, vol. 7, no. 1, pp. 107–113, Mar. 2024, doi: 10.1007/s42398-024-00304-0.

[3] A. B. Hani and B. Abdelhamid, “Energy Transition and Sustainable Development in Algeria: The Challenges of Green Economy,” vol. 8, no. 1, 2024, doi: 10.58205/fber.v8i1.1809.

[4] D. Zebbar, A. Guelib, Z. Rahmani, S. Zebbar, and S. Kherris, “Machine thermohydraulique pour la production continue de puissance mécanique avec piston liquide fonctionnant suivant le cycle de Rankine,” N° 220156, 2022

[5] A. Sircar, G. Tripathi, N. Bist, K. A. Shakil, and M. Sathiyanarayanan, *Emerging Technologies for Sustainable and Smart Energy*, 1st ed. Boca Raton: CRC Press, 2022. doi: 10.1201/b23013.

[6] Statistical review of world energy. Accessed: Jul. 21, 2024. [Online]. Available: https://www.energyinst.org/statistical-review/home

[7] Q. Hassan *et al.*, “The renewable energy role in the global energy transition,” *Renewable Energy Focus*, p. 100545, Jan. 2024, doi: 10.1016/j.ref.2024.100545.

[8] B. Saboori and J. Sulaiman, “Environmental degradation, economic growth and energy consumption: Evidence of the environmental Kuznets curve in Malaysia,” *Energy Policy*, vol. 60, pp. 892–905, Sep. 2013, doi: 10.1016/j.enpol.2013.05.099.

[9] E. Dogan and F. Seker, “Determinants of CO2 emissions in the European Union: The role of renewable and non-renewable energy,” *Renewable Energy*, vol. 94, pp. 429–439, Aug. 2016, doi: 10.1016/j.renene.2016.03.078.

[10] M. U. Rehman and M. Rashid, “Energy consumption to environmental degradation, the growth appetite in SAARC nations,” *Renewable Energy*, vol. 111, pp. 284–294, Oct. 2017, doi: 10.1016/j.renene.2017.03.100.

[11] F. V. Bekun, A. A. Alola, and S. A. Sarkodie, “Toward a sustainable environment: Nexus between CO2 emissions, resource rent, renewable and nonrenewable energy in 16-EU countries,” *Science of The Total Environment*, vol. 657, pp. 1023–1029, Mar. 2019, doi: 10.1016/j.scitotenv.2018.12.104.

[12] M. Bouznit and M. D. P. Pablo-Romero, “CO2 emission and economic growth in Algeria,” *Energy Policy*, vol. 96, pp. 93–104, Sep. 2016, doi: 10.1016/j.enpol.2016.05.036.

[13] F. Bélaïd and M. Youssef, “Environmental degradation, renewable and non-renewable electricity consumption, and economic growth: Assessing the evidence from Algeria,” *Energy Policy*, vol. 102, pp. 277–287, Mar. 2017, doi: 10.1016/j.enpol.2016.12.012.

[14] A. Hussain, S. M. Arif, and M. Aslam, “Emerging renewable and sustainable energy technologies: State of the art,” *Renewable and Sustainable Energy Reviews*, vol. 71, pp. 12–28, May 2017, doi: 10.1016/j.rser.2016.12.033.

[15] P. A. Owusu and S. Asumadu-Sarkodie, "A review of renewable energy sources, sustainability issues and climate change mitigation," *Cogent Engineering*, vol. 3, no. 1, p. 1167990, Dec. 2016, doi: 10.1080/23311916.2016.1167990.

[16] N. L. Panwar, S. C. Kaushik, and S. Kothari, "Role of renewable energy sources in environmental protection: A review," *Renewable and Sustainable Energy Reviews*, vol. 15, no. 3, pp. 1513–1524, Apr. 2011, doi: 10.1016/j.rser.2010.11.037.

[17] S. A. Sarkodie and S. Adams, "Renewable energy, nuclear energy, and environmental pollution: Accounting for political institutional quality in South Africa," *Science of The Total Environment*, vol. 643, pp. 1590–1601, Dec. 2018, doi: 10.1016/j.scitotenv.2018.06.320.

[18] A. Sharif, O. Baris-Tuzemen, G. Uzuner, I. Ozturk, and A. Sinha, "Revisiting the role of renewable and non-renewable energy consumption on Turkey's ecological footprint: Evidence from Quantile ARDL approach," *Sustainable Cities and Society*, vol. 57, p. 102138, Jun. 2020, doi: 10.1016/j.scs.2020.102138.

[19] S. Shan, S. Y. Genç, H. W. Kamran, and G. Dinca, "Role of green technology innovation and renewable energy in carbon neutrality: A sustainable investigation from Turkey," *Journal of Environmental Management*, vol. 294, p. 113004, Sep. 2021, doi: 10.1016/j.jenvman.2021.113004.

[20] F. Sahnoune and K. Imessad, "Analysis and impact of the measures to mitigate climate change in Algeria," *Energy Procedia*, vol. 136, pp. 495–500, Oct. 2017, doi: 10.1016/j.egypro.2017.10.263.

[21] S. E. Sari Hassoun, M. Mékidiche, and M. S. Guellil, "Examining the Connection amongst Renewable Energy, Economic Growth and Carbon Dioxide Emissions in Algeria," *Ekoist*, Jul. 2019, doi: 10.26650/ekoist.2018.14.29.0013.

[22] "Energy Institute releases 2024 Statistical Review of World Energy." Accessed: Jul. 22, 2024. [Online]. Available: https://dieselnet.com/news/2024/06energyreview.php?fbclid=IwZXh0bgNhZW0CMTEAAR0Jjoek8KgD_IBrMAuaMBhz6TDxGDtPKBwg5KfS-1mM_mvY5nukmmMCr9U_aem_3ELeWS3Qfgjop4DwS-fZnQ

[23] "Consommation Energétique Finale de l'Algérie – APRUE. Rapport technique, Agence pour la promotion et la rationalisation de l'usage de l'énergie, Ministère de l'Énergie, Algeria," 2017.

[24] H. Semmari, "Production d'électricité par procédé thermo-hydraulique: application à l'exploitation de l'énergie thermique des mers," Thése, Université de Perpignan, 2012.

[25] R. Borgogno, "Procédé thermo-hydraulique solaire appliqué à la trigénération dans le secteur résidentiel.," thése, Université de Perpignan, 2017. Accessed: Jul. 25, 2020. [Online]. Available: https://tel.archives-ouvertes.fr/tel-01620245

[26] A. B. Stambouli, "Promotion of renewable energies in Algeria: Strategies and perspectives," *Renewable and Sustainable Energy Reviews*, vol. 15, no. 2, pp. 1169–1181, Feb. 2011, doi: 10.1016/j.rser.2010.11.017.

[27] K. Farida, A. Hanene, and N. Bilal, "Energy security and diversification of energy resources are imperative for building a new model of development in Algeria," vol. 9, no. 1, 2024, doi: https://doi.org/10.33182/rr.v9i1.010.

[28] A. Fleming, R. M. Wise, H. Hansen, and L. Sams, “The sustainable development goals: A case study,” *Marine Policy*, vol. 86, pp. 94–103, Dec. 2017, doi: 10.1016/j.marpol.2017.09.019.

[29] P. Katila, C. J. Pierce Colfer, W. De Jong, G. Galloway, P. Pacheco, and G. Winkel, Eds., *Sustainable Development Goals: Their Impacts on Forests and People*, 1st ed. Cambridge University Press, 2019. doi: 10.1017/9781108765015.

[30] Vereinte Nationen, Ed., *The 2030 Agenda and the Sustainable Development Goals: an opportunity for Latin America and the Caribbean*. in United Nations publication. Santiago: United Nations, ECLAC, 2018.

[31] P. K. Nag, *Basic and Applied Thermodynamics*, Second. West Patel Nagar, New Delhi: Tata McGraw Hill Education Private Limited, 2010.

[32] Stepehen L. Turns and L. L. Pauley, *Thermodynamics Concepts and Applications*, Second. Cambridge, New York: Cambridge University Press, 2018.

[33] A. Shavit and C. Gutfinger, *Thermodynamics From Concepts to Applications*, Second. CRC Press.

[34] R. E. Sonntag, C. Borgnakke, and G. J. V. Wylen, *Fundamentals_of_thermodynamics*, Sixth. United States of America: John Wiley & Sons, Inc., 2003.

[35] A. Y. Çengel, *Introduction to Thermodynamics and Heat Transfer*, Second. the United States of America.: McGraw-Hill Primis, 2008.

[36] M. C. Potter, *Thermodynamics Demystified*. United States of America: The McGraw-Hill Companies, Inc, 2009.

[37] R. Shankar, *Fundamentals of Physics, Mechanics, Relativity, and Thermodynamics*. United States of America.: Yale University Press, 2014.

[38] Kanoglu Mehmet, Çengel Yunus A., and Dinçer Ibrahim, *Efficiency Evaluation of Energy Systems*. New York Heidelberg Dordrecht London: Springer, 2012.

[39] M. Brouche and C. Lahoud, “Review of cogeneration and trigeneration systems,” *Afr J Eng Res*, vol. 6, no. 3, pp. 39–54, Oct. 2018, doi: 10.30918/AJER.63.18.016.

[40] S. Martinez, “Études expérimentales et numériques d’un micro-cogénérateur solaire - intégration à un bâtiment résidentiel”.

[41] M. E. S. Reyes, “Methodology to identify the key variables driving the techno-economic feasibility of Trigeneration – Thermal Storage systems”.

[42] M. Wołowicz, P. Kolasiński, and K. Badyda, “Modern Small and Microcogeneration Systems—A Review,” *Energies*, vol. 14, no. 3, p. 785, Feb. 2021, doi: 10.3390/en14030785.

[43] R. B. de Rougé, “Modélisation des solutions de micro-cogénération en vue de leur intégration optimale au sein des bâtiments”.

[44] B. Andlauer, “Optimisation systémique de micro-cogénérateurs intégrés au bâtiment”.

[45] S. Laurence, “Life cycle environmental andeconomic sustainability of Stirling engine micro-CHP systems,” *Energy Technology*, doi: 10.1002/ente.201700854.

[46] H. Al Moussawi, F. Fardoun, and H. Louahlia-Gualous, "Review of tri-generation technologies: Design evaluation, optimization, decision-making, and selection approach," *Energy Conversion and Management*, vol. 120, pp. 157–196, Jul. 2016, doi: 10.1016/j.enconman.2016.04.085.

[47] F. A. Al-Sulaiman, F. Hamdullahpur, and I. Dincer, "Performance comparison of three trigeneration systems using organic rankine cycles," *Energy*, vol. 36, no. 9, pp. 5741–5754, Sep. 2011, doi: 10.1016/j.energy.2011.06.003.

[48] J. Wang, Y. Dai, L. Gao, and S. Ma, "A new combined cooling, heating and power system driven by solar energy," *Renewable Energy*, vol. 34, no. 12, pp. 2780–2788, Dec. 2009, doi: 10.1016/j.renene.2009.06.010.

[49] M. Martins, S. Mauran, D. Stitou, and P. Neveu, "A new thermal–hydraulic process for solar cooling," *Energy*, vol. 41, no. 1, pp. 104–112, May 2012, doi: 10.1016/j.energy.2011.05.030.

[50] S. Mauran, M. Martins, D. Stitou, and H. Semmari, "A novel process for engines or heat pumps based on thermal-hydraulic conversion," *Applied Thermal Engineering*, vol. 37, pp. 249–257, May 2012, doi: 10.1016/j.applthermaleng.2011.11.026.

[51] "Scientific Reports - PROMES," 2016. [Online]. Available: chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.promes.cnrs.fr/wp-content/uploads/2021/03/RS_PROMES2016_VF.pdf

[52] F. Gilles, "RS_PROMES2016_VF.pdf, Laboratoire procédés matériaux et énergie solaire Promes CNRS." Accessed: Mar. 13, 2020. [Online]. Available: https://www.promes.cnrs.fr/uploads/pdfs/production/rapport_2016/RS_PROMES2016_VF.pdf

[53] D. Stitou, "Transformation, Conversion, Stockage, Transport de l'énergie thermique par procédés thermochimiques et thermo-hydrauliques," thése, Université de Perpignan, 2013. Accessed: Jul. 25, 2020. [Online]. Available: https://tel.archives-ouvertes.fr/tel-00841655

[54] H. Semmari, D. Stitou, and S. Mauran, "A novel Carnot-based cycle for ocean thermal energy conversion," *Energy*, vol. 43, no. 1, pp. 361–375, Jul. 2012, doi: 10.1016/j.energy.2012.04.017.

[55] H. A. Humphrey, "An Internal-Combustion Pump, and other Applications of a New Principle," *Proceedings of the Institution of Mechanical Engineers*, vol. 77, no. 1, pp. 1075–1200, Jun. 1909, doi: 10.1243/PIME_PROC_1909_077_019_02.

[56] J. Gerstmann and Y. Friedman, "Liquid piston heat-actuated heat pump and methods of operating same," US4148195A, Apr. 10, 1979 Accessed: Jul. 26, 2020. [Online]. Available: https://patents.google.com/patent/US4148195A/en

[57] D. R. Cutler, "Liquid piston heat pump," US4501122A, Feb. 26, 1985 Accessed: Jul. 26, 2020. [Online]. Available: https://patents.google.com/patent/US4501122A/en

[58] D. L. Howard, "Liquid piston heat engine," US5195321A, Mar. 23, 1993 Accessed: Jul. 26, 2020. [Online]. Available: https://patents.google.com/patent/US5195321A/en?oq=Howard+DL%2c+(1993).+Liquid+piston+heat+engine.+US+patent+5195321.+

[59] R. Conde and D. Faroughy, "Fluidic-piston engine," US6568169B2, May 27, 2003 Accessed: Jul. 26, 2020. [Online]. Available:

https://patents.google.com/patent/US6568169B2/en?oq=Conde+R%2c+Faroughy+D%2c(2003).+Fluidic-piston+engine.+US+patent+6568169.

[60] R. P. Klüppel and J. M. Gurgel, “Thermodynamic cycle of a liquid piston pump,” *Renewable Energy*, vol. 13, no. 2, pp. 261–268, Feb. 1998, doi: 10.1016/S0960-1481(97)00049-9.

[61] P. Gaffuri, B. Mies, G. A. Cole, and J. D. V. de Ven, “Developments Towards a Liquid Piston Stirling Engine,” 2008. doi: 10.2514/6.2008-5635.

[62] J. D. Van de Ven, “Mobile hydraulic power supply: Liquid piston Stirling engine pump,” *Renewable Energy*, vol. 34, no. 11, pp. 2317–2322, Nov. 2009, doi: 10.1016/j.renene.2009.01.020.

[63] M. Motamedi, R. Ahmadi, and H. Jokar, “A solar pressurizable liquid piston stirling engine: Part 1, mathematical modeling, simulation and validation,” *Energy*, vol. 155, no. C, pp. 796–814, 2018, doi: 10.1016/j.energy.2018.05.002.

[64] R. Ahmadi, H. Jokar, and M. Motamedi, “A solar pressurizable liquid piston stirling engine: Part 2, optimization and development,” *Energy*, vol. 164, no. C, pp. 1200–1215, 2018, doi: 10.1016/j.energy.2018.08.197.

[65] S. Langdon-Arms, M. Gschwendtner, and M. Neumaier, “A novel solar-powered liquid piston Stirling refrigerator,” *Applied Energy*, vol. 229, pp. 603–613, Nov. 2018, doi: 10.1016/j.apenergy.2018.08.040.

[66] H. Semmari, S. Mauran, and D. Stitou, “Experimental validation of an analytical model of hydraulic motor operating under variable electrical loads and pressure heads,” *Applied Energy*, vol. 206, pp. 1309–1320, Nov. 2017, doi: 10.1016/j.apenergy.2017.10.010.

[67] D. Zebbar, A Guelib, S Kherris, S Zebbar, K Mostefa, and N. Kaddouri, “Thermodynamic study and analysis of thermohydraulic cycle for power generation,” Mar. 2019, doi: 10.5281/ZENODO.2581463.

[68] R. Rayegan and Y. X. Tao, “A procedure to select working fluids for Solar Organic Rankine Cycles (ORCs),” *Renewable Energy*, vol. 36, no. 2, pp. 659–670, Feb. 2011, doi: 10.1016/j.renene.2010.07.010.

[69] W. Fan, Z. Han, P. Li, and Y. Jia, “Analysis of the thermodynamic performance of the organic Rankine cycle (ORC) based on the characteristic parameters of the working fluid and criterion for working fluid selection,” *Energy Conversion and Management*, vol. 211, p. 112746, May 2020, doi: 10.1016/j.enconman.2020.112746.

[70] F. Daw *et al.*, “R1224yd(Z), R1233zd(E) and R1336mzz(Z) as replacements for R245fa: Experimental performance, interaction with lubricants and environmental impact,” *Applied Energy*, vol. 288, p. 116661, Apr. 2021, doi: 10.1016/j.apenergy.2021.116661.

[71] L. E. Méndez-Cruz, M. Á. Gutiérrez-Limón, H. Lugo-Méndez, R. Lugo-Leyte, T. Lopez-Arenas, and M. Sales-Cruz, “Comparative Thermodynamic Analysis of the Performance of an Organic Rankine Cycle Using Different Working Fluids,” *Energies*, vol. 15, no. 7, p. 2588, Apr. 2022, doi: 10.3390/en15072588.

[72] J. Nouman, “Comparative studies and analyses of working fluids for Organic Rankine Cycles - ORC”.

[73] G. Lhermet, “Etude d’un cycle organique de Rankine couplé à un système passif innovant: application aux réacteurs nucléaires avancés”.

[74] Y. Maalem, H. Madani, and M. Mehemmai, “Modélisation Mathématique et Simulation Numérique des Performances de Refroidissement de Différentes Unités de Réfrigération à Compression de Vapeur : Application de Nouveaux Fluides Frigorigènes,” vol. 05, no. 01, 2023.

[75] I. H. Bell, J. Wronski, S. Quoilin, and V. Lemort, “Pure and Pseudo-pure Fluid Thermophysical Property Evaluation and the Open-Source Thermophysical Property Library CoolProp,” *Ind. Eng. Chem. Res.*, vol. 53, no. 6, pp. 2498–2508, Feb. 2014, doi: 10.1021/ie4033999.

[76] N. Casari, M. Pinelli, and A. Suman, “Analysis of CoolProp library for the assessment of uncertainty propagation for refrigerant fluids in state diagrams and thermodynamic properties,” *International Journal of Refrigeration*, vol. 107, pp. 214–224, Nov. 2019, doi: 10.1016/j.ijrefrig.2019.08.015.

[77] V. L. LE, “Étude de la faisabilité des cycles sous-critiques et supercritiques de Rankine pour la valorisation de rejets thermiques,” thése de doctorat, Université de Lorraine, 2014.

[78] M. Annan and E. A. Gooda, “Effect of minor losses during steady flow in transmission pipelines – Case study ‘water transmission system upgrade in Northern Saudi Arabia,’” *Alexandria Engineering Journal*, vol. 57, no. 4, pp. 4299–4305, Dec. 2018, doi: 10.1016/j.aej.2018.12.002.

[79] Y. A. Çengel and J. M. Cimbala, *Fluid mechanics: fundamentals and applications*. in McGraw-Hill series in mechanical engineering. Boston, Mass.: McGraw-Hill Higher Education, 2006.

[80] “GF2/GF3 Rev. C 2– and 3–way DIN-standard flanged valve.” [Online]. Available: chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.regincontrols.com/globalassets/pimmediafiles/documents/gf2_gf3_ps10097_en.pdf

[81] V. Savi, “Determination of Pressure Losses in Hydraulic Pipeline Systems by Considering Temperature and Pressure,” *Journal of Mechanical Engineering*, 2009.

[82] D. M. Pirro, A. A. Wessol, and J. G. Wills, *Lubrication fundamentals*, 2. ed., rev.Expanded. in Mechanical engineering, no. 137. New York Basel: Dekker, 2001.

[83] “OIL VISCOSITY / TEMPERATURE CHART - OEM Dynamics,.” [Online]. Available: https://www.oemdynamics.com.au/wp-content/uploads/2013/11/viscosity.pdf

[84] S. R Majumdar, *Oil Hydraulic systems - Principles and maintenance*. 2002.

[85] P. Chapple, *Principles of Hydraulic System Design,* First edition. Coxmoor Publishing Company, 2002.

Appendix

Appendix A: INAPI Patent

REPUBLIQUE ALGERIENNE DEMOCRATIQUE ET POPULAIRE الجمهورية الجزائرية الديمقراطية الشعبية

المعهد الوطني الجزائري للملكية الصناعية

INSTITUT NATIONAL ALGERIEN DE LA PROPRIETE INDUSTRIELLE (19) DZ

FO-10

بـــراءة إختـــراع

BREVET D'INVENTION

(22) **Date de dépôt:** 08/03/2022 (11) **N° du brevet : 12468**

(21) **N° Dépôt:** 220156

(54) **Titre de l'invention:**
Machine thermohydraulique pour la production continue de puissance mécanique avec piston liquide fonctionnant suivant le cycle de Rankine organique..

(71) **Déposant :**
Laboratoire de l'ingénierie mécanique, matériaux et structures {LiMMaS}, Faculté des sciences et de la technologie, Université de Tissemsilt. , Route de Bougara BP 180 Abdelhak Benhamouda- 38010- Tissemsilt

(72) **Inventeur**
ZEBBAR, Djallel-GUELIB, Asmaa-RAHMANI, Zakaria-ZEBBAR, Souhila-MOSTEFA, Kouider- KHERRIS, Sahraoui

(73) **Titulaire :**
Laboratoire de l'ingénierie mécanique, matériaux et structures {LiMMaS}, Faculté des sciences et de la technologie, Université de Tissemsilt. , Route de Bougara BP 180 Abdelhak Benhamouda- 38010- Tissemsilt

(30) **Mandataire :**

(74) **Données relatives à la priorité:**

Appendix B: Results of thermodynamic calculations for various working fluids

Properties of working fluid R1233ZD

T_{sc} (K)	T_{evap} (K)	T_{cond} (K)	P_{cond} (Pa)	S_1 (J/kg/K)	S_2 (J/kg/K)	P_{evap} (Pa)	h_1 (J/kg)	h_2 (J/kg)	S_4 (J/kg/K)	h_4 (J/kg)	S_5 (J/kg/K)	h_5 (J.kg)	Y	W_{exp} (J/kg)	W_{pump} (J/kg)	$W_{turbine}$ (J/kg)	Q_{in} (J/kg)	η_{th}	η_{carnot}	η_{II}	W_{cycle} (J/kg)	ΔP (Pa)
338	333	303	153917.5	1249.728	1249.728	389258.6762	267423.2	267611.3	1895.825	481021.7	1895.825	463292.2	0.010609	17541.44	188.0905	188.0905	213410.4	0.081314	0.09009	0.90259	17353.35	235341.2
343	333	303	153917.5	1249.728	1249.728	389258.6762	267423.2	267611.3	1909.475	485669.6	1909.475	467580	0.010398	17901.42	188.0905	188.0905	218058.3	0.081232	0.09009	0.901676	17713.32	235341.2
348	333	303	153917.5	1249.728	1249.728	389258.6762	267423.2	267611.3	1922.96	490328.7	1922.96	471883.9	0.010197	18256.72	188.0905	188.0905	222717.4	0.081128	0.09009	0.900521	18068.63	235341.2
353	333	303	153917.5	1249.728	1249.728	389258.6762	267423.2	267611.3	1936.29	495000.5	1936.29	476204.7	0.010007	18607.77	188.0905	188.0905	227389.3	0.081005	0.09009	0.899156	18419.68	235341.2
358	333	303	153917.5	1249.728	1249.728	389258.6762	267423.2	267611.3	1949.471	499686.3	1949.471	480543.3	0.009826	18954.96	188.0905	188.0905	232075	0.080866	0.09009	0.897607	18766.87	235341.2
363	333	303	153917.5	1249.728	1249.728	389258.6762	267423.2	267611.3	1962.51	504387.1	1962.51	484900.4	0.009652	19298.61	188.0905	188.0905	236775.8	0.080711	0.09009	0.895897	19110.52	235341.2
368	333	303	153917.5	1249.728	1249.728	389258.6762	267423.2	267611.3	1975.415	509103.7	1975.415	489276.6	0.009487	19639.02	188.0905	188.0905	241492.4	0.080545	0.09009	0.894046	19450.93	235341.2
373	333	303	153917.5	1249.728	1249.728	389258.6762	267423.2	267611.3	1988.191	513837.1	1988.191	493672.6	0.009328	19976.45	188.0905	188.0905	246225.9	0.080367	0.09009	0.89207	19788.36	235341.2
378	333	303	153917.5	1249.728	1249.728	389258.6762	267423.2	267611.3	2000.843	518588.1	2000.843	498088.8	0.009175	20311.15	188.0905	188.0905	250976.8	0.080179	0.09009	0.889987	20123.06	235341.2
383	333	303	153917.5	1249.728	1249.728	389258.6762	267423.2	267611.3	2013.377	523357.1	2013.377	502525.7	0.009029	20643.33	188.0905	188.0905	255745.9	0.079983	0.09009	0.887808	20455.24	235341.2
388	333	303	153917.5	1249.728	1249.728	389258.6762	267423.2	267611.3	2025.797	528144.9	2025.797	506983.7	0.008888	20973.18	188.0905	188.0905	260533.7	0.079779	0.09009	0.885546	20785.09	235341.2
393	333	303	153917.5	1249.728	1249.728	389258.6762	267423.2	267611.3	2038.107	532952	2038.107	511463.1	0.008753	21300.89	188.0905	188.0905	265340.7	0.079569	0.09009	0.883212	21112.8	235341.2
398	333	303	153917.5	1249.728	1249.728	389258.6762	267423.2	267611.3	2050.312	537778.8	2050.312	515964.2	0.008622	21626.61	188.0905	188.0905	270167.6	0.079353	0.09009	0.880815	21438.51	235341.2
403	333	303	153917.5	1249.728	1249.728	389258.6762	267423.2	267611.3	2062.414	542625.8	2062.414	520487.3	0.008496	21950.48	188.0905	188.0905	275014.5	0.079132	0.09009	0.878363	21762.39	235341.2
343	338	303	153917.5	1249.728	1249.728	446222.9616	267423.2	267656.8	1897.954	484384.4	1897.954	463956.5	0.011436	20194.26	233.6059	233.6059	216727.6	0.0921	0.10355	0.889425	19960.66	292305.5
348	338	303	153917.5	1249.728	1249.728	446222.9616	267423.2	267656.8	1911.634	489110.8	1911.634	468264.6	0.011206	20612.6	233.6059	233.6059	221454	0.092024	0.10355	0.888685	20378.99	292305.5
353	338	303	153917.5	1249.728	1249.728	446222.9616	267423.2	267656.8	1925.139	493844.4	1925.139	472585.7	0.010989	21025.04	233.6059	233.6059	226187.6	0.091921	0.10355	0.887696	20791.44	292305.5
358	338	303	153917.5	1249.728	1249.728	446222.9616	267423.2	267656.8	1938.48	498586.9	1938.48	476921.2	0.010782	21432.15	233.6059	233.6059	230930.1	0.091796	0.10355	0.886491	21198.55	292305.5
363	338	303	153917.5	1249.728	1249.728	446222.9616	267423.2	267656.8	1951.665	503340.1	1951.665	481272	0.010586	21834.42	233.6059	233.6059	235683.3	0.091652	0.10355	0.885095	21600.81	292305.5
368	338	303	153917.5	1249.728	1249.728	446222.9616	267423.2	267656.8	1964.703	508105.2	1964.703	485639.4	0.010398	22232.26	233.6059	233.6059	240448.4	0.09149	0.10355	0.883533	21998.66	292305.5
373	338	303	153917.5	1249.728	1249.728	446222.9616	267423.2	267656.8	1977.6	512883.6	1977.6	490024	0.010219	22626.07	233.6059	233.6059	245226.8	0.091313	0.10355	0.881825	22392.47	292305.5
378	338	303	153917.5	1249.728	1249.728	446222.9616	267423.2	267656.8	1990.364	517676.4	1990.364	494426.6	0.010048	23016.19	233.6059	233.6059	250019.6	0.091123	0.10355	0.87999	22782.59	292305.5
383	338	303	153917.5	1249.728	1249.728	446222.9616	267423.2	267656.8	2003	522484.4	2003	498847.8	0.009883	23402.92	233.6059	233.6059	254827.6	0.090922	0.10355	0.878042	23169.32	292305.5
388	338	303	153917.5	1249.728	1249.728	446222.9616	267423.2	267656.8	2015.514	527308.5	2015.514	503288.3	0.009725	23786.53	233.6059	233.6059	259651.7	0.09071	0.10355	0.875997	23552.93	292305.5
393	338	303	153917.5	1249.728	1249.728	446222.9616	267423.2	267656.8	2027.911	532149.5	2027.911	507748.6	0.009574	24167.28	233.6059	233.6059	264492.7	0.090489	0.10355	0.873865	23933.67	292305.5
398	338	303	153917.5	1249.728	1249.728	446222.9616	267423.2	267656.8	2040.196	537008.1	2040.196	512229.1	0.009428	24545.37	233.6059	233.6059	269351.3	0.09026	0.10355	0.871658	24311.77	292305.5
403	338	303	153917.5	1249.728	1249.728	446222.9616	267423.2	267656.8	2052.372	541884.8	2052.372	516730.1	0.009287	24921.02	233.6059	233.6059	274228	0.090025	0.10355	0.869386	24687.41	292305.5
348	343	303	153917.5	1249.728	1249.728	509270.5932	267423.2	267707.2	1900.164	487707	1900.164	464648	0.012315	22775.05	283.9765	283.9765	219999.8	0.102232	0.116618	0.876641	22491.07	355353.1
353	343	303	153917.5	1249.728	1249.728	509270.5932	267423.2	267707.2	1913.885	492516.1	1913.885	468980.2	0.012066	23251.92	283.9765	283.9765	224808.9	0.102167	0.116618	0.876078	22967.95	355353.1
358	343	303	153917.5	1249.728	1249.728	509270.5932	267423.2	267707.2	1927.42	497327.5	1927.42	473322.1	0.01183	23721.49	283.9765	283.9765	229620.4	0.102071	0.116618	0.875256	23437.52	355353.1
363	343	303	153917.5	1249.728	1249.728	509270.5932	267423.2	267707.2	1940.78	502143.8	1940.78	477675.4	0.011606	24184.49	283.9765	283.9765	234436.7	0.101949	0.116618	0.87421	23900.51	355353.1

Properties of working fluid R1233ZD — continued

T_{sc} (K)	T_{evap} (K)	T_{cond} (K)	P_{cond} (Pa)	S_1 (J/kg/K)	S_2 (J/kg/K)	P_{evap} (Pa)	h_1 (J/kg)	h_2 (J/kg)	S_4 (J/kg/K)	h_4 (J/kg)	S_5 (J/kg/K)	h_5 (J.kg)	Y	W_{exp} (J/kg)	W_{pump} (J/kg)	$W_{turbine}$ (J/kg)	Q_{in} (J/kg)	η_{th}	η_{carnot}	η_{II}	W_{cycle} (J/kg)	ΔP (Pa)
368	343	303	153917.5	1249.728	1249.728	509270.5932	267423.2	267707.2	1953.977	506967.1	1953.977	482041.6	0.011393	24641.53	283.9765	283.9765	239259.9	0.101804	0.116618	0.872967	24357.55	355353.1
373	343	303	153917.5	1249.728	1249.728	509270.5932	267423.2	267707.2	1967.018	511799	1967.018	486421.9	0.01119	25093.16	283.9765	283.9765	244091.8	0.101639	0.116618	0.871552	24809.19	355353.1
378	343	303	153917.5	1249.728	1249.728	509270.5932	267423.2	267707.2	1979.914	516641.2	1979.914	490817.4	0.010997	25539.87	283.9765	283.9765	248934.1	0.101456	0.116618	0.869987	25255.9	355353.1
383	343	303	153917.5	1249.728	1249.728	509270.5932	267423.2	267707.2	1992.671	521495.1	1992.671	495229.1	0.010812	25982.09	283.9765	283.9765	253788	0.101258	0.116618	0.868289	25698.11	355353.1
388	343	303	153917.5	1249.728	1249.728	509270.5932	267423.2	267707.2	2005.295	526361.9	2005.295	499657.7	0.010634	26420.19	283.9765	283.9765	258654.7	0.101047	0.116618	0.866476	26136.21	355353.1
393	343	303	153917.5	1249.728	1249.728	509270.5932	267423.2	267707.2	2017.794	531242.6	2017.794	504104.1	0.010464	26854.51	283.9765	283.9765	263535.4	0.100823	0.116618	0.864561	26570.54	355353.1
398	343	303	153917.5	1249.728	1249.728	509270.5932	267423.2	267707.2	2030.172	536138.2	2030.172	508568.8	0.0103	27285.36	283.9765	283.9765	268431	0.10059	0.116618	0.862557	27001.39	355353.1
403	343	303	153917.5	1249.728	1249.728	509270.5932	267423.2	267707.2	2042.435	541049.4	2042.435	513052.4	0.010143	27713.02	283.9765	283.9765	273342.3	0.100347	0.116618	0.860474	27429.04	355353.1
353	348	303	153917.5	1249.728	1249.728	578806.6264	267423.2	267762.7	1902.435	490984.5	1902.435	465360.1	0.01325	25284.88	339.5243	339.5243	223221.8	0.111751	0.12931	0.864211	24945.36	424889.1
358	348	303	153917.5	1249.728	1249.728	578806.6264	267423.2	267762.7	1916.209	495880.9	1916.209	469720.6	0.012979	25820.74	339.5243	339.5243	228118.2	0.111702	0.12931	0.863827	25481.22	424889.1
363	348	303	153917.5	1249.728	1249.728	578806.6264	267423.2	267762.7	1929.783	500774.2	1929.783	474087	0.012722	26347.67	339.5243	339.5243	233011.5	0.111617	0.12931	0.863175	26008.15	424889.1
368	348	303	153917.5	1249.728	1249.728	578806.6264	267423.2	267762.7	1943.171	505667.7	1943.171	478461.6	0.01248	26866.6	339.5243	339.5243	237905	0.111503	0.12931	0.862288	26527.07	424889.1
373	348	303	153917.5	1249.728	1249.728	578806.6264	267423.2	267762.7	1956.387	510564	1956.387	482846.2	0.012249	27378.31	339.5243	339.5243	242801.3	0.111362	0.12931	0.861198	27038.79	424889.1
378	348	303	153917.5	1249.728	1249.728	578806.6264	267423.2	267762.7	1969.44	515465.3	1969.44	487242.3	0.01203	27883.51	339.5243	339.5243	247702.6	0.111198	0.12931	0.85993	27543.98	424889.1
383	348	303	153917.5	1249.728	1249.728	578806.6264	267423.2	267762.7	1982.34	520373.7	1982.34	491651.4	0.011821	28382.78	339.5243	339.5243	252611	0.111014	0.12931	0.858505	28043.26	424889.1
388	348	303	153917.5	1249.728	1249.728	578806.6264	267423.2	267762.7	1995.095	525290.8	1995.095	496074.6	0.011621	28876.66	339.5243	339.5243	257528.1	0.110812	0.12931	0.856944	28537.14	424889.1
393	348	303	153917.5	1249.728	1249.728	578806.6264	267423.2	267762.7	2007.713	530218.2	2007.713	500513	0.01143	29365.62	339.5243	339.5243	262455.5	0.110594	0.12931	0.855263	29026.1	424889.1
398	348	303	153917.5	1249.728	1249.728	578806.6264	267423.2	267762.7	2020.201	535157.1	2020.201	504967.5	0.011246	29850.07	339.5243	339.5243	267394.4	0.110363	0.12931	0.853477	29510.55	424889.1
403	348	303	153917.5	1249.728	1249.728	578806.6264	267423.2	267762.7	2032.565	540108.7	2032.565	509438.8	0.01107	30330.39	339.5243	339.5243	272346	0.11012	0.12931	0.851598	29990.86	424889.1
358	353	303	153917.5	1249.728	1249.728	655247.8939	267423.2	267823.8	1904.745	494211.4	1904.745	466086.4	0.014243	27724.45	400.5804	400.5804	226387.6	0.120695	0.141643	0.852107	27323.87	501330.4
363	353	303	153917.5	1249.728	1249.728	655247.8939	267423.2	267823.8	1918.584	499200.4	1918.584	470479.8	0.013947	28320.05	400.5804	400.5804	231376.6	0.120667	0.141643	0.851907	27919.47	501330.4
368	353	303	153917.5	1249.728	1249.728	655247.8939	267423.2	267823.8	1932.209	504180.2	1932.209	474874.7	0.013669	28904.83	400.5804	400.5804	236356.4	0.120599	0.141643	0.851426	28504.25	501330.4
373	353	303	153917.5	1249.728	1249.728	655247.8939	267423.2	267823.8	1945.635	509154.7	1945.635	479274.1	0.013406	29479.97	400.5804	400.5804	241330.9	0.120496	0.141643	0.850701	29079.39	501330.4
378	353	303	153917.5	1249.728	1249.728	655247.8939	267423.2	267823.8	1958.878	514127.4	1958.878	483680.3	0.013157	30046.47	400.5804	400.5804	246303.6	0.120363	0.141643	0.849764	29645.89	501330.4
383	353	303	153917.5	1249.728	1249.728	655247.8939	267423.2	267823.8	1971.95	519101	1971.95	488095.3	0.01292	30605.18	400.5804	400.5804	251277.2	0.120204	0.141643	0.848642	30204.6	501330.4
388	353	303	153917.5	1249.728	1249.728	655247.8939	267423.2	267823.8	1984.861	524078.1	1984.861	492520.7	0.012694	31156.85	400.5804	400.5804	256254.3	0.120022	0.141643	0.847358	30756.27	501330.4
393	353	303	153917.5	1249.728	1249.728	655247.8939	267423.2	267823.8	1997.621	529060.7	1997.621	496958	0.012478	31702.12	400.5804	400.5804	261236.9	0.119821	0.141643	0.845933	31301.54	501330.4
398	353	303	153917.5	1249.728	1249.728	655247.8939	267423.2	267823.8	2010.237	534050.6	2010.237	501408.5	0.012272	32241.58	400.5804	400.5804	266226.8	0.119601	0.141643	0.844383	31841	501330.4
403	353	303	153917.5	1249.728	1249.728	655247.8939	267423.2	267823.8	2022.719	539049.5	2022.719	505873.2	0.012074	32775.71	400.5804	400.5804	271225.7	0.119366	0.141643	0.842724	32375.13	501330.4
363	358	303	153917.5	1249.728	1249.728	739023.9066	267423.2	267890.7	1907.071	497381.4	1907.071	466819.9	0.015297	30094	467.4854	467.4854	229490.7	0.129097	0.153631	0.840303	29626.52	585106.4
368	358	303	153917.5	1249.728	1249.728	739023.9066	267423.2	267890.7	1920.991	502469.2	1920.991	471251.3	0.014975	30750.45	467.4854	467.4854	234578.5	0.129095	0.153631	0.840292	30282.97	585106.4

Properties of working fluid R1233ZDu_continued

T_{sc} (K)	T_{evap} (K)	T_{cond} (K)	P_{cond} (Pa)	S_1 (J/kg/K)	S_2 (J/kg/K)	P_{evap} (Pa)	h_1 (J/kg)	h_2 (J/kg)	S_4 (J/kg/K)	h_4 (J/kg)	S_5 (J/kg/K)	h_5 (J.kg)	Y	W_{exp} (J/kg)	W_{pump} (J/kg)	$W_{turbine}$ (J/kg)	Q_{in} (J/kg)	η_{th}	η_{carnot}	η_{II}	W_{cycle} (J/kg)	ΔP (Pa)
373	358	303	153917.5	1249.728	1249.728	739023.9066	267423.2	267890.7	1934.679	507540.6	1934.679	475679.2	0.014672	31393.88	467.4854	467.4854	239649.9	0.129048	0.153631	0.839987	30926.4	585106.4
378	358	303	153917.5	1249.728	1249.728	739023.9066	267423.2	267890.7	1948.155	512600.5	1948.155	480107.3	0.014387	32025.78	467.4854	467.4854	244709.9	0.128962	0.153631	0.839426	31558.29	585106.4
383	358	303	153917.5	1249.728	1249.728	739023.9066	267423.2	267890.7	1961.435	517653.4	1961.435	484538.5	0.014117	32647.38	467.4854	467.4854	249762.7	0.128842	0.153631	0.838644	32179.9	585106.4
388	358	303	153917.5	1249.728	1249.728	739023.9066	267423.2	267890.7	1974.533	522702.6	1974.533	488975.3	0.013861	33259.77	467.4854	467.4854	254811.9	0.128692	0.153631	0.837669	32792.28	585106.4
393	358	303	153917.5	1249.728	1249.728	739023.9066	267423.2	267890.7	1987.461	527751.2	1987.461	493419.8	0.013617	33863.84	467.4854	467.4854	259860.5	0.128516	0.153631	0.836525	33396.36	585106.4
398	358	303	153917.5	1249.728	1249.728	739023.9066	267423.2	267890.7	2000.232	532801.7	2000.232	497873.8	0.013384	34460.4	467.4854	467.4854	264911	0.128318	0.153631	0.835235	33992.91	585106.4
403	358	303	153917.5	1249.728	1249.728	739023.9066	267423.2	267890.7	2012.853	537856.4	2012.853	502338.8	0.013162	35050.14	467.4854	467.4854	269965.8	0.1281	0.153631	0.833815	34582.65	585106.4
368	363	303	153917.5	1249.728	1249.728	830578.09	267423.2	267963.8	1909.391	500487.4	1909.391	467553.5	0.016414	32393.35	540.5908	540.5908	232523.6	0.136987	0.165289	0.828772	31852.76	676660.6
373	363	303	153917.5	1249.728	1249.728	830578.09	267423.2	267963.8	1923.41	505681.3	1923.41	472028.5	0.016064	33112.18	540.5908	540.5908	237717.5	0.137018	0.165289	0.828959	32571.59	676660.6
378	363	303	153917.5	1249.728	1249.728	830578.09	267423.2	267963.8	1937.176	510850.2	1937.176	476494.2	0.015735	33815.38	540.5908	540.5908	242886.4	0.136997	0.165289	0.828834	33274.79	676660.6
383	363	303	153917.5	1249.728	1249.728	830578.09	267423.2	267963.8	1950.712	516000.6	1950.712	480955.2	0.015425	34504.85	540.5908	540.5908	248036.9	0.136932	0.165289	0.82844	33964.26	676660.6
388	363	303	153917.5	1249.728	1249.728	830578.09	267423.2	267963.8	1964.038	521137.9	1964.038	485415.2	0.015133	35182.14	540.5908	540.5908	253174.1	0.136829	0.165289	0.827815	34641.55	676660.6
393	363	303	153917.5	1249.728	1249.728	830578.09	267423.2	267963.8	1977.171	526266.3	1977.171	489877.2	0.014856	35848.56	540.5908	540.5908	258302.5	0.136692	0.165289	0.826989	35307.97	676660.6
398	363	303	153917.5	1249.728	1249.728	830578.09	267423.2	267963.8	1990.125	531389.6	1990.125	494343.8	0.014592	36505.25	540.5908	540.5908	263425.8	0.136527	0.165289	0.825987	35964.66	676660.6
403	363	303	153917.5	1249.728	1249.728	830578.09	267423.2	267963.8	2002.913	536510.9	2002.913	498817.1	0.014342	37153.15	540.5908	540.5908	268547.1	0.136336	0.165289	0.824831	36612.56	676660.6
373	368	303	153917.5	1249.728	1249.728	930369.4141	267423.2	268043.5	1911.68	503521.2	1911.68	468279.2	0.0176	34621.79	620.26	620.26	235477.8	0.144394	0.17663	0.817491	34001.53	776451.9
378	368	303	153917.5	1249.728	1249.728	930369.4141	267423.2	268043.5	1925.818	508829.7	1925.818	472804.5	0.017217	35405.02	620.26	620.26	240786.3	0.144463	0.17663	0.817884	34784.76	776451.9
383	368	303	153917.5	1249.728	1249.728	930369.4141	267423.2	268043.5	1939.677	514103.2	1939.677	477313.4	0.01686	36169.53	620.26	620.26	246059.8	0.144474	0.17663	0.817946	35549.27	776451.9
388	368	303	153917.5	1249.728	1249.728	930369.4141	267423.2	268043.5	1953.287	519349.9	1953.287	481811.9	0.016524	36917.71	620.26	620.26	251306.5	0.144435	0.17663	0.817724	36297.45	776451.9
393	368	303	153917.5	1249.728	1249.728	930369.4141	267423.2	268043.5	1966.672	524576.4	1966.672	486304.6	0.016207	37651.52	620.26	620.26	256533	0.144353	0.17663	0.817259	37031.26	776451.9
398	368	303	153917.5	1249.728	1249.728	930369.4141	267423.2	268043.5	1979.85	529788.2	1979.85	490795.3	0.015907	38372.59	620.26	620.26	261744.7	0.144233	0.17663	0.816583	37752.33	776451.9
403	368	303	153917.5	1249.728	1249.728	930369.4141	267423.2	268043.5	1992.837	534989.7	1992.837	495287.2	0.015623	39082.29	620.26	620.26	266946.3	0.144082	0.17663	0.815723	38462.03	776451.9
378	373	303	153917.5	1249.728	1249.728	1038874.495	267423.2	268130.1	1913.911	506473.4	1913.911	468988.4	0.018857	36778.09	706.8699	706.8699	238343.3	0.151341	0.187668	0.806433	36071.22	884957
383	373	303	153917.5	1249.728	1249.728	1038874.495	267423.2	268130.1	1928.191	511906.8	1928.191	473571.6	0.018439	37628.33	706.8699	706.8699	243776.7	0.151456	0.187668	0.807044	36921.46	884957
388	373	303	153917.5	1249.728	1249.728	1038874.495	267423.2	268130.1	1942.164	517293.1	1942.164	478130	0.018049	38456.13	706.8699	706.8699	249163	0.151504	0.187668	0.807301	37749.26	884957
393	373	303	153917.5	1249.728	1249.728	1038874.495	267423.2	268130.1	1955.863	522642.7	1955.863	482671.3	0.017684	39264.55	706.8699	706.8699	254512.6	0.151496	0.187668	0.807258	38557.68	884957
398	373	303	153917.5	1249.728	1249.728	1038874.495	267423.2	268130.1	1969.319	527964.1	1969.319	487201.2	0.017341	40056.03	706.8699	706.8699	259834	0.15144	0.187668	0.806957	39349.16	884957
403	373	303	153917.5	1249.728	1249.728	1038874.495	267423.2	268130.1	1982.552	533263.9	1982.552	491724.4	0.017017	40832.61	706.8699	706.8699	265133.8	0.151341	0.187668	0.806434	40125.74	884957
383	378	303	153917.5	1249.728	1249.728	1156590.275	267423.2	268224	1916.055	509332.8	1916.055	469671.7	0.020191	38860.33	800.8132	800.8132	241108.8	0.157852	0.198413	0.795574	38059.52	1002673
388	378	303	153917.5	1249.728	1249.728	1156590.275	267423.2	268224	1930.506	514903.5	1930.506	474321.8	0.019733	39780.96	800.8132	800.8132	246679.5	0.158019	0.198413	0.796418	38980.15	1002673
393	378	303	153917.5	1249.728	1249.728	1156590.275	267423.2	268224	1944.614	520412.3	1944.614	478936.9	0.019308	40674.61	800.8132	800.8132	252188.3	0.158111	0.198413	0.79688	39873.8	1002673

Properties of working fluid R1233ZD_continued

T_{sc} (K)	T_{evap} (K)	T_{cond} (K)	P_{cond} (Pa)	S_1 (J/kg/K)	S_2 (J/kg/K)	P_{evap} (Pa)	h_1 (J/kg)	h_2 (J/kg)	S_4 (J/kg/K)	h_4 (J/kg)	S_5 (J/kg/K)	h_5 (J.kg)	Y	W_{exp} (J/kg)	W_{pump} (J/kg)	$W_{turbine}$ (J/kg)	Q_{in} (J/kg)	η_{th}	η_{carnot}	η_{II}	W_{cycle} (J/kg)	ΔP (Pa)
398	378	303	153917.5	1249.728	1249.728	1156590.275	267423.2	268224	1958.42	525872.8	1958.42	483526.8	0.018911	41545.21	800.8132	800.8132	257648.8	0.158139	0.198413	0.797022	40744.4	1002673
403	378	303	153917.5	1249.728	1249.728	1156590.275	267423.2	268224	1971.96	531295.5	1971.96	488098.8	0.018539	42395.87	800.8132	800.8132	263071.5	0.158113	0.198413	0.79689	41595.06	1002673
388	383	303	153917.5	1249.728	1249.728	1284037.417	267423.2	268325.7	1918.079	512086.6	1918.079	470318.2	0.021607	40865.87	902.5006	902.5006	243760.9	0.163945	0.208877	0.784886	39963.37	1130120
393	383	303	153917.5	1249.728	1249.728	1284037.417	267423.2	268325.7	1932.735	517809.7	1932.735	475046.1	0.021104	41861.2	902.5006	902.5006	249484.1	0.164174	0.208877	0.785981	40958.7	1130120
398	383	303	153917.5	1249.728	1249.728	1284037.417	267423.2	268325.7	1947.004	523452.8	1947.004	479726.4	0.02064	42823.93	902.5006	902.5006	255127.1	0.164316	0.208877	0.786662	41921.43	1130120
403	383	303	153917.5	1249.728	1249.728	1284037.417	267423.2	268325.7	1960.938	529033.3	1960.938	484371.6	0.020207	43759.19	902.5006	902.5006	260707.6	0.164386	0.208877	0.786998	42856.69	1130120
393	388	303	153917.5	1249.728	1249.728	1421764.621	267423.2	268435.6	1919.945	514719.2	1919.945	470915.7	0.023112	42791.12	1012.365	1012.365	246283.6	0.169637	0.219072	0.774342	41778.8	1267847
398	388	303	153917.5	1249.728	1249.728	1421764.621	267423.2	268435.6	1934.849	520613.6	1934.849	475734.6	0.022558	43866.68	1012.365	1012.365	252178.1	0.169937	0.219072	0.775711	42854.31	1267847
403	388	303	153917.5	1249.728	1249.728	1421764.621	267423.2	268435.6	1949.31	526405	1949.31	480490.1	0.022049	44902.59	1012.365	1012.365	257969.5	0.170137	0.219072	0.776627	43890.22	1267847
398	393	303	153917.5	1249.728	1249.728	1570354.131	267423.2	268554.1	1921.61	517212.1	1921.61	471449.8	0.024712	44631.41	1130.864	1130.864	248658.1	0.174941	0.229008	0.76391	43500.55	1416437
403	393	303	153917.5	1249.728	1249.728	1570354.131	267423.2	268554.1	1936.815	523301.5	1936.815	476376.4	0.024099	45794.31	1130.864	1130.864	254747.5	0.175324	0.229008	0.765583	44663.45	1416437

Properties of R600a

T_{sc} (K)	T_{evap} (K)	T_{cond} (K)	P_{cond} (Pa)	S_1 (J/kg/K)	S_2 (J/kg/K)	P_{evap} (Pa)	h_1 (J/kg)	h_2 (J/kg)	S_4 (J/kg/K)	h_4 (J/kg)	S_5 (J/kg/K)	h_5 (J.kg)	Y	W_{exp} (J/kg)	W_{pump} (J/kg)	$W_{turbine}$ (J/kg)	Q_{in} (J/kg)	η_{th}	η_{carnot}	η_{II}	W_{cycle} (J/kg)	ΔP (Pa)
338	333	303	403015.7	1244.559	1244.559	866154.1519	270870.8	271721.3	2372.844	643940.9	2372.844	613046.9	0.027532	30043.4	850.5709	850.5709	372219.5	0.078429	0.09009	0.870563	29192.83	463138.5
343	333	303	403015.7	1244.559	1244.559	866154.1519	270870.8	271721.3	2403.923	654523.2	2403.923	622860.1	0.026863	30812.51	850.5709	850.5709	382801.8	0.07827	0.09009	0.868798	29961.93	463138.5
348	333	303	403015.7	1244.559	1244.559	866154.1519	270870.8	271721.3	2434.563	665109	2434.563	632695.2	0.026241	31563.23	850.5709	850.5709	393387.6	0.078072	0.09009	0.866602	30712.66	463138.5
353	333	303	403015.7	1244.559	1244.559	866154.1519	270870.8	271721.3	2464.825	675715.7	2464.825	642566.9	0.025659	32298.14	850.5709	850.5709	403994.3	0.077842	0.09009	0.864042	31447.57	463138.5
358	333	303	403015.7	1244.559	1244.559	866154.1519	270870.8	271721.3	2494.758	686356.9	2494.758	652487	0.025113	33019.31	850.5709	850.5709	414635.6	0.077583	0.09009	0.861173	32168.74	463138.5
363	333	303	403015.7	1244.559	1244.559	866154.1519	270870.8	271721.3	2524.402	697043.5	2524.402	662464.6	0.024598	33728.37	850.5709	850.5709	425322.2	0.077301	0.09009	0.85804	32877.8	463138.5
368	333	303	403015.7	1244.559	1244.559	866154.1519	270870.8	271721.3	2553.788	707783.8	2553.788	672506.6	0.024111	34426.66	850.5709	850.5709	436062.5	0.076998	0.09009	0.854682	33576.09	463138.5
373	333	303	403015.7	1244.559	1244.559	866154.1519	270870.8	271721.3	2582.939	718584.3	2582.939	682618.5	0.023649	35115.28	850.5709	850.5709	446863	0.076678	0.09009	0.851129	34264.71	463138.5
378	333	303	403015.7	1244.559	1244.559	866154.1519	270870.8	271721.3	2611.877	729450.5	2611.877	692804.7	0.023211	35795.17	850.5709	850.5709	457729.1	0.076343	0.09009	0.847412	34944.6	463138.5
383	333	303	403015.7	1244.559	1244.559	866154.1519	270870.8	271721.3	2640.619	740386.6	2640.619	703068.9	0.022793	36467.16	850.5709	850.5709	468665.3	0.075996	0.09009	0.843553	35616.58	463138.5
388	333	303	403015.7	1244.559	1244.559	866154.1519	270870.8	271721.3	2669.179	751396.6	2669.179	713414.1	0.022394	37131.95	850.5709	850.5709	479675.3	0.075637	0.09009	0.839575	36281.38	463138.5
393	333	303	403015.7	1244.559	1244.559	866154.1519	270870.8	271721.3	2697.572	762483.9	2697.572	723843.1	0.022012	37790.19	850.5709	850.5709	490762.5	0.07527	0.09009	0.835495	36939.62	463138.5
398	333	303	403015.7	1244.559	1244.559	866154.1519	270870.8	271721.3	2725.808	773651.3	2725.808	734358.3	0.021647	38442.45	850.5709	850.5709	501929.9	0.074895	0.09009	0.831331	37591.88	463138.5
403	333	303	403015.7	1244.559	1244.559	866154.1519	270870.8	271721.3	2753.899	784901.3	2753.899	744961.5	0.021296	39089.22	850.5709	850.5709	513180	0.074513	0.09009	0.827096	38238.64	463138.5
343	338	303	403015.7	1244.559	1244.559	970586.5953	270870.8	271913.1	2378.562	650422.6	2378.562	614840.3	0.029294	34539.95	1042.365	1042.365	378509.5	0.088499	0.10355	0.854644	33497.59	567570.9
348	338	303	403015.7	1244.559	1244.559	970586.5953	270870.8	271913.1	2409.963	661271.3	2409.963	624786.3	0.02857	35442.72	1042.365	1042.365	389358.2	0.088351	0.10355	0.853222	34400.35	567570.9

Properties of working fluid R600a — continued

T_{sc} (K)	T_{evap} (K)	T_{cond} (K)	P_{cond} (Pa)	S_1 (J/kg/K)	S_2 (J/kg/K)	P_{evap} (Pa)	h_1 (J/kg)	h_2 (J/kg)	S_4 (J/kg/K)	h_4 (J/kg)	S_5 (J/kg/K)	h_5 (J.kg)	Y	W_{exp} (J/kg)	W_{pump} (J/kg)	$W_{turbine}$ (J/kg)	Q_{in} (J/kg)	η_{th}	η_{carnot}	η_{II}	W_{cycle} (J/kg)	ΔP (Pa)
353	338	303	403015.7	1244.559	1244.559	970586.5953	270870.8	271913.1	2440.878	672107	2440.878	634742.5	0.027897	36322.13	1042.365	1042.365	400193.9	0.088157	0.10355	0.851342	35279.77	567570.9
358	338	303	403015.7	1244.559	1244.559	970586.5953	270870.8	271913.1	2471.38	682950.2	2471.38	644726.3	0.02727	37181.59	1042.365	1042.365	411037.1	0.087922	0.10355	0.849076	36139.22	567570.9
363	338	303	403015.7	1244.559	1244.559	970586.5953	270870.8	271913.1	2501.524	693816.9	2501.524	654750.8	0.026682	38023.73	1042.365	1042.365	421903.7	0.087654	0.10355	0.846483	36981.37	567570.9
368	338	303	403015.7	1244.559	1244.559	970586.5953	270870.8	271913.1	2531.352	704718.9	2531.352	664825.9	0.026129	38850.66	1042.365	1042.365	432805.7	0.087356	0.10355	0.843612	37808.3	567570.9
373	338	303	403015.7	1244.559	1244.559	970586.5953	270870.8	271913.1	2560.898	715665.6	2560.898	674959.1	0.025607	39664.08	1042.365	1042.365	443752.4	0.087034	0.10355	0.840503	38621.71	567570.9
378	338	303	403015.7	1244.559	1244.559	970586.5953	270870.8	271913.1	2590.19	726664.5	2590.19	685156.7	0.025113	40465.39	1042.365	1042.365	454751.3	0.086691	0.10355	0.837191	39423.03	567570.9
383	338	303	403015.7	1244.559	1244.559	970586.5953	270870.8	271913.1	2619.25	737721.7	2619.25	695423.5	0.024643	41255.83	1042.365	1042.365	465808.6	0.08633	0.10355	0.833705	40213.46	567570.9
388	338	303	403015.7	1244.559	1244.559	970586.5953	270870.8	271913.1	2648.098	748842.6	2648.098	705763.8	0.024197	42036.44	1042.365	1042.365	476929.5	0.085954	0.10355	0.830072	40994.07	567570.9
393	338	303	403015.7	1244.559	1244.559	970586.5953	270870.8	271913.1	2676.752	760031.9	2676.752	716181.4	0.023771	42808.16	1042.365	1042.365	488118.7	0.085565	0.10355	0.826312	41765.79	567570.9
398	338	303	403015.7	1244.559	1244.559	970586.5953	270870.8	271913.1	2705.226	771293.4	2705.226	726679.2	0.023364	43571.79	1042.365	1042.365	499380.3	0.085164	0.10355	0.822445	42529.43	567570.9
403	338	303	403015.7	1244.559	1244.559	970586.5953	270870.8	271913.1	2733.534	782630.6	2733.534	737260.2	0.022975	44328.06	1042.365	1042.365	510717.5	0.084755	0.10355	0.818488	43285.7	567570.9
348	343	303	403015.7	1244.559	1244.559	1083991.935	270870.8	272121.4	2384.299	656789.4	2384.299	616644.9	0.031153	38893.84	1250.638	1250.638	384667.9	0.097859	0.116618	0.839141	37643.2	680976.3
353	343	303	403015.7	1244.559	1244.559	1083991.935	270870.8	272121.4	2416.073	667925.8	2416.073	626740.9	0.030366	39934.24	1250.638	1250.638	395804.3	0.097734	0.116618	0.83807	38683.6	680976.3
358	343	303	403015.7	1244.559	1244.559	1083991.935	270870.8	272121.4	2447.307	679029.3	2447.307	636833.3	0.029639	40945.37	1250.638	1250.638	406907.8	0.097552	0.116618	0.83651	39694.73	680976.3
363	343	303	403015.7	1244.559	1244.559	1083991.935	270870.8	272121.4	2478.084	690124.1	2478.084	646941.9	0.028962	41931.61	1250.638	1250.638	418002.7	0.097322	0.116618	0.834538	40680.97	680976.3
368	343	303	403015.7	1244.559	1244.559	1083991.935	270870.8	272121.4	2508.465	701228.4	2508.465	657081.4	0.028329	42896.33	1250.638	1250.638	429107	0.097052	0.116618	0.832221	41645.7	680976.3
373	343	303	403015.7	1244.559	1244.559	1083991.935	270870.8	272121.4	2538.499	712355.8	2538.499	667263	0.027735	43842.2	1250.638	1250.638	440234.4	0.096747	0.116618	0.829609	42591.56	680976.3
378	343	303	403015.7	1244.559	1244.559	1083991.935	270870.8	272121.4	2568.223	723517.1	2568.223	677495	0.027175	44771.37	1250.638	1250.638	451395.6	0.096414	0.116618	0.826748	43520.73	680976.3
383	343	303	403015.7	1244.559	1244.559	1083991.935	270870.8	272121.4	2597.669	734721	2597.669	687784.7	0.026645	45685.67	1250.638	1250.638	462599.6	0.096055	0.116618	0.823672	44435.03	680976.3
388	343	303	403015.7	1244.559	1244.559	1083991.935	270870.8	272121.4	2626.863	745975.2	2626.863	698137.9	0.026144	46586.66	1250.638	1250.638	473853.8	0.095675	0.116618	0.820414	45336.02	680976.3
393	343	303	403015.7	1244.559	1244.559	1083991.935	270870.8	272121.4	2655.828	757286.1	2655.828	708559.8	0.025667	47475.69	1250.638	1250.638	485164.7	0.095277	0.116618	0.817001	46225.05	680976.3
398	343	303	403015.7	1244.559	1244.559	1083991.935	270870.8	272121.4	2684.584	768659.1	2684.584	719054.5	0.025212	48353.93	1250.638	1250.638	496537.7	0.094863	0.116618	0.813454	47103.3	680976.3
403	343	303	403015.7	1244.559	1244.559	1083991.935	270870.8	272121.4	2713.148	780099	2713.148	729626	0.024778	49222.41	1250.638	1250.638	507977.6	0.094437	0.116618	0.809795	47971.77	680976.3
353	348	303	403015.7	1244.559	1244.559	1206846.798	270870.8	272347	2389.985	663019.1	2389.985	618439.1	0.033115	43103.7	1476.266	1476.266	390672	0.106553	0.12931	0.824013	41627.43	803831.1
358	348	303	403015.7	1244.559	1244.559	1206846.798	270870.8	272347	2422.197	674470.2	2422.197	628706.8	0.032259	44287.15	1476.266	1476.266	402123.2	0.106462	0.12931	0.823307	42810.88	803831.1
363	348	303	403015.7	1244.559	1244.559	1206846.798	270870.8	272347	2453.802	685863.3	2453.802	638952.9	0.03147	45434.08	1476.266	1476.266	413516.2	0.106303	0.12931	0.822073	43957.82	803831.1
368	348	303	403015.7	1244.559	1244.559	1206846.798	270870.8	272347	2484.893	697227	2484.893	649200.6	0.030739	46550.15	1476.266	1476.266	424880	0.106086	0.12931	0.8204	45073.88	803831.1
373	348	303	403015.7	1244.559	1244.559	1206846.798	270870.8	272347	2515.543	708582.5	2515.543	659466.6	0.030057	47639.64	1476.266	1476.266	436235.5	0.105822	0.12931	0.818358	46163.37	803831.1
378	348	303	403015.7	1244.559	1244.559	1206846.798	270870.8	272347	2545.806	719946.1	2545.806	669763.8	0.029418	48705.97	1476.266	1476.266	447599	0.105518	0.12931	0.816005	47229.7	803831.1
383	348	303	403015.7	1244.559	1244.559	1206846.798	270870.8	272347	2575.726	731330.7	2575.726	680102.5	0.028817	49751.92	1476.266	1476.266	458983.6	0.105179	0.12931	0.813388	48275.66	803831.1
388	348	303	403015.7	1244.559	1244.559	1206846.798	270870.8	272347	2605.341	742747.2	2605.341	690491	0.028251	50779.85	1476.266	1476.266	470400.1	0.104812	0.12931	0.810546	49303.59	803831.1

Properties of working fluid R600a — continued

T_{sc} (K)	T_{evap} (K)	T_{cond} (K)	P_{cond} (Pa)	S_1 (J/kg/K)	S_2 (J/kg/K)	P_{evap} (Pa)	h_1 (J/kg)	h_2 (J/kg)	S_4 (J/kg/K)	h_4 (J/kg)	S_5 (J/kg/K)	h_5 (J.kg)	Y	W_{exp} (J/kg)	W_{pump} (J/kg)	$W_{turbine}$ (J/kg)	Q_{in} (J/kg)	η_{th}	η_{carnot}	η_{II}	W_{cycle} (J/kg)	ΔP (Pa)
393	348	303	403015.7	1244.559	1244.559	1206846.798	270870.8	272347	2634.682	754204.7	2634.682	700936.7	0.027714	51791.74	1476.266	1476.266	481857.7	0.10442	0.12931	0.807513	50315.47	803831.1
398	348	303	403015.7	1244.559	1244.559	1206846.798	270870.8	272347	2663.776	765711.1	2663.776	711445.6	0.027204	52789.29	1476.266	1476.266	493364.1	0.104006	0.12931	0.804316	51313.02	803831.1
403	348	303	403015.7	1244.559	1244.559	1206846.798	270870.8	272347	2692.644	777273	2692.644	722022.8	0.02672	53773.95	1476.266	1476.266	504925.9	0.103575	0.12931	0.80098	52297.68	803831.1
358	353	303	403015.7	1244.559	1244.559	1339645.273	270870.8	272590.9	2395.551	669087.5	2395.551	620200.4	0.035186	47166.9	1720.155	1720.155	396496.6	0.114621	0.141643	0.809223	45446.74	936629.6
363	353	303	403015.7	1244.559	1244.559	1339645.273	270870.8	272590.9	2428.283	680887.2	2428.283	630666.4	0.034252	48500.62	1720.155	1720.155	408296.2	0.114575	0.141643	0.808898	46780.46	936629.6
368	353	303	403015.7	1244.559	1244.559	1339645.273	270870.8	272590.9	2460.317	692595.5	2460.317	641086.7	0.033395	49788.67	1720.155	1720.155	420004.5	0.114448	0.141643	0.808	48068.52	936629.6
373	353	303	403015.7	1244.559	1244.559	1339645.273	270870.8	272590.9	2491.767	704247.5	2491.767	651488.9	0.032604	51038.44	1720.155	1720.155	431656.6	0.114254	0.141643	0.80663	49318.28	936629.6
378	353	303	403015.7	1244.559	1244.559	1339645.273	270870.8	272590.9	2522.718	715869.2	2522.718	661893.5	0.031869	52255.52	1720.155	1720.155	443278.2	0.114004	0.141643	0.804866	50535.36	936629.6
383	353	303	403015.7	1244.559	1244.559	1339645.273	270870.8	272590.9	2553.235	727480.6	2553.235	672316.1	0.031182	53444.36	1720.155	1720.155	454889.7	0.113707	0.141643	0.802772	51724.2	936629.6
388	353	303	403015.7	1244.559	1244.559	1339645.273	270870.8	272590.9	2583.371	739098.3	2583.371	682769.5	0.030538	54608.58	1720.155	1720.155	466507.3	0.113371	0.141643	0.8004	52888.42	936629.6
393	353	303	403015.7	1244.559	1244.559	1339645.273	270870.8	272590.9	2613.173	750735.5	2613.173	693264.2	0.029931	55751.17	1720.155	1720.155	478144.5	0.113001	0.141643	0.79779	54031.01	936629.6
398	353	303	403015.7	1244.559	1244.559	1339645.273	270870.8	272590.9	2642.675	762403.5	2642.675	703808.7	0.029357	56874.64	1720.155	1720.155	489812.6	0.112603	0.141643	0.794979	55154.49	936629.6
403	353	303	403015.7	1244.559	1244.559	1339645.273	270870.8	272590.9	2671.909	774111.8	2671.909	714410.5	0.028813	57981.11	1720.155	1720.155	501520.9	0.112181	0.141643	0.791996	56260.96	936629.6
363	358	303	403015.7	1244.559	1244.559	1482902.046	270870.8	272854	2400.92	674967.3	2400.92	621904.7	0.037376	51079.44	1983.251	1983.251	402113.3	0.122095	0.153631	0.79473	49096.18	1079886
368	358	303	403015.7	1244.559	1244.559	1482902.046	270870.8	272854	2434.272	687157.2	2434.272	632601.1	0.036353	52572.83	1983.251	1983.251	414303.2	0.122108	0.153631	0.79481	50589.58	1079886
373	358	303	403015.7	1244.559	1244.559	1482902.046	270870.8	272854	2466.806	699210.6	2466.806	643218.7	0.03542	54008.7	1983.251	1983.251	426356.6	0.122023	0.153631	0.794261	52025.45	1079886
378	358	303	403015.7	1244.559	1244.559	1482902.046	270870.8	272854	2498.663	711172.8	2498.663	653792.5	0.034563	55397	1983.251	1983.251	438318.8	0.121861	0.153631	0.793201	53413.75	1079886
383	358	303	403015.7	1244.559	1244.559	1482902.046	270870.8	272854	2529.95	723077.2	2529.95	664348.7	0.03377	56745.21	1983.251	1983.251	450223.1	0.121633	0.153631	0.79172	54761.96	1079886
388	358	303	403015.7	1244.559	1244.559	1482902.046	270870.8	272854	2560.748	734949.7	2560.748	674907.3	0.033031	58059.19	1983.251	1983.251	462095.7	0.121351	0.153631	0.789887	56075.94	1079886
393	358	303	403015.7	1244.559	1244.559	1482902.046	270870.8	272854	2591.123	746811.2	2591.123	685484.3	0.032339	59343.63	1983.251	1983.251	473957.1	0.121024	0.153631	0.787759	57360.38	1079886
398	358	303	403015.7	1244.559	1244.559	1482902.046	270870.8	272854	2621.129	758678.3	2621.129	696092.7	0.031689	60602.35	1983.251	1983.251	485824.3	0.120659	0.153631	0.785381	58619.1	1079886
403	358	303	403015.7	1244.559	1244.559	1482902.046	270870.8	272854	2650.809	770564.8	2650.809	706743.1	0.031075	61838.48	1983.251	1983.251	497710.8	0.120261	0.153631	0.78279	59855.22	1079886
368	363	303	403015.7	1244.559	1244.559	1637156.888	270870.8	273137.3	2406.01	680627.3	2406.01	623525.1	0.039693	54835.7	2266.546	2266.546	407490	0.129007	0.165289	0.780494	52569.16	1234141
373	363	303	403015.7	1244.559	1244.559	1637156.888	270870.8	273137.3	2440.103	693258.1	2440.103	634490.7	0.038568	56500.85	2266.546	2266.546	420120.8	0.129092	0.165289	0.781008	54234.3	1234141
378	363	303	403015.7	1244.559	1244.559	1637156.888	270870.8	273137.3	2473.215	705691.3	2473.215	645331.9	0.037551	58092.86	2266.546	2266.546	432553.9	0.129062	0.165289	0.780826	55826.32	1234141
383	363	303	403015.7	1244.559	1244.559	1637156.888	270870.8	273137.3	2505.534	717988.3	2505.534	656096.2	0.036621	59625.63	2266.546	2266.546	444851	0.12894	0.165289	0.780087	57359.08	1234141
388	363	303	403015.7	1244.559	1244.559	1637156.888	270870.8	273137.3	2537.197	730194.1	2537.197	666818.3	0.035764	61109.34	2266.546	2266.546	457056.8	0.128743	0.165289	0.778894	58842.79	1234141
393	363	303	403015.7	1244.559	1244.559	1637156.888	270870.8	273137.3	2568.307	742342.6	2568.307	677524.3	0.034968	62551.75	2266.546	2266.546	469205.3	0.128484	0.165289	0.777326	60285.2	1234141
398	363	303	403015.7	1244.559	1244.559	1637156.888	270870.8	273137.3	2598.946	754460.2	2598.946	688234.7	0.034225	63958.93	2266.546	2266.546	481322.8	0.128173	0.165289	0.775444	61692.38	1234141
403	363	303	403015.7	1244.559	1244.559	1637156.888	270870.8	273137.3	2629.177	766567.6	2629.177	698965.4	0.033528	65335.71	2266.546	2266.546	493430.3	0.127818	0.165289	0.773298	63069.16	1234141
373	368	303	403015.7	1244.559	1244.559	1802980.993	270870.8	273441.9	2410.729	686030.1	2410.729	625030.9	0.04215	58428.05	2571.088	2571.088	412588.2	0.135382	0.17663	0.76647	55856.97	1399965

Properties of working fluid R600a — continued

T_{sc} (K)	T_{evap} (K)	T_{cond} (K)	P_{cond} (Pa)	S_1 (J/kg/K)	S_2 (J/kg/K)	P_{evap} (Pa)	h_1 (J/kg)	h_2 (J/kg)	S_4 (J/kg/K)	h_4 (J/kg)	S_5 (J/kg/K)	h_5 (J.kg)	Y	W_{exp} (J/kg)	W_{pump} (J/kg)	$W_{turbine}$ (J/kg)	Q_{in} (J/kg)	η_{th}	η_{carnot}	η_{II}	W_{cycle} (J/kg)	ΔP (Pa)
378	368	303	403015.7	1244.559	1244.559	1802980.993	270870.8	273441.9	2445.707	699163.9	2445.707	636312.4	0.040907	60280.39	2571.088	2571.088	425722	0.135556	0.17663	0.767457	57709.3	1399965
383	368	303	403015.7	1244.559	1244.559	1802980.993	270870.8	273441.9	2479.489	712017.3	2479.489	647407.4	0.039794	62038.86	2571.088	2571.088	438575.5	0.135593	0.17663	0.767665	59467.77	1399965
388	368	303	403015.7	1244.559	1244.559	1802980.993	270870.8	273441.9	2512.332	724677.9	2512.332	658383.4	0.038783	63723.37	2571.088	2571.088	451236	0.135522	0.17663	0.767261	61152.28	1399965
393	368	303	403015.7	1244.559	1244.559	1802980.993	270870.8	273441.9	2544.416	737206.6	2544.416	669287.5	0.037855	65347.93	2571.088	2571.088	463764.7	0.135364	0.17663	0.766366	62776.84	1399965
398	368	303	403015.7	1244.559	1244.559	1802980.993	270870.8	273441.9	2575.874	749648	2575.874	680154	0.036997	66922.84	2571.088	2571.088	476206.1	0.135134	0.17663	0.765068	64351.75	1399965
403	368	303	403015.7	1244.559	1244.559	1802980.993	270870.8	273441.9	2606.805	762035.6	2606.805	691008.6	0.036199	68455.91	2571.088	2571.088	488593.7	0.134846	0.17663	0.763435	65884.83	1399965
378	373	303	403015.7	1244.559	1244.559	1980985.879	270870.8	273768.8	2414.963	691129.7	2414.963	626385.5	0.044761	61846.21	2898.001	2898.001	417360.9	0.14124	0.187668	0.752609	58948.21	1577970
383	373	303	403015.7	1244.559	1244.559	1980985.879	270870.8	273768.8	2451.006	704843.4	2451.006	638039.8	0.043381	63905.61	2898.001	2898.001	431074.6	0.141524	0.187668	0.754123	61007.61	1577970
388	373	303	403015.7	1244.559	1244.559	1980985.879	270870.8	273768.8	2485.566	718165.6	2485.566	649424.2	0.042158	65843.37	2898.001	2898.001	444396.8	0.141642	0.187668	0.754751	62945.36	1577970
393	373	303	403015.7	1244.559	1244.559	1980985.879	270870.8	273768.8	2519.005	731223.2	2519.005	660636.6	0.041056	67688.54	2898.001	2898.001	457454.4	0.141633	0.187668	0.7547	64790.54	1577970
398	373	303	403015.7	1244.559	1244.559	1980985.879	270870.8	273768.8	2551.564	744099.7	2551.564	671741.2	0.040051	69460.49	2898.001	2898.001	470331	0.141523	0.187668	0.754114	66562.49	1577970
403	373	303	403015.7	1244.559	1244.559	1980985.879	270870.8	273768.8	2583.409	756853.7	2583.409	682782.8	0.039125	71172.87	2898.001	2898.001	483084.9	0.141331	0.187668	0.753092	68274.87	1577970
383	378	303	403015.7	1244.559	1244.559	2171835.971	270870.8	274119.3	2418.576	695868.6	2418.576	627543.7	0.047545	65076.4	3248.504	3248.504	421749.3	0.146599	0.198413	0.738857	61827.9	1768820
388	378	303	403015.7	1244.559	1244.559	2171835.971	270870.8	274119.3	2455.91	710259.9	2455.91	639642.6	0.046002	67368.79	3248.504	3248.504	436140.6	0.147017	0.198413	0.740968	64120.29	1768820
393	378	303	403015.7	1244.559	1244.559	2171835.971	270870.8	274119.3	2491.379	724109.7	2491.379	651359.3	0.044653	69501.91	3248.504	3248.504	449990.5	0.147233	0.198413	0.742054	66253.41	1768820
398	378	303	403015.7	1244.559	1244.559	2171835.971	270870.8	274119.3	2525.5	737604.2	2525.5	662836.9	0.043448	71518.71	3248.504	3248.504	463484.9	0.147298	0.198413	0.74238	68270.21	1768820
403	378	303	403015.7	1244.559	1244.559	2171835.971	270870.8	274119.3	2558.594	750857.9	2558.594	674163.4	0.042356	73446.02	3248.504	3248.504	476738.6	0.147245	0.198413	0.742116	70197.51	1768820
388	383	303	403015.7	1244.559	1244.559	2376266.922	270870.8	274494.7	2421.396	700173.3	2421.396	628449.1	0.050526	68100.16	3623.949	3623.949	425678.5	0.151467	0.208877	0.725148	64476.22	1973251
393	383	303	403015.7	1244.559	1244.559	2376266.922	270870.8	274494.7	2460.314	715369.7	2460.314	641085.7	0.048785	70660.05	3623.949	3623.949	440874.9	0.152052	0.208877	0.727951	67036.11	1973251
398	383	303	403015.7	1244.559	1244.559	2376266.922	270870.8	274494.7	2496.853	729819.9	2496.853	653187.1	0.04729	73008.87	3623.949	3623.949	455325.2	0.152385	0.208877	0.729545	69384.92	1973251
403	383	303	403015.7	1244.559	1244.559	2376266.922	270870.8	274494.7	2531.759	743799	2531.759	664964.3	0.045969	75210.8	3623.949	3623.949	469304.3	0.152538	0.208877	0.730277	71586.85	1973251
393	388	303	403015.7	1244.559	1244.559	2595113.936	270870.8	274896.6	2423.206	703949.8	2423.206	629031.2	0.053737	70892.76	4025.87	4025.87	429053.1	0.155848	0.219072	0.711398	66866.89	2192098
398	388	303	403015.7	1244.559	1244.559	2595113.936	270870.8	274896.6	2464.1	720121.5	2464.1	642328.6	0.051751	73767.03	4025.87	4025.87	445224.9	0.156643	0.219072	0.715027	69741.16	2192098
403	388	303	403015.7	1244.559	1244.559	2595113.936	270870.8	274896.6	2501.909	735263	2501.909	654879.7	0.050083	76357.42	4025.87	4025.87	460366.4	0.157117	0.219072	0.717195	72331.55	2192098
398	393	303	403015.7	1244.559	1244.559	2829359.785	270870.8	275326.8	2423.732	707077.6	2423.732	629200.4	0.057219	73421.06	4456.071	4456.071	431750.7	0.159733	0.229008	0.697502	68964.99	2426344
403	393	303	403015.7	1244.559	1244.559	2829359.785	270870.8	275326.8	2467.131	724456.6	2467.131	643325.9	0.054925	76674.64	4456.071	4456.071	449129.8	0.160797	0.229008	0.702145	72218.57	2426344

Properties of working fluid R600

T_{sc} (K)	T_{evap} (K)	T_{cond} (K)	P_{cond} (Pa)	S_1 (J/kg/K)	S_2 (J/kg/K)	P_{evap} (Pa)	h_1 (J/kg)	h_2 (J/kg)	S_4 (J/kg/K)	h_4 (J/kg)	S_5 (J/kg/K)	h_5 (J.kg)	Y	W_{exp} (J/kg)	W_{pump} (J/kg)	$W_{turbine}$ (J/kg)	Q_{in} (J/kg)	η_{th}	η_{carnot}	η_{II}	W_{cycle} (J/kg)	ΔP (Pa)
338	333	303	282139.8	1246.841	1246.841	635897.3558	271391.2	272014.9	2483.655	680354.4	2483.655	646449.4	0.018397	33281.16	623.7424	623.7424	408339.4	0.079976	0.09009	0.887735	32657.42	353757.5
343	333	303	282139.8	1246.841	1246.841	635897.3558	271391.2	272014.9	2514.187	690750.1	2514.187	656086.9	0.017994	34039.44	623.7424	623.7424	418735.2	0.079801	0.09009	0.885797	33415.69	353757.5
348	333	303	282139.8	1246.841	1246.841	635897.3558	271391.2	272014.9	2544.372	701179.2	2544.372	665770.9	0.017616	34784.5	623.7424	623.7424	429164.3	0.079598	0.09009	0.883541	34160.76	353757.5
353	333	303	282139.8	1246.841	1246.841	635897.3558	271391.2	272014.9	2574.249	711650.9	2574.249	675509.3	0.017258	35517.88	623.7424	623.7424	439636	0.079371	0.09009	0.881013	34894.14	353757.5
358	333	303	282139.8	1246.841	1246.841	635897.3558	271391.2	272014.9	2603.848	722173.2	2603.848	685308.6	0.01692	36240.87	623.7424	623.7424	450158.3	0.079121	0.09009	0.878247	35617.13	353757.5
363	333	303	282139.8	1246.841	1246.841	635897.3558	271391.2	272014.9	2633.196	732752.9	2633.196	695174.5	0.016598	36954.58	623.7424	623.7424	460737.9	0.078854	0.09009	0.875275	36330.84	353757.5
368	333	303	282139.8	1246.841	1246.841	635897.3558	271391.2	272014.9	2662.315	743395.7	2662.315	705112	0.016293	37659.96	623.7424	623.7424	471380.8	0.07857	0.09009	0.872123	37036.22	353757.5
373	333	303	282139.8	1246.841	1246.841	635897.3558	271391.2	272014.9	2691.224	754106.7	2691.224	715125.1	0.016001	38357.82	623.7424	623.7424	482091.8	0.078272	0.09009	0.868814	37734.07	353757.5
378	333	303	282139.8	1246.841	1246.841	635897.3558	271391.2	272014.9	2719.941	764889.9	2719.941	725217.3	0.015722	39048.85	623.7424	623.7424	492874.9	0.077961	0.09009	0.865369	38425.1	353757.5
383	333	303	282139.8	1246.841	1246.841	635897.3558	271391.2	272014.9	2748.479	775748.5	2748.479	735391.1	0.015455	39733.64	623.7424	623.7424	503733.6	0.07764	0.09009	0.861805	39109.9	353757.5
388	333	303	282139.8	1246.841	1246.841	635897.3558	271391.2	272014.9	2776.85	786685.4	2776.85	745649	0.0152	40412.73	623.7424	623.7424	514670.5	0.07731	0.09009	0.858137	39788.99	353757.5
393	333	303	282139.8	1246.841	1246.841	635897.3558	271391.2	272014.9	2805.064	797702.9	2805.064	755992.6	0.014954	41086.56	623.7424	623.7424	525688	0.076971	0.09009	0.85438	40462.82	353757.5
398	333	303	282139.8	1246.841	1246.841	635897.3558	271391.2	272014.9	2833.13	808802.9	2833.13	766423.6	0.014718	41755.55	623.7424	623.7424	536787.9	0.076626	0.09009	0.850546	41131.81	353757.5
403	333	303	282139.8	1246.841	1246.841	635897.3558	271391.2	272014.9	2861.055	819987	2861.055	776943.2	0.014491	42420.06	623.7424	623.7424	547972.1	0.076275	0.09009	0.846647	41796.31	353757.5
343	338	303	282139.8	1246.841	1246.841	717352.7024	271391.2	272158.6	2489.664	687422.9	2489.664	648333.6	0.019631	38321.95	767.3638	767.3638	415264.4	0.090435	0.10355	0.873347	37554.58	435212.9
348	338	303	282139.8	1246.841	1246.841	717352.7024	271391.2	272158.6	2520.39	698038.7	2520.39	658064.4	0.019196	39206.94	767.3638	767.3638	425880.2	0.090259	0.10355	0.871645	38439.58	435212.9
353	338	303	282139.8	1246.841	1246.841	717352.7024	271391.2	272158.6	2550.742	708677	2550.742	667834.4	0.018788	40075.32	767.3638	767.3638	436518.5	0.090049	0.10355	0.869614	39307.95	435212.9
358	338	303	282139.8	1246.841	1246.841	717352.7024	271391.2	272158.6	2580.762	719349	2580.762	677652.5	0.018404	40929.08	767.3638	767.3638	447190.4	0.089809	0.10355	0.867298	40161.72	435212.9
363	338	303	282139.8	1246.841	1246.841	717352.7024	271391.2	272158.6	2610.485	730064	2610.485	687526.7	0.01804	41769.93	767.3638	767.3638	457905.4	0.089544	0.10355	0.864737	41002.56	435212.9
368	338	303	282139.8	1246.841	1246.841	717352.7024	271391.2	272158.6	2639.941	740830	2639.941	697463.3	0.017695	42599.27	767.3638	767.3638	468671.4	0.089256	0.10355	0.861961	41831.9	435212.9
373	338	303	282139.8	1246.841	1246.841	717352.7024	271391.2	272158.6	2669.155	751653.6	2669.155	707467.9	0.017367	43418.3	767.3638	767.3638	479495	0.08895	0.10355	0.859	42650.94	435212.9
378	338	303	282139.8	1246.841	1246.841	717352.7024	271391.2	272158.6	2698.148	762540.3	2698.148	717544.9	0.017054	44228.04	767.3638	767.3638	490381.7	0.088626	0.10355	0.855876	43460.68	435212.9
383	338	303	282139.8	1246.841	1246.841	717352.7024	271391.2	272158.6	2726.937	773494.5	2726.937	727697.8	0.016756	45029.35	767.3638	767.3638	501336	0.088288	0.10355	0.85261	44261.98	435212.9
388	338	303	282139.8	1246.841	1246.841	717352.7024	271391.2	272158.6	2755.537	784520	2755.537	737929.6	0.01647	45822.97	767.3638	767.3638	512361.4	0.087937	0.10355	0.849222	45055.6	435212.9
393	338	303	282139.8	1246.841	1246.841	717352.7024	271391.2	272158.6	2783.962	795619.6	2783.962	748242.7	0.016197	46609.54	767.3638	767.3638	523461.1	0.087575	0.10355	0.845726	45842.18	435212.9
398	338	303	282139.8	1246.841	1246.841	717352.7024	271391.2	272158.6	2812.221	806796.1	2812.221	758639.1	0.015935	47389.65	767.3638	767.3638	534637.6	0.087204	0.10355	0.842137	46622.28	435212.9
403	338	303	282139.8	1246.841	1246.841	717352.7024	271391.2	272158.6	2840.325	818051.7	2840.325	769120.5	0.015683	48163.8	767.3638	767.3638	545893.1	0.086824	0.10355	0.838468	47396.44	435212.9
348	343	303	282139.8	1246.841	1246.841	806291.352	271391.2	272315.4	2495.821	694420.8	2495.821	650270.7	0.020933	43225.92	924.1798	924.1798	422105.5	0.100216	0.116618	0.859353	42301.74	524151.5
353	343	303	282139.8	1246.841	1246.841	806291.352	271391.2	272315.4	2526.77	705268.2	2526.77	660104.9	0.020463	44239.16	924.1798	924.1798	432952.9	0.100045	0.116618	0.85789	43314.98	524151.5
358	343	303	282139.8	1246.841	1246.841	806291.352	271391.2	272315.4	2557.312	716125.7	2557.312	669969.6	0.020023	45231.88	924.1798	924.1798	443810.3	0.099835	0.116618	0.856083	44307.71	524151.5
363	343	303	282139.8	1246.841	1246.841	806291.352	271391.2	272315.4	2587.495	727006.6	2587.495	679875.8	0.019609	46206.68	924.1798	924.1798	454691.3	0.09959	0.116618	0.85398	45282.5	524151.5
368	343	303	282139.8	1246.841	1246.841	806291.352	271391.2	272315.4	2617.36	737922.2	2617.36	689832.3	0.019218	47165.68	924.1798	924.1798	465606.8	0.099314	0.116618	0.851622	46241.5	524151.5
373	343	303	282139.8	1246.841	1246.841	806291.352	271391.2	272315.4	2646.94	748881.6	2646.94	699846.7	0.018847	48110.68	924.1798	924.1798	476566.2	0.099014	0.116618	0.849041	47186.5	524151.5
378	343	303	282139.8	1246.841	1246.841	806291.352	271391.2	272315.4	2676.263	759892.2	2676.263	709924.8	0.018496	49043.16	924.1798	924.1798	487576.8	0.09869	0.116618	0.846267	48118.98	524151.5
383	343	303	282139.8	1246.841	1246.841	806291.352	271391.2	272315.4	2705.351	770960	2705.351	720071.5	0.018161	49964.34	924.1798	924.1798	498644.7	0.098347	0.116618	0.843325	49040.16	524151.5
388	343	303	282139.8	1246.841	1246.841	806291.352	271391.2	272315.4	2734.223	782090.1	2734.223	730290.6	0.017841	50875.3	924.1798	924.1798	509774.7	0.097987	0.116618	0.840236	49951.12	524151.5
393	343	303	282139.8	1246.841	1246.841	806291.352	271391.2	272315.4	2762.895	793286.4	2762.895	740585.3	0.017536	51776.95	924.1798	924.1798	520971.1	0.097612	0.116618	0.837019	50852.77	524151.5

Properties of working fluid R600 — continued

T_{sc} (K)	T_{evap} (K)	T_{cond} (K)	P_{cond} (Pa)	S_1 (J/kg/K)	S_2 (J/kg/K)	P_{evap} (Pa)	h_1 (J/kg)	h_2 (J/kg)	S_4 (J/kg/K)	h_4 (J/kg)	S_5 (J/kg/K)	h_5 (J.kg)	Y	W_{exp} (J/kg)	W_{pump} (J/kg)	$W_{turbine}$ (J/kg)	Q_{in} (J/kg)	η_{th}	η_{carnot}	η_{II}	W_{cycle} (J/kg)	ΔP (Pa)
398	343	303	282139.8	1246.841	1246.841	806291.352	271391.2	272315.4	2791.381	804552.5	2791.381	750958.2	0.017244	52670.08	924.1798	924.1798	532237.1	0.097223	0.116618	0.833691	51745.9	524151.5
403	343	303	282139.8	1246.841	1246.841	806291.352	271391.2	272315.4	2819.692	815891.3	2819.692	761411.7	0.016964	53555.4	924.1798	924.1798	543575.9	0.096824	0.116618	0.830266	52631.22	524151.5
353	348	303	282139.8	1246.841	1246.841	903131.1	271391.2	272486.1	2502.076	701334	2502.076	652245.1	0.022305	47993.99	1094.927	1094.927	428847.9	0.109361	0.12931	0.845722	46899.06	620991.3
358	348	303	282139.8	1246.841	1246.841	903131.1	271391.2	272486.1	2533.279	712426.6	2533.279	662193.9	0.021797	49137.74	1094.927	1094.927	439940.4	0.109203	0.12931	0.844503	48042.81	620991.3
363	348	303	282139.8	1246.841	1246.841	903131.1	271391.2	272486.1	2564.037	723514.8	2564.037	672163.4	0.021322	50256.46	1094.927	1094.927	451028.7	0.108999	0.12931	0.842923	49161.54	620991.3
368	348	303	282139.8	1246.841	1246.841	903131.1	271391.2	272486.1	2594.408	734615	2594.408	682166.6	0.020876	51353.46	1094.927	1094.927	462128.9	0.108754	0.12931	0.841034	50258.54	620991.3
373	348	303	282139.8	1246.841	1246.841	903131.1	271391.2	272486.1	2624.436	745740.3	2624.436	692213.9	0.020456	52431.42	1094.927	1094.927	473254.1	0.108476	0.12931	0.838877	51336.49	620991.3
378	348	303	282139.8	1246.841	1246.841	903131.1	271391.2	272486.1	2654.158	756900.9	2654.158	702313.4	0.020058	53492.52	1094.927	1094.927	484414.8	0.108167	0.12931	0.83649	52397.59	620991.3
383	348	303	282139.8	1246.841	1246.841	903131.1	271391.2	272486.1	2683.605	768105.3	2683.605	712471.8	0.019681	54538.57	1094.927	1094.927	495619.1	0.107832	0.12931	0.833901	53443.64	620991.3
388	348	303	282139.8	1246.841	1246.841	903131.1	271391.2	272486.1	2712.8	779360.1	2712.8	722694.1	0.019322	55571.09	1094.927	1094.927	506874	0.107475	0.12931	0.831138	54476.16	620991.3
393	348	303	282139.8	1246.841	1246.841	903131.1	271391.2	272486.1	2741.766	790671.1	2741.766	732984.8	0.018981	56591.36	1094.927	1094.927	518184.9	0.107098	0.12931	0.828222	55496.43	620991.3
398	348	303	282139.8	1246.841	1246.841	903131.1	271391.2	272486.1	2770.519	802042.7	2770.519	743347.3	0.018654	57600.5	1094.927	1094.927	529556.6	0.106704	0.12931	0.825174	56505.58	620991.3
403	348	303	282139.8	1246.841	1246.841	903131.1	271391.2	272486.1	2799.074	813479.1	2799.074	753784.7	0.018342	58599.5	1094.927	1094.927	540993	0.106294	0.12931	0.822011	57504.58	620991.3
358	353	303	282139.8	1246.841	1246.841	1008301.673	271391.2	272671.6	2508.373	708146.2	2508.373	654239.8	0.023752	52626.08	1280.363	1280.363	435474.7	0.117907	0.141643	0.832427	51345.72	726161.9
363	353	303	282139.8	1246.841	1246.841	1008301.673	271391.2	272671.6	2539.869	719500.2	2539.869	664316.3	0.023202	53903.49	1280.363	1280.363	446828.6	0.11777	0.141643	0.831458	52623.13	726161.9
368	353	303	282139.8	1246.841	1246.841	1008301.673	271391.2	272671.6	2570.876	730833.2	2570.876	674402.2	0.022689	55150.62	1280.363	1280.363	458161.7	0.117579	0.141643	0.830109	53870.26	726161.9
373	353	303	282139.8	1246.841	1246.841	1008301.673	271391.2	272671.6	2601.461	742164.8	2601.461	684512.8	0.022208	56371.63	1280.363	1280.363	469493.2	0.117342	0.141643	0.828434	55091.27	726161.9
378	353	303	282139.8	1246.841	1246.841	1008301.673	271391.2	272671.6	2631.675	753510	2631.675	694659.8	0.021756	57569.83	1280.363	1280.363	480838.4	0.117065	0.141643	0.826481	56289.47	726161.9
383	353	303	282139.8	1246.841	1246.841	1008301.673	271391.2	272671.6	2661.559	764880.6	2661.559	704852.3	0.021329	58747.9	1280.363	1280.363	492209.1	0.116754	0.141643	0.824286	57467.54	726161.9
388	353	303	282139.8	1246.841	1246.841	1008301.673	271391.2	272671.6	2691.146	776286.2	2691.146	715097.8	0.020925	59908.03	1280.363	1280.363	503614.6	0.116414	0.141643	0.821881	58627.67	726161.9
393	353	303	282139.8	1246.841	1246.841	1008301.673	271391.2	272671.6	2720.463	787734.3	2720.463	725401.9	0.020541	61052.08	1280.363	1280.363	515062.8	0.116047	0.141643	0.819295	59771.72	726161.9
398	353	303	282139.8	1246.841	1246.841	1008301.673	271391.2	272671.6	2749.533	799231.6	2749.533	735769.6	0.020175	62181.62	1280.363	1280.363	526560	0.115659	0.141643	0.816551	60901.26	726161.9
403	353	303	282139.8	1246.841	1246.841	1008301.673	271391.2	272671.6	2778.377	810783.3	2778.377	746204.9	0.019826	63298.01	1280.363	1280.363	538111.7	0.115251	0.141643	0.813669	62017.65	726161.9
363	358	303	282139.8	1246.841	1246.841	1122246.493	271391.2	272872.5	2514.656	714838.8	2514.656	656236.4	0.025277	57121.1	1481.269	1481.269	441966.4	0.125892	0.153631	0.819439	55639.83	840106.7
368	358	303	282139.8	1246.841	1246.841	1122246.493	271391.2	272872.5	2546.491	726474.2	2546.491	666456.5	0.024681	58536.43	1481.269	1481.269	453601.8	0.125782	0.153631	0.81873	57055.16	840106.7
373	358	303	282139.8	1246.841	1246.841	1122246.493	271391.2	272872.5	2577.786	738068.9	2577.786	676672.4	0.024126	59915.25	1481.269	1481.269	465196.4	0.125611	0.153631	0.817616	58433.98	840106.7
378	358	303	282139.8	1246.841	1246.841	1122246.493	271391.2	272872.5	2608.618	749645.8	2608.618	686901.8	0.023608	61262.77	1481.269	1481.269	476773.4	0.125388	0.153631	0.81616	59781.5	840106.7
383	358	303	282139.8	1246.841	1246.841	1122246.493	271391.2	272872.5	2639.043	761222.6	2639.043	697158.2	0.023122	62583.06	1481.269	1481.269	488350.1	0.125119	0.153631	0.81441	61101.79	840106.7
388	358	303	282139.8	1246.841	1246.841	1122246.493	271391.2	272872.5	2669.109	772812.9	2669.109	707452.2	0.022663	63879.41	1481.269	1481.269	499940.4	0.124811	0.153631	0.812407	62398.14	840106.7
393	358	303	282139.8	1246.841	1246.841	1122246.493	271391.2	272872.5	2698.853	784427.6	2698.853	717791.9	0.022229	65154.51	1481.269	1481.269	511555.2	0.12447	0.153631	0.810186	63673.24	840106.7
398	358	303	282139.8	1246.841	1246.841	1122246.493	271391.2	272872.5	2728.305	796076	2728.305	728184.1	0.021818	66410.63	1481.269	1481.269	523203.5	0.1241	0.153631	0.807776	64929.36	840106.7
403	358	303	282139.8	1246.841	1246.841	1122246.493	271391.2	272872.5	2757.493	807765.4	2757.493	738634.4	0.021427	67649.7	1481.269	1481.269	534892.9	0.123704	0.153631	0.805201	66168.43	840106.7
368	363	303	282139.8	1246.841	1246.841	1245424.969	271391.2	273089.6	2520.863	721390.7	2520.863	658215.4	0.026885	61476.81	1698.457	1698.457	448301	0.133344	0.165289	0.806733	59778.35	963285.2
373	363	303	282139.8	1246.841	1246.841	1245424.969	271391.2	273089.6	2553.095	733332.4	2553.095	668598.2	0.026237	63035.72	1698.457	1698.457	460242.7	0.133272	0.165289	0.806293	61337.26	963285.2
378	363	303	282139.8	1246.841	1246.841	1245424.969	271391.2	273089.6	2584.724	745208.7	2584.724	678959.7	0.025637	64550.54	1698.457	1698.457	472119	0.133128	0.165289	0.805422	62852.08	963285.2
383	363	303	282139.8	1246.841	1246.841	1245424.969	271391.2	273089.6	2615.837	757047.1	2615.837	689320.8	0.025078	66027.83	1698.457	1698.457	483957.4	0.132924	0.165289	0.804188	64329.37	963285.2
388	363	303	282139.8	1246.841	1246.841	1245424.969	271391.2	273089.6	2646.502	768868.4	2646.502	699697.3	0.024554	67472.65	1698.457	1698.457	495778.8	0.132668	0.165289	0.802644	65774.2	963285.2
393	363	303	282139.8	1246.841	1246.841	1245424.969	271391.2	273089.6	2676.773	780689	2676.773	710101.4	0.024062	68889.09	1698.457	1698.457	507599.3	0.132369	0.165289	0.800835	67190.63	963285.2

Properties of working fluid R600 — continued

T_{sc} (K)	T_{evap} (K)	T_{cond} (K)	P_{cond} (Pa)	S_1 (J/kg/K)	S_2 (J/kg/K)	P_{evap} (Pa)	h_1 (J/kg)	h_2 (J/kg)	S_4 (J/kg/K)	h_4 (J/kg)	S_5 (J/kg/K)	h_5 (J.kg)	Y	W_{exp} (J/kg)	W_{pump} (J/kg)	$W_{turbine}$ (J/kg)	Q_{in} (J/kg)	η_{th}	η_{carnot}	η_{II}	W_{cycle} (J/kg)	ΔP (Pa)
398	363	303	282139.8	1246.841	1246.841	1245424.969	271391.2	273089.6	2706.692	792521.8	2706.692	720542.9	0.023597	70280.46	1698.457	1698.457	519432.2	0.132033	0.165289	0.798797	68582	963285.2
403	363	303	282139.8	1246.841	1246.841	1245424.969	271391.2	273089.6	2736.295	804377.8	2736.295	731029.8	0.023156	71649.56	1698.457	1698.457	531288.1	0.131663	0.165289	0.796562	69951.1	963285.2
373	368	303	282139.8	1246.841	1246.841	1378315.561	271391.2	273324	2526.927	727777.9	2526.927	660155.3	0.028582	65689.79	1932.768	1932.768	454453.9	0.140294	0.17663	0.794278	63757.03	1096176
378	368	303	282139.8	1246.841	1246.841	1378315.561	271391.2	273324	2559.627	740056.5	2559.627	670724.1	0.027877	67399.62	1932.768	1932.768	466732.5	0.140266	0.17663	0.794123	65466.85	1096176
383	368	303	282139.8	1246.841	1246.841	1378315.561	271391.2	273324	2591.643	752238.1	2591.643	681249.3	0.027226	69055.95	1932.768	1932.768	478914.1	0.140157	0.17663	0.793504	67123.18	1096176
388	368	303	282139.8	1246.841	1246.841	1378315.561	271391.2	273324	2623.079	764356.4	2623.079	691756.5	0.026622	70667.14	1932.768	1932.768	491032.4	0.139979	0.17663	0.792498	68734.37	1096176
393	368	303	282139.8	1246.841	1246.841	1378315.561	271391.2	273324	2654.015	776436.9	2654.015	702264.5	0.026058	72239.6	1932.768	1932.768	503112.9	0.139744	0.17663	0.791164	70306.84	1096176
398	368	303	282139.8	1246.841	1246.841	1378315.561	271391.2	273324	2684.515	788499.5	2684.515	712788.2	0.025528	73778.46	1932.768	1932.768	515175.5	0.139459	0.17663	0.789551	71845.69	1096176
403	368	303	282139.8	1246.841	1246.841	1378315.561	271391.2	273324	2714.629	800560.2	2714.629	723339.5	0.025029	75287.85	1932.768	1932.768	527236.2	0.139131	0.17663	0.787697	73355.09	1096176
378	373	303	282139.8	1246.841	1246.841	1521419.969	271391.2	273576.3	2532.777	733973	2532.777	662032.7	0.030374	69755.21	2185.089	2185.089	460396.7	0.146765	0.187668	0.782048	67570.13	1239280
383	373	303	282139.8	1246.841	1246.841	1521419.969	271391.2	273576.3	2566.032	746626	2566.032	672815.6	0.029604	71625.39	2185.089	2185.089	473049.8	0.146793	0.187668	0.782196	69440.3	1239280
388	373	303	282139.8	1246.841	1246.841	1521419.969	271391.2	273576.3	2598.496	759140.6	2598.496	683525.4	0.028897	73430.12	2185.089	2185.089	485564.4	0.146726	0.187668	0.781841	71245.04	1239280
393	373	303	282139.8	1246.841	1246.841	1521419.969	271391.2	273576.3	2630.3	771559.9	2630.3	694194.5	0.028244	75180.34	2185.089	2185.089	497983.6	0.146582	0.187668	0.781071	72995.25	1239280
398	373	303	282139.8	1246.841	1246.841	1521419.969	271391.2	273576.3	2661.542	783916	2661.542	704846.6	0.027635	76884.3	2185.089	2185.089	510339.7	0.146372	0.187668	0.779951	74699.22	1239280
403	373	303	282139.8	1246.841	1246.841	1521419.969	271391.2	273576.3	2692.299	796233.8	2692.299	715500.2	0.027065	78548.53	2185.089	2185.089	522657.6	0.146106	0.187668	0.778537	76363.44	1239280
383	378	303	282139.8	1246.841	1246.841	1675268.911	271391.2	273847.5	2538.333	739943.8	2538.333	663820.9	0.032268	73666.55	2456.354	2456.354	466096.3	0.15278	0.198413	0.770011	71210.2	1393129
388	378	303	282139.8	1246.841	1246.841	1675268.911	271391.2	273847.5	2572.247	753017.3	2572.247	674851.8	0.031425	75709.12	2456.354	2456.354	479169.7	0.152874	0.198413	0.770487	73252.76	1393129
393	378	303	282139.8	1246.841	1246.841	1675268.911	271391.2	273847.5	2605.232	765897.6	2605.232	685770.4	0.030656	77670.83	2456.354	2456.354	492050.1	0.152859	0.198413	0.770411	75214.47	1393129
398	378	303	282139.8	1246.841	1246.841	1675268.911	271391.2	273847.5	2637.456	778642.1	2637.456	696619.3	0.029947	79566.35	2456.354	2456.354	504794.5	0.152755	0.198413	0.769886	77110	1393129
403	378	303	282139.8	1246.841	1246.841	1675268.911	271391.2	273847.5	2669.043	791292.5	2669.043	707429.5	0.02929	81406.57	2456.354	2456.354	517444.9	0.152577	0.198413	0.768988	78950.21	1393129
388	383	303	282139.8	1246.841	1246.841	1840430.092	271391.2	274138.8	2543.5	745651.7	2543.5	665489	0.034275	77415.16	2747.565	2747.565	471513	0.158357	0.208877	0.758136	74667.59	1558290
393	383	303	282139.8	1246.841	1246.841	1840430.092	271391.2	274138.8	2578.202	759202.3	2578.202	676809.2	0.033347	79645.47	2747.565	2747.565	485063.5	0.158532	0.208877	0.75897	76897.91	1558290
398	383	303	282139.8	1246.841	1246.841	1840430.092	271391.2	274138.8	2611.794	772487.3	2611.794	687964.9	0.032507	81774.8	2747.565	2747.565	498348.5	0.158578	0.208877	0.759193	79027.23	1558290
403	383	303	282139.8	1246.841	1246.841	1840430.092	271391.2	274138.8	2644.498	785585.2	2644.498	699014.3	0.031738	83823.36	2747.565	2747.565	511446.5	0.158523	0.208877	0.758927	81075.79	1558290
393	388	303	282139.8	1246.841	1246.841	2017519.21	271391.2	274451	2548.169	751049.3	2548.169	666999.9	0.036405	80989.59	3059.807	3059.807	476598.3	0.163512	0.219072	0.746386	77929.78	1735379
398	388	303	282139.8	1246.841	1246.841	2017519.21	271391.2	274451	2583.818	765148	2583.818	678660.7	0.035379	83427.44	3059.807	3059.807	490697	0.163783	0.219072	0.747619	80367.63	1735379
403	388	303	282139.8	1246.841	1246.841	2017519.21	271391.2	274451	2618.118	778884.6	2618.118	690087.1	0.034458	85737.65	3059.807	3059.807	504433.6	0.163902	0.219072	0.748166	82677.85	1735379
398	393	313	376902.5	1327.61	1327.61	2207215.292	296436.6	299733.8	2552.202	756077.2	2552.202	680940.8	0.043884	71839.15	3297.257	3297.257	456343.4	0.150198	0.203562	0.737848	68541.89	1830313
403	393	303	282139.8	1246.841	1246.841	2207215.292	271391.2	274785.5	2589.002	770814.7	2589.002	680374.5	0.037531	87045.93	3394.277	3394.277	496029.3	0.168643	0.229008	0.736406	83651.65	1925075

Properties of working fluid R1234yf

T_{sc} (K)	T_{evap} (K)	T_{cond} (K)	P_{cond} (Pa)	S_1 (J/kg/K)	S_2 (J/kg/K)	P_{evap} (Pa)	h_1 (J/kg)	h_2 (J/kg)	S_4 (J/kg/K)	h_4 (J/kg)	S_5 (J/kg/K)	h_5 (J.kg)	Y	W_{exp} (J/kg)	W_{pump} (J/kg)	$W_{turbine}$ (J/kg)	Q_{in} (J/kg)	η_{th}	η_{carnot}	η_{II}	W_{cycle} (J/kg)	ΔP (Pa)
338	333	303	780330	1138.484	1138.484	1636342.245	240301.2	241096.7	1630.067	402828.8	1630.067	389339.5	0.058968	12693.86	795.4422	795.4422	161732.1	0.073569	0.09009	0.816612	11898.42	856012.3
343	333	303	780330	1138.484	1138.484	1636342.245	240301.2	241096.7	1649.44	409425	1649.44	395402.4	0.056726	13227.11	795.4422	795.4422	168328.3	0.073854	0.09009	0.819776	12431.66	856012.3
348	333	303	780330	1138.484	1138.484	1636342.245	240301.2	241096.7	1667.873	415793.3	1667.873	401274.6	0.054787	13723.3	795.4422	795.4422	174696.6	0.074002	0.09009	0.821419	12927.86	856012.3
353	333	303	780330	1138.484	1138.484	1636342.245	240301.2	241096.7	1685.598	422005.7	1685.598	407018.3	0.053074	14191.88	795.4422	795.4422	180909	0.074051	0.09009	0.821963	13396.44	856012.3

Properties of working fluid R1234yf — continued

T_{sc} (K)	T_{evap} (K)	T_{cond} (K)	P_{cond} (Pa)	S_1 (J/kg/K)	S_2 (J/kg/K)	P_{evap} (Pa)	h_1 (J/kg)	h_2 (J/kg)	S_4 (J/kg/K)	h_4 (J/kg)	S_5 (J/kg/K)	h_5 (J.kg)	Y	W_{exp} (J/kg)	W_{pump} (J/kg)	$W_{turbine}$ (J/kg)	Q_{in} (J/kg)	η_{th}	η_{carnot}	η_{II}	W_{cycle} (J/kg)	ΔP (Pa)
358	333	303	780330	1138.484	1138.484	1636342.245	240301.2	241096.7	1702.763	428107.4	1702.763	412673	0.051537	14638.89	795.4422	795.4422	187010.7	0.074025	0.09009	0.821676	13843.45	856012.3
363	333	303	780330	1138.484	1138.484	1636342.245	240301.2	241096.7	1719.466	434128.9	1719.466	418265	0.050142	15068.46	795.4422	795.4422	193032.2	0.073941	0.09009	0.820747	14273.02	856012.3
368	333	303	780330	1138.484	1138.484	1636342.245	240301.2	241096.7	1735.781	440091.8	1735.781	423812.8	0.048863	15483.57	795.4422	795.4422	198995.1	0.073811	0.09009	0.819308	14688.13	856012.3
373	333	303	780330	1138.484	1138.484	1636342.245	240301.2	241096.7	1751.76	446011.9	1751.76	429330	0.047683	15886.45	795.4422	795.4422	204915.2	0.073645	0.09009	0.817461	15091.01	856012.3
343	338	303	780330	1138.484	1138.484	1828777.978	240301.2	241275	1630.345	404837.5	1630.345	389425.8	0.063186	14437.89	973.8061	973.8061	163562.5	0.082318	0.10355	0.794954	13464.08	1048448
348	338	303	780330	1138.484	1138.484	1828777.978	240301.2	241275	1650.397	411764.8	1650.397	395704.7	0.060635	15086.32	973.8061	973.8061	170489.8	0.082776	0.10355	0.799383	14112.52	1048448
353	338	303	780330	1138.484	1138.484	1828777.978	240301.2	241275	1669.3	418390	1669.3	401733.3	0.058463	15682.85	973.8061	973.8061	177115	0.083048	0.10355	0.802007	14709.05	1048448
358	338	303	780330	1138.484	1138.484	1828777.978	240301.2	241275	1687.371	424814	1687.371	407598.2	0.056565	16242.04	973.8061	973.8061	183539	0.083188	0.10355	0.803358	15268.23	1048448
363	338	303	780330	1138.484	1138.484	1828777.978	240301.2	241275	1704.801	431097	1704.801	413350.5	0.054873	16772.7	973.8061	973.8061	189822	0.08323	0.10355	0.803764	15798.89	1048448
368	338	303	780330	1138.484	1138.484	1828777.978	240301.2	241275	1721.712	437278	1721.712	419023.5	0.053346	17280.65	973.8061	973.8061	196003	0.083197	0.10355	0.803445	16306.84	1048448
373	338	303	780330	1138.484	1138.484	1828777.978	240301.2	241275	1738.192	443383.8	1738.192	424640	0.051954	17769.99	973.8061	973.8061	202108.7	0.083105	0.10355	0.802554	16796.19	1048448
348	343	303	780330	1138.484	1138.484	2037987.6	240301.2	241468.8	1630.108	406578.4	1630.108	389352.3	0.067777	16058.53	1167.532	1167.532	165109.7	0.090189	0.116618	0.773367	14891	1257658
353	343	303	780330	1138.484	1138.484	2037987.6	240301.2	241468.8	1651.012	413904.3	1651.012	395899.1	0.064844	16837.72	1167.532	1167.532	172435.6	0.090876	0.116618	0.779258	15670.18	1257658
358	343	303	780330	1138.484	1138.484	2037987.6	240301.2	241468.8	1670.485	420826.6	1670.485	402114.8	0.062396	17544.25	1167.532	1167.532	179357.8	0.091308	0.116618	0.782962	16376.72	1257658
363	343	303	780330	1138.484	1138.484	2037987.6	240301.2	241468.8	1688.968	427489.2	1688.968	408121	0.060281	18200.63	1167.532	1167.532	186020.5	0.091566	0.116618	0.785176	17033.1	1257658
368	343	303	780330	1138.484	1138.484	2037987.6	240301.2	241468.8	1706.708	433972.9	1706.708	413985.7	0.058414	18819.7	1167.532	1167.532	192504.2	0.091698	0.116618	0.786307	17652.17	1257658
373	343	303	780330	1138.484	1138.484	2037987.6	240301.2	241468.8	1723.861	440328	1723.861	419750.9	0.056739	19409.59	1167.532	1167.532	198859.3	0.091734	0.116618	0.786615	18242.06	1257658
353	348	303	780330	1138.484	1138.484	2265164.48	240301.2	241678.9	1629.215	407996.2	1629.215	389075.4	0.072813	17543.12	1377.68	1377.68	166317.3	0.097196	0.12931	0.751652	16165.44	1484834
358	348	303	780330	1138.484	1138.484	2265164.48	240301.2	241678.9	1651.205	415812.7	1651.205	395960.2	0.069396	18474.82	1377.68	1377.68	174133.8	0.098184	0.12931	0.759289	17097.14	1484834
363	348	303	780330	1138.484	1138.484	2265164.48	240301.2	241678.9	1671.374	423082.9	1671.374	402401.2	0.066613	19304.03	1377.68	1377.68	181404	0.09882	0.12931	0.764208	17926.35	1484834
368	348	303	780330	1138.484	1138.484	2265164.48	240301.2	241678.9	1690.346	430016.8	1690.346	408573.1	0.064247	20065.98	1377.68	1377.68	188337.9	0.099228	0.12931	0.76736	18688.3	1484834
373	348	303	780330	1138.484	1138.484	2265164.48	240301.2	241678.9	1708.45	436724	1708.45	414566.9	0.062178	20779.38	1377.68	1377.68	195045.1	0.099473	0.12931	0.769257	19401.7	1484834
358	353	303	780330	1138.484	1138.484	2511730.484	240301.2	241906.7	1627.481	409018.2	1627.481	388538.6	0.078396	18874.11	1605.513	1605.513	167111.5	0.103336	0.141643	0.729551	17268.6	1731400
363	353	303	780330	1138.484	1138.484	2511730.484	240301.2	241906.7	1650.883	417453.2	1650.883	395858.3	0.074347	19989.37	1605.513	1605.513	175546.5	0.104724	0.141643	0.739349	18383.86	1731400
368	353	303	780330	1138.484	1138.484	2511730.484	240301.2	241906.7	1671.904	425135.8	1671.904	402572.4	0.071155	20957.96	1605.513	1605.513	183229.1	0.105619	0.141643	0.745669	19352.45	1731400
373	353	303	780330	1138.484	1138.484	2511730.484	240301.2	241906.7	1691.459	432380.2	1691.459	408938.6	0.06849	21836.04	1605.513	1605.513	190473.5	0.106212	0.141643	0.749855	20230.53	1731400
363	358	303	780330	1138.484	1138.484	2779511.974	240301.2	242153.9	1624.664	409547.7	1624.664	387668	0.084675	20026.97	1852.658	1852.658	167393.8	0.108572	0.153631	0.706706	18174.31	1999182
368	358	303	780330	1138.484	1138.484	2779511.974	240301.2	242153.9	1649.93	418780.8	1649.93	395557.2	0.079775	21370.92	1852.658	1852.658	176626.9	0.110506	0.153631	0.719291	19518.26	1999182
373	358	303	780330	1138.484	1138.484	2779511.974	240301.2	242153.9	1672.002	426957.3	1672.002	402603.7	0.076073	22500.9	1852.658	1852.658	184803.4	0.111731	0.153631	0.727266	20648.25	1999182
368	363	303	780330	1138.484	1138.484	3071172.041	240301.2	242422.7	1620.428	409452.2	1620.428	386363.7	0.091886	20966.94	2121.5	2121.5	167029.4	0.112827	0.165289	0.682604	18845.44	2290842
373	363	303	780330	1138.484	1138.484	3071172.041	240301.2	242422.7	1648.191	419735.8	1648.191	395008.3	0.085795	22606	2121.5	2121.5	177313.1	0.115527	0.165289	0.69894	20484.5	2290842

Properties of working fluid R1234ZE — continued

T_{sc} (K)	T_{evap} (K)	T_{cond} (K)	P_{cond} (Pa)	S_1 (J/kg/K)	S_2 (J/kg/K)	P_{evap} (Pa)	h_1 (J/kg)	h_2 (J/kg)	S_4 (J/kg/K)	h_4 (J/kg)	S_5 (J/kg/K)	h_5 (J.kg)	Y	W_{exp} (J/kg)	W_{pump} (J/kg)	$W_{turbine}$ (J/kg)	Q_{in} (J/kg)	η_{th}	η_{carnot}	η_{II}	W_{cycle} (J/kg)	ΔP (Pa)
338	333	303	575800.3	1139.854	1139.854	1271988.577	240569.9	241176.2	1701.211	426138.9	1701.211	410740.8	0.039375	14791.73	606.2938	606.2938	184962.7	0.076694	0.09009	0.851298	14185.44	696188.3
343	333	303	575800.3	1139.854	1139.854	1271988.577	240569.9	241176.2	1718.317	431963.3	1718.317	416090	0.038196	15267.01	606.2938	606.2938	190787.1	0.076843	0.09009	0.852961	14660.72	696188.3
348	333	303	575800.3	1139.854	1139.854	1271988.577	240569.9	241176.2	1734.926	437701.2	1734.926	421372.1	0.03713	15722.75	606.2938	606.2938	196525	0.076919	0.09009	0.853798	15116.46	696188.3
353	333	303	575800.3	1139.854	1139.854	1271988.577	240569.9	241176.2	1751.111	443374.2	1751.111	426605.6	0.036156	16162.32	606.2938	606.2938	202198	0.076935	0.09009	0.853974	15556.03	696188.3
358	333	303	575800.3	1139.854	1139.854	1271988.577	240569.9	241176.2	1766.933	448998.7	1766.933	431804.1	0.035261	16588.28	606.2938	606.2938	207822.5	0.076902	0.09009	0.853613	15981.99	696188.3
363	333	303	575800.3	1139.854	1139.854	1271988.577	240569.9	241176.2	1782.437	454587.5	1782.437	436978.6	0.034431	17002.64	606.2938	606.2938	213411.3	0.07683	0.09009	0.852811	16396.34	696188.3
368	333	303	575800.3	1139.854	1139.854	1271988.577	240569.9	241176.2	1797.658	460150.7	1797.658	442137.4	0.033658	17406.98	606.2938	606.2938	218974.5	0.076724	0.09009	0.851641	16800.69	696188.3
373	333	303	575800.3	1139.854	1139.854	1271988.577	240569.9	241176.2	1812.626	465696.3	1812.626	447287.4	0.032935	17802.58	606.2938	606.2938	224520.1	0.076591	0.09009	0.850164	17196.29	696188.3
378	333	303	575800.3	1139.854	1139.854	1271988.577	240569.9	241176.2	1827.365	471230.8	1827.365	452434	0.032255	18190.49	606.2938	606.2938	230054.6	0.076435	0.09009	0.848427	17584.19	696188.3
383	333	303	575800.3	1139.854	1139.854	1271988.577	240569.9	241176.2	1841.896	476759.6	1841.896	457581.8	0.031614	18571.57	606.2938	606.2938	235583.4	0.076259	0.09009	0.846471	17965.28	696188.3
388	333	303	575800.3	1139.854	1139.854	1271988.577	240569.9	241176.2	1856.235	482287.2	1856.235	462734.4	0.031008	18946.56	606.2938	606.2938	241111	0.076066	0.09009	0.844329	18340.27	696188.3
343	338	303	575800.3	1139.854	1139.854	1431449.222	240569.9	241314.9	1701.868	428586.5	1701.868	410944.6	0.042227	16896.97	744.9711	744.9711	187271.6	0.086249	0.10355	0.832919	16152	855649
348	338	303	575800.3	1139.854	1139.854	1431449.222	240569.9	241314.9	1719.337	434621.6	1719.337	416411.6	0.04091	17465.01	744.9711	744.9711	193306.7	0.086495	0.10355	0.835293	16720.04	855649
353	338	303	575800.3	1139.854	1139.854	1431449.222	240569.9	241314.9	1736.219	440538.5	1736.219	421787.1	0.039729	18006.4	744.9711	744.9711	199223.6	0.086643	0.10355	0.836728	17261.43	855649
358	338	303	575800.3	1139.854	1139.854	1431449.222	240569.9	241314.9	1752.617	446367.8	1752.617	427096.6	0.038657	18526.24	744.9711	744.9711	205052.9	0.086715	0.10355	0.837424	17781.27	855649
363	338	303	575800.3	1139.854	1139.854	1431449.222	240569.9	241314.9	1768.606	452131.8	1768.606	432358.5	0.037676	19028.26	744.9711	744.9711	210816.9	0.086726	0.10355	0.837525	18283.29	855649
368	338	303	575800.3	1139.854	1139.854	1431449.222	240569.9	241314.9	1784.243	457847	1784.243	437586.7	0.03677	19515.27	744.9711	744.9711	216532.1	0.086686	0.10355	0.837139	18770.3	855649
373	338	303	575800.3	1139.854	1139.854	1431449.222	240569.9	241314.9	1799.572	463526.1	1799.572	442791.7	0.035929	19989.46	744.9711	744.9711	222211.3	0.086604	0.10355	0.836352	19244.49	855649
378	338	303	575800.3	1139.854	1139.854	1431449.222	240569.9	241314.9	1814.627	469179.2	1814.627	447981.7	0.035144	20452.53	744.9711	744.9711	227864.3	0.086488	0.10355	0.835228	19707.56	855649
383	338	303	575800.3	1139.854	1139.854	1431449.222	240569.9	241314.9	1829.436	474814	1829.436	453163.2	0.034408	20905.87	744.9711	744.9711	233499.1	0.086343	0.10355	0.833822	20160.9	855649
388	338	303	575800.3	1139.854	1139.854	1431449.222	240569.9	241314.9	1844.022	480437.1	1844.022	458341.5	0.033716	21350.64	744.9711	744.9711	239122.2	0.086172	0.10355	0.832177	20605.67	855649
348	343	303	575800.3	1139.854	1139.854	1605511.115	240569.9	241466.2	1702.258	430853.4	1702.258	411065.4	0.045293	18891.73	896.2657	896.2657	189387.2	0.095019	0.116618	0.814791	17995.46	1029711
353	343	303	575800.3	1139.854	1139.854	1605511.115	240569.9	241466.2	1720.173	437132.4	1720.173	416675.8	0.043813	19560.36	896.2657	896.2657	195666.2	0.095387	0.116618	0.817947	18664.1	1029711
358	343	303	575800.3	1139.854	1139.854	1605511.115	240569.9	241466.2	1737.386	443251.3	1737.386	422162.2	0.042499	20192.87	896.2657	896.2657	201785.1	0.095629	0.116618	0.820023	19296.6	1029711
363	343	303	575800.3	1139.854	1139.854	1605511.115	240569.9	241466.2	1754.037	449254	1754.037	427560.8	0.041315	20796.97	896.2657	896.2657	207787.8	0.095774	0.116618	0.821263	19900.7	1029711
368	343	303	575800.3	1139.854	1139.854	1605511.115	240569.9	241466.2	1770.226	455170.7	1770.226	432896.4	0.040238	21378.04	896.2657	896.2657	213704.5	0.095842	0.116618	0.821841	20481.77	1029711
373	343	303	575800.3	1139.854	1139.854	1605511.115	240569.9	241466.2	1786.022	461022.9	1786.022	438186.7	0.039248	21939.98	896.2657	896.2657	219556.7	0.095846	0.116618	0.821883	21043.71	1029711
378	343	303	575800.3	1139.854	1139.854	1605511.115	240569.9	241466.2	1801.478	466826.7	1801.478	443444.7	0.038331	22485.74	896.2657	896.2657	225360.5	0.0958	0.116618	0.821482	21589.47	1029711
383	343	303	575800.3	1139.854	1139.854	1605511.115	240569.9	241466.2	1816.637	472594.4	1816.637	448680.5	0.037479	23017.59	896.2657	896.2657	231128.2	0.09571	0.116618	0.820715	22121.32	1029711
388	343	303	575800.3	1139.854	1139.854	1605511.115	240569.9	241466.2	1831.53	478335.6	1831.53	453902	0.036682	23537.36	896.2657	896.2657	236869.4	0.095585	0.116618	0.819639	22641.1	1029711

Properties of working fluid R1234ZE — continued

T_{sc} (K)	T_{evap} (K)	T_{cond} (K)	P_{cond} (Pa)	S_1 (J/kg/K)	S_2 (J/kg/K)	P_{evap} (Pa)	h_1 (J/kg)	h_2 (J/kg)	S_4 (J/kg/K)	h_4 (J/kg)	S_5 (J/kg/K)	h_5 (J.kg)	Y	W_{exp} (J/kg)	W_{pump} (J/kg)	$W_{turbine}$ (J/kg)	Q_{in} (J/kg)	η_{th}	η_{carnot}	η_{II}	W_{cycle} (J/kg)	ΔP (Pa)
353	348	303	575800.3	1139.854	1139.854	1795111.73	240569.9	241630.9	1702.305	432910.9	1702.305	411080.1	0.0486	20769.86	1060.971	1060.971	191280	0.103037	0.12931	0.796818	19708.89	1219311
358	348	303	575800.3	1139.854	1139.854	1795111.73	240569.9	241630.9	1720.774	439476.2	1720.774	416865.6	0.046924	21549.53	1060.971	1060.971	197845.3	0.103559	0.12931	0.800853	20488.56	1219311
363	348	303	575800.3	1139.854	1139.854	1795111.73	240569.9	241630.9	1738.387	445825.3	1738.387	422484.1	0.045455	22280.24	1060.971	1060.971	204194.4	0.103917	0.12931	0.803625	21219.27	1219311
368	348	303	575800.3	1139.854	1139.854	1795111.73	240569.9	241630.9	1755.341	452021.9	1755.341	427987.2	0.044143	22973.7	1060.971	1060.971	210391	0.104152	0.12931	0.805445	21912.72	1219311
373	348	303	575800.3	1139.854	1139.854	1795111.73	240569.9	241630.9	1771.765	458106.8	1771.765	433408.2	0.042957	23637.6	1060.971	1060.971	216475.9	0.104292	0.12931	0.806522	22576.63	1219311
378	348	303	575800.3	1139.854	1139.854	1795111.73	240569.9	241630.9	1787.748	464108.2	1787.748	438769.9	0.041872	24277.35	1060.971	1060.971	222477.3	0.104354	0.12931	0.807004	23216.38	1219311
383	348	303	575800.3	1139.854	1139.854	1795111.73	240569.9	241630.9	1803.355	470046.5	1803.355	444088.6	0.040873	24896.89	1060.971	1060.971	228415.6	0.104353	0.12931	0.806999	23835.92	1219311
388	348	303	575800.3	1139.854	1139.854	1795111.73	240569.9	241630.9	1818.635	475936.9	1818.635	449376.7	0.039946	25499.24	1060.971	1060.971	234306	0.104301	0.12931	0.806592	24438.27	1219311
358	353	303	575800.3	1139.854	1139.854	2001270.021	240569.9	241809.9	1701.918	434722.9	1701.918	410960	0.05218	22522.86	1239.947	1239.947	192913	0.110324	0.141643	0.778887	21282.91	1425470
363	353	303	575800.3	1139.854	1139.854	2001270.021	240569.9	241809.9	1721.078	441629.6	1721.078	416962	0.050266	23427.67	1239.947	1239.947	199819.7	0.111039	0.141643	0.783933	22187.72	1425470
368	353	303	575800.3	1139.854	1139.854	2001270.021	240569.9	241809.9	1739.177	448244.3	1739.177	422738.6	0.048614	24265.78	1239.947	1239.947	206434.4	0.111541	0.141643	0.787477	23025.84	1425470
373	353	303	575800.3	1139.854	1139.854	2001270.021	240569.9	241809.9	1756.492	454659.4	1756.492	428364.4	0.047155	25055.07	1239.947	1239.947	212849.5	0.111887	0.141643	0.789923	23815.12	1425470
378	353	303	575800.3	1139.854	1139.854	2001270.021	240569.9	241809.9	1773.195	460930.8	1773.195	433884.3	0.045845	25806.56	1239.947	1239.947	219120.9	0.112114	0.141643	0.791528	24566.61	1425470
383	353	303	575800.3	1139.854	1139.854	2001270.021	240569.9	241809.9	1789.396	467095.4	1789.396	439327.8	0.044654	26527.7	1239.947	1239.947	225285.6	0.112248	0.141643	0.792468	25287.75	1425470
388	353	303	575800.3	1139.854	1139.854	2001270.021	240569.9	241809.9	1805.178	473179.2	1805.178	444715.5	0.043562	27223.77	1239.947	1239.947	231369.4	0.112305	0.141643	0.79287	25983.83	1425470
363	358	303	575800.3	1139.854	1139.854	2225116.068	240569.9	242004.1	1700.981	436242.8	1700.981	410669.6	0.05608	24139.04	1434.148	1434.148	194238.7	0.116892	0.153631	0.760859	22704.89	1649316
368	358	303	575800.3	1139.854	1139.854	2225116.068	240569.9	242004.1	1721.017	443565	1721.017	416942.5	0.05387	25188.35	1434.148	1434.148	201560.9	0.117851	0.153631	0.767104	23754.2	1649316
373	358	303	575800.3	1139.854	1139.854	2225116.068	240569.9	242004.1	1739.708	450489.7	1739.708	422909.7	0.052	26145.88	1434.148	1434.148	208485.6	0.11853	0.153631	0.77152	24711.73	1649316
378	358	303	575800.3	1139.854	1139.854	2225116.068	240569.9	242004.1	1757.455	457153.2	1757.455	428679.9	0.050368	27039.17	1434.148	1434.148	215149.1	0.119011	0.153631	0.774651	25605.02	1649316
383	358	303	575800.3	1139.854	1139.854	2225116.068	240569.9	242004.1	1774.484	463632.5	1774.484	434314.2	0.048916	27884.14	1434.148	1434.148	221628.4	0.119344	0.153631	0.77682	26450	1649316
388	358	303	575800.3	1139.854	1139.854	2225116.068	240569.9	242004.1	1790.941	469976.4	1790.941	439851.2	0.047606	28691.06	1434.148	1434.148	227972.3	0.119562	0.153631	0.778242	27256.91	1649316
368	363	303	575800.3	1139.854	1139.854	2467938.665	240569.9	242214.6	1699.347	437410.4	1699.347	410163.4	0.060361	25602.31	1644.659	1644.659	195195.8	0.122736	0.165289	0.742556	23957.65	1892138
373	363	303	575800.3	1139.854	1139.854	2467938.665	240569.9	242214.6	1720.507	445249.3	1720.507	416781.4	0.057772	26823.27	1644.659	1644.659	203034.7	0.124011	0.165289	0.750269	25178.61	1892138
378	363	303	575800.3	1139.854	1139.854	2467938.665	240569.9	242214.6	1739.926	452540.6	1739.926	422979.9	0.055637	27915.97	1644.659	1644.659	210326	0.124908	0.165289	0.755691	26271.31	1892138
383	363	303	575800.3	1139.854	1139.854	2467938.665	240569.9	242214.6	1758.187	459488.5	1758.187	428920.3	0.053803	28923.57	1644.659	1644.659	217273.9	0.125551	0.165289	0.759582	27278.91	1892138
388	363	303	575800.3	1139.854	1139.854	2467938.665	240569.9	242214.6	1775.6	466200.7	1775.6	434686.8	0.052188	29869.25	1644.659	1644.659	223986.1	0.12601	0.165289	0.762363	28224.59	1892138
373	368	303	575800.3	1139.854	1139.854	2731268.212	240569.9	242442.7	1696.823	438146.6	1696.823	409383.4	0.06511	26890.48	1872.769	1872.769	195703.9	0.127834	0.17663	0.72374	25017.71	2155468
378	368	303	575800.3	1139.854	1139.854	2731268.212	240569.9	242442.7	1719.455	446643.6	1719.455	416448.9	0.062023	28321.93	1872.769	1872.769	204201	0.129525	0.17663	0.733312	26449.16	2155468
383	368	303	575800.3	1139.854	1139.854	2731268.212	240569.9	242442.7	1739.771	454373	1739.771	422929.8	0.05956	29570.45	1872.769	1872.769	211930.3	0.130692	0.17663	0.73992	27697.68	2155468
388	368	303	575800.3	1139.854	1139.854	2731268.212	240569.9	242442.7	1758.645	461648.7	1758.645	429070.7	0.057486	30705.28	1872.769	1872.769	219206	0.131532	0.17663	0.744671	28832.51	2155468
378	373	303	575800.3	1139.854	1139.854	3017040.731	240569.9	242690	1693.16	438348.1	1693.16	408255	0.070452	27972.98	2120.113	2120.113	195658	0.132133	0.187668	0.70408	25852.87	2441240

Properties of working fluid R1234ZE — continued

T_{sc} (K)	T_{evap} (K)	T_{cond} (K)	P_{cond} (Pa)	S_1 (J/kg/K)	S_2 (J/kg/K)	P_{evap} (Pa)	h_1 (J/kg)	h_2 (J/kg)	S_4 (J/kg/K)	h_4 (J/kg)	S_5 (J/kg/K)	h_5 (J.kg)	Y	W_{exp} (J/kg)	W_{pump} (J/kg)	$W_{turbine}$ (J/kg)	Q_{in} (J/kg)	η_{th}	η_{carnot}	η_{II}	W_{cycle} (J/kg)	ΔP (Pa)
383	373	303	575800.3	1139.854	1139.854	3017040.731	240569.9	242690	1717.748	447701.9	1717.748	415910.5	0.066688	29671.29	2120.113	2120.113	205011.9	0.134388	0.187668	0.716097	27551.18	2441240
388	373	303	575800.3	1139.854	1139.854	3017040.731	240569.9	242690	1739.17	455959.3	1739.17	422736.5	0.063815	31102.67	2120.113	2120.113	213269.2	0.135897	0.187668	0.724135	28982.56	2441240
383	378	303	575800.3	1139.854	1139.854	3328007.946	240569.9	242958.9	1688.039	437881.5	1688.039	406684.1	0.076578	28808.33	2389.019	2389.019	194922.6	0.135537	0.198413	0.683109	26419.31	2752208
388	378	303	575800.3	1139.854	1139.854	3328007.946	240569.9	242958.9	1715.248	448367.6	1715.248	415123.3	0.071862	30855.34	2389.019	2389.019	205408.7	0.138584	0.198413	0.698462	28466.32	2752208

Properties of working fluid SES36

T_{sc} (K)	T_{evap} (K)	T_{cond} (K)	P_{cond} (Pa)	S_1 (J/kg/K)	S_2 (J/kg/K)	P_{evap} (Pa)	h_1 (J/kg)	h_2 (J/kg)	S_4 (J/kg/K)	h_4 (J/kg)	S_5 (J/kg/K)	h_5 (J.kg)	Y	W_{exp} (J/kg)	W_{pump} (J/kg)	$W_{turbine}$ (J/kg)	Q_{in} (J/kg)	η_{th}	η_{carnot}	η_{II}	W_{cycle} (J/kg)	ΔP (Pa)
338	333	303	82544.28	1131.622	1131.622	218857.351	222345.9	222446.2	1686.694	407920.7	1686.694	394368.3	0.007396	13452.17	100.2267	100.2267	185474.5	0.071988	0.09009	0.799067	13351.94	136313.1
343	333	303	82544.28	1131.622	1131.622	218857.351	222345.9	222446.2	1699.678	412341.6	1699.678	398527.3	0.007255	13714.05	100.2267	100.2267	189895.4	0.071691	0.09009	0.795772	13613.82	136313.1
348	333	303	82544.28	1131.622	1131.622	218857.351	222345.9	222446.2	1712.679	416833.5	1712.679	402760	0.007122	13973.35	100.2267	100.2267	194387.4	0.071368	0.09009	0.79219	13873.13	136313.1
353	333	303	82544.28	1131.622	1131.622	218857.351	222345.9	222446.2	1725.707	421399.9	1725.707	407069.4	0.006994	14230.28	100.2267	100.2267	198953.8	0.071022	0.09009	0.788342	14130.05	136313.1
358	333	303	82544.28	1131.622	1131.622	218857.351	222345.9	222446.2	1738.771	426043.9	1738.771	411458.6	0.006872	14485.02	100.2267	100.2267	203597.7	0.070653	0.09009	0.784248	14384.79	136313.1
363	333	303	82544.28	1131.622	1131.622	218857.351	222345.9	222446.2	1751.876	430768.4	1751.876	415930.4	0.006755	14737.73	100.2267	100.2267	208322.2	0.070264	0.09009	0.779928	14637.51	136313.1
368	333	303	82544.28	1131.622	1131.622	218857.351	222345.9	222446.2	1765.03	435576.3	1765.03	420487.5	0.006642	14988.58	100.2267	100.2267	213130.1	0.069856	0.09009	0.775398	14888.35	136313.1
373	333	303	82544.28	1131.622	1131.622	218857.351	222345.9	222446.2	1778.239	440470.3	1778.239	425132.4	0.006535	15237.69	100.2267	100.2267	218024.1	0.06943	0.09009	0.770675	15137.46	136313.1
378	333	303	82544.28	1131.622	1131.622	218857.351	222345.9	222446.2	1791.509	445452.9	1791.509	429867.5	0.006431	15485.19	100.2267	100.2267	223006.8	0.068989	0.09009	0.765775	15384.96	136313.1
383	333	303	82544.28	1131.622	1131.622	218857.351	222345.9	222446.2	1804.843	450526.6	1804.843	434695.2	0.006331	15731.2	100.2267	100.2267	228080.5	0.068533	0.09009	0.760713	15630.97	136313.1
388	333	303	82544.28	1131.622	1131.622	218857.351	222345.9	222446.2	1818.246	455693.7	1818.246	439617.7	0.006235	15975.82	100.2267	100.2267	233247.5	0.068063	0.09009	0.755502	15875.59	136313.1
393	333	303	82544.28	1131.622	1131.622	218857.351	222345.9	222446.2	1831.723	460956.3	1831.723	444636.9	0.006142	16219.14	100.2267	100.2267	238510.1	0.067582	0.09009	0.750156	16118.91	136313.1
398	333	303	82544.28	1131.622	1131.622	218857.351	222345.9	222446.2	1845.275	466316.4	1845.275	449754.9	0.006052	16461.25	100.2267	100.2267	243870.2	0.067089	0.09009	0.744688	16361.02	136313.1
403	333	303	82544.28	1131.622	1131.622	218857.351	222345.9	222446.2	1858.907	471775.9	1858.907	454973.4	0.005965	16702.23	100.2267	100.2267	249329.7	0.066587	0.09009	0.739111	16602	136313.1
343	338	303	82544.28	1131.622	1131.622	253276.3933	222345.9	222471.5	1691.358	411550.8	1691.358	395854.3	0.007997	15570.99	125.5301	125.5301	189079.4	0.081688	0.10355	0.78887	15445.46	170732.1
348	338	303	82544.28	1131.622	1131.622	253276.3933	222345.9	222471.5	1704.48	416084.7	1704.48	400082.9	0.007845	15876.29	125.5301	125.5301	193613.2	0.081352	0.10355	0.785625	15750.76	170732.1
353	338	303	82544.28	1131.622	1131.622	253276.3933	222345.9	222471.5	1717.619	420689.7	1717.619	404385.8	0.007699	16178.31	125.5301	125.5301	198218.2	0.080985	0.10355	0.782087	16052.78	170732.1
358	338	303	82544.28	1131.622	1131.622	253276.3933	222345.9	222471.5	1730.782	425369.3	1730.782	408766.4	0.007561	16477.32	125.5301	125.5301	202897.8	0.080591	0.10355	0.778281	16351.79	170732.1
363	338	303	82544.28	1131.622	1131.622	253276.3933	222345.9	222471.5	1743.979	430126.8	1743.979	413227.7	0.007428	16773.56	125.5301	125.5301	207655.3	0.080171	0.10355	0.774227	16648.03	170732.1
368	338	303	82544.28	1131.622	1131.622	253276.3933	222345.9	222471.5	1757.217	434965.3	1757.217	417772.5	0.007301	17067.26	125.5301	125.5301	212493.8	0.079728	0.10355	0.769945	16941.73	170732.1
373	338	303	82544.28	1131.622	1131.622	253276.3933	222345.9	222471.5	1770.503	439887.8	1770.503	422403.6	0.00718	17358.6	125.5301	125.5301	217416.3	0.079263	0.10355	0.765454	17233.07	170732.1
378	338	303	82544.28	1131.622	1131.622	253276.3933	222345.9	222471.5	1783.843	444896.9	1783.843	427123.6	0.007063	17647.78	125.5301	125.5301	222425.4	0.078778	0.10355	0.760771	17522.25	170732.1
383	338	303	82544.28	1131.622	1131.622	253276.3933	222345.9	222471.5	1797.242	449995.2	1797.242	431934.8	0.006951	17934.94	125.5301	125.5301	227523.8	0.078275	0.10355	0.755912	17809.41	170732.1

Properties of working fluid SES36 — continued

T_{sc} (K)	T_{evap} (K)	T_{cond} (K)	P_{cond} (Pa)	S_1 (J/kg/K)	S_2 (J/kg/K)	P_{evap} (Pa)	h_1 (J/kg)	h_2 (J/kg)	S_4 (J/kg/K)	h_4 (J/kg)	S_5 (J/kg/K)	h_5 (J.kg)	Y	W_{exp} (J/kg)	W_{pump} (J/kg)	$W_{turbine}$ (J/kg)	Q_{in} (J/kg)	η_{th}	η_{carnot}	η_{II}	W_{cycle} (J/kg)	ΔP (Pa)
388	338	303	82544.28	1131.622	1131.622	253276.3933	222345.9	222471.5	1810.705	455185.3	1810.705	436839.6	0.006842	18220.23	125.5301	125.5301	232713.9	0.077755	0.10355	0.750893	18094.7	170732.1
393	338	303	82544.28	1131.622	1131.622	253276.3933	222345.9	222471.5	1824.237	460469.4	1824.237	441840.1	0.006738	18503.79	125.5301	125.5301	237997.9	0.07722	0.10355	0.745727	18378.26	170732.1
398	338	303	82544.28	1131.622	1131.622	253276.3933	222345.9	222471.5	1837.84	465849.6	1837.84	446938.3	0.006638	18785.73	125.5301	125.5301	243378.1	0.076672	0.10355	0.740429	18660.2	170732.1
403	338	303	82544.28	1131.622	1131.622	253276.3933	222345.9	222471.5	1851.519	471327.9	1851.519	452136.2	0.006541	19066.17	125.5301	125.5301	248856.4	0.076111	0.10355	0.735012	18940.64	170732.1
348	343	303	82544.28	1131.622	1131.622	291842.3041	222345.9	222499.8	1696.196	415213.2	1696.196	397405.2	0.008641	17654.06	153.8801	153.8801	192713.4	0.090809	0.116618	0.77869	17500.18	209298
353	343	303	82544.28	1131.622	1131.622	291842.3041	222345.9	222499.8	1709.469	419865.5	1709.469	401708.6	0.008475	18003	153.8801	153.8801	197365.7	0.090437	0.116618	0.775496	17849.12	209298
358	343	303	82544.28	1131.622	1131.622	291842.3041	222345.9	222499.8	1722.755	424588.6	1722.755	406086.8	0.008317	18347.84	153.8801	153.8801	202088.8	0.09003	0.116618	0.772004	18193.96	209298
363	343	303	82544.28	1131.622	1131.622	291842.3041	222345.9	222499.8	1736.063	429386.1	1736.063	410543.2	0.008167	18688.94	153.8801	153.8801	206886.3	0.089591	0.116618	0.768239	18535.06	209298
368	343	303	82544.28	1131.622	1131.622	291842.3041	222345.9	222499.8	1749.402	434261.5	1749.402	415081	0.008023	19026.61	153.8801	153.8801	211761.7	0.089123	0.116618	0.764226	18872.73	209298
373	343	303	82544.28	1131.622	1131.622	291842.3041	222345.9	222499.8	1762.78	439218	1762.78	419703	0.007885	19361.13	153.8801	153.8801	216718.2	0.088628	0.116618	0.759983	19207.25	209298
378	343	303	82544.28	1131.622	1131.622	291842.3041	222345.9	222499.8	1776.204	444258.7	1776.204	424412	0.007753	19692.76	153.8801	153.8801	221758.9	0.088109	0.116618	0.755532	19538.88	209298
383	343	303	82544.28	1131.622	1131.622	291842.3041	222345.9	222499.8	1789.68	449386.4	1789.68	429210.8	0.007627	20021.72	153.8801	153.8801	226886.6	0.087567	0.116618	0.750889	19867.84	209298
388	343	303	82544.28	1131.622	1131.622	291842.3041	222345.9	222499.8	1803.214	454603.7	1803.214	434101.6	0.007506	20348.2	153.8801	153.8801	232103.9	0.087006	0.116618	0.746072	20194.32	209298
393	343	303	82544.28	1131.622	1131.622	291842.3041	222345.9	222499.8	1816.81	459913.1	1816.81	439086.8	0.007389	20672.4	153.8801	153.8801	237413.3	0.086425	0.116618	0.741097	20518.52	209298
398	343	303	82544.28	1131.622	1131.622	291842.3041	222345.9	222499.8	1830.473	465316.9	1830.473	444168.5	0.007276	20994.48	153.8801	153.8801	242817.1	0.085828	0.116618	0.735978	20840.6	209298
403	343	303	82544.28	1131.622	1131.622	291842.3041	222345.9	222499.8	1844.207	470817.3	1844.207	449348.8	0.007168	21314.59	153.8801	153.8801	248317.5	0.085216	0.116618	0.73073	21160.71	209298
353	348	303	82544.28	1131.622	1131.622	334874.8847	222345.9	222531.4	1701.203	418906.8	1701.203	399020.1	0.009328	19701.2	185.5114	185.5114	196375.4	0.099379	0.12931	0.768535	19515.69	252330.6
358	348	303	82544.28	1131.622	1131.622	334874.8847	222345.9	222531.4	1714.639	423683.5	1714.639	403403.8	0.009148	20094.13	185.5114	185.5114	201152	0.098973	0.12931	0.765391	19908.62	252330.6
363	348	303	82544.28	1131.622	1131.622	334874.8847	222345.9	222531.4	1728.083	428529.9	1728.083	407862.4	0.008976	20482	185.5114	185.5114	205998.5	0.098527	0.12931	0.761945	20296.49	252330.6
368	348	303	82544.28	1131.622	1131.622	334874.8847	222345.9	222531.4	1741.544	433450.1	1741.544	412399.3	0.008813	20865.28	185.5114	185.5114	210918.7	0.098046	0.12931	0.758224	20679.76	252330.6
373	348	303	82544.28	1131.622	1131.622	334874.8847	222345.9	222531.4	1755.033	438447.8	1755.033	417017.9	0.008657	21244.36	185.5114	185.5114	215916.3	0.097532	0.12931	0.754251	21058.85	252330.6
378	348	303	82544.28	1131.622	1131.622	334874.8847	222345.9	222531.4	1768.558	443526.4	1768.558	421721.3	0.008508	21619.62	185.5114	185.5114	220994.9	0.096989	0.12931	0.750049	21434.1	252330.6
383	348	303	82544.28	1131.622	1131.622	334874.8847	222345.9	222531.4	1782.126	448689.1	1782.126	426512.2	0.008365	21991.35	185.5114	185.5114	226157.6	0.096419	0.12931	0.745639	21805.84	252330.6
388	348	303	82544.28	1131.622	1131.622	334874.8847	222345.9	222531.4	1795.744	453938.8	1795.744	431393.4	0.008228	22359.86	185.5114	185.5114	231407.3	0.095824	0.12931	0.741038	22174.35	252330.6
393	348	303	82544.28	1131.622	1131.622	334874.8847	222345.9	222531.4	1809.417	459278.2	1809.417	436367.3	0.008097	22725.38	185.5114	185.5114	236746.8	0.095207	0.12931	0.736265	22539.87	252330.6
398	348	303	82544.28	1131.622	1131.622	334874.8847	222345.9	222531.4	1823.151	464709.9	1823.151	441436.3	0.007971	23088.15	185.5114	185.5114	242178.5	0.094569	0.12931	0.731335	22902.63	252330.6
403	348	303	82544.28	1131.622	1131.622	334874.8847	222345.9	222531.4	1836.949	470236.3	1836.949	446602.4	0.007849	23448.36	185.5114	185.5114	247704.8	0.093914	0.12931	0.726265	23262.85	252330.6
358	353	303	82544.28	1131.622	1131.622	382700.1503	222345.9	222566.6	1706.371	422630.6	1706.371	400697.8	0.010061	21712.21	220.6626	220.6626	200064	0.107423	0.141643	0.758409	21491.55	300155.9
363	353	303	82544.28	1131.622	1131.622	382700.1503	222345.9	222566.6	1719.983	427537.8	1719.983	405167.5	0.009864	22149.6	220.6626	220.6626	204971.2	0.106985	0.141643	0.755318	21928.94	300155.9
368	353	303	82544.28	1131.622	1131.622	382700.1503	222345.9	222566.6	1733.595	432513	1733.595	409711.6	0.009678	22580.82	220.6626	220.6626	209946.5	0.106504	0.141643	0.751919	22360.15	300155.9
373	353	303	82544.28	1131.622	1131.622	382700.1503	222345.9	222566.6	1747.22	437560.9	1747.22	414333.8	0.0095	23006.45	220.6626	220.6626	214994.3	0.105983	0.141643	0.748241	22785.79	300155.9

Properties of working fluid SES36 — continued

T_{sc} (K)	T_{evap} (K)	T_{cond} (K)	P_{cond} (Pa)	S_1 (J/kg/K)	S_2 (J/kg/K)	P_{evap} (Pa)	h_1 (J/kg)	h_2 (J/kg)	S_4 (J/kg/K)	h_4 (J/kg)	S_5 (J/kg/K)	h_5 (J.kg)	Y	W_{exp} (J/kg)	W_{pump} (J/kg)	$W_{turbine}$ (J/kg)	Q_{in} (J/kg)	η_{th}	η_{carnot}	η_{II}	W_{cycle} (J/kg)	ΔP (Pa)
378	353	303	82544.28	1131.622	1131.622	382700.1503	222345.9	222566.6	1760.867	442685.5	1760.867	419037.8	0.009331	23427.02	220.6626	220.6626	220118.9	0.105426	0.141643	0.744311	23206.36	300155.9
383	353	303	82544.28	1131.622	1131.622	382700.1503	222345.9	222566.6	1774.546	447890.3	1774.546	423826.6	0.00917	23842.98	220.6626	220.6626	225323.7	0.104837	0.141643	0.740151	23622.31	300155.9
388	353	303	82544.28	1131.622	1131.622	382700.1503	222345.9	222566.6	1788.264	453178.7	1788.264	428703.4	0.009016	24254.71	220.6626	220.6626	230612.2	0.104218	0.141643	0.735783	24034.05	300155.9
393	353	303	82544.28	1131.622	1131.622	382700.1503	222345.9	222566.6	1802.029	458554	1802.029	433670.7	0.008868	24662.58	220.6626	220.6626	235987.4	0.103573	0.141643	0.731225	24441.92	300155.9
398	353	303	82544.28	1131.622	1131.622	382700.1503	222345.9	222566.6	1815.846	464018.8	1815.846	438731.2	0.008726	25066.89	220.6626	220.6626	241452.2	0.102903	0.141643	0.726497	24846.23	300155.9
403	353	303	82544.28	1131.622	1131.622	382700.1503	222345.9	222566.6	1829.722	469575.7	1829.722	443887.2	0.00859	25467.93	220.6626	220.6626	247009.1	0.102212	0.141643	0.721616	25247.26	300155.9
363	358	303	82544.28	1131.622	1131.622	435649.693	222345.9	222605.5	1711.693	426383	1711.693	402436.5	0.01084	23686.89	259.5766	259.5766	203777.5	0.114965	0.153631	0.748319	23427.31	353105.4
368	358	303	82544.28	1131.622	1131.622	435649.693	222345.9	222605.5	1725.494	431427.1	1725.494	406998.2	0.010626	24169.36	259.5766	259.5766	208821.6	0.114499	0.153631	0.745282	23909.79	353105.4
373	358	303	82544.28	1131.622	1131.622	435649.693	222345.9	222605.5	1739.286	436537.1	1739.286	411633.2	0.010423	24644.35	259.5766	259.5766	213931.6	0.113984	0.153631	0.741932	24384.78	353105.4
378	358	303	82544.28	1131.622	1131.622	435649.693	222345.9	222605.5	1753.083	441718	1753.083	416345.8	0.010231	25112.62	259.5766	259.5766	219112.4	0.113426	0.153631	0.7383	24853.05	353105.4
383	358	303	82544.28	1131.622	1131.622	435649.693	222345.9	222605.5	1766.897	446974	1766.897	421139.6	0.010048	25574.82	259.5766	259.5766	224368.5	0.112829	0.153631	0.734413	25315.24	353105.4
388	358	303	82544.28	1131.622	1131.622	435649.693	222345.9	222605.5	1780.737	452309.3	1780.737	426018.2	0.009873	26031.52	259.5766	259.5766	229703.8	0.112196	0.153631	0.730297	25771.94	353105.4
393	358	303	82544.28	1131.622	1131.622	435649.693	222345.9	222605.5	1794.611	457727.5	1794.611	430984.7	0.009706	26483.2	259.5766	259.5766	235122	0.111532	0.153631	0.725972	26223.62	353105.4
398	358	303	82544.28	1131.622	1131.622	435649.693	222345.9	222605.5	1808.529	463231.8	1808.529	436041.9	0.009547	26930.3	259.5766	259.5766	240626.2	0.110839	0.153631	0.72146	26670.72	353105.4
403	358	303	82544.28	1131.622	1131.622	435649.693	222345.9	222605.5	1822.495	468825.1	1822.495	441192.4	0.009394	27373.2	259.5766	259.5766	246219.6	0.11012	0.153631	0.716779	27113.62	353105.4
368	363	303	82544.28	1131.622	1131.622	494060.3399	222345.9	222648.4	1717.16	430161.8	1717.16	404234.3	0.011667	25625	302.4998	302.4998	207513.3	0.122028	0.165289	0.738271	25322.51	411516.1
373	363	303	82544.28	1131.622	1131.622	494060.3399	222345.9	222648.4	1731.163	435350.1	1731.163	408894.2	0.011434	26153.35	302.4998	302.4998	212701.7	0.121536	0.165289	0.735291	25850.85	411516.1
378	363	303	82544.28	1131.622	1131.622	494060.3399	222345.9	222648.4	1745.147	440601	1745.147	413625.9	0.011214	26672.67	302.4998	302.4998	217952.6	0.12099	0.165289	0.731992	26370.18	411516.1
383	363	303	82544.28	1131.622	1131.622	494060.3399	222345.9	222648.4	1759.127	445920.3	1759.127	418433.8	0.011005	27183.96	302.4998	302.4998	223271.9	0.120398	0.165289	0.728407	26881.46	411516.1
388	363	303	82544.28	1131.622	1131.622	494060.3399	222345.9	222648.4	1773.115	451312.8	1773.115	423322.3	0.010807	27688.02	302.4998	302.4998	228664.4	0.119763	0.165289	0.724566	27385.52	411516.1
393	363	303	82544.28	1131.622	1131.622	494060.3399	222345.9	222648.4	1787.123	456783	1787.123	428295	0.010618	28185.57	302.4998	302.4998	234134.6	0.11909	0.165289	0.720494	27883.07	411516.1
398	363	303	82544.28	1131.622	1131.622	494060.3399	222345.9	222648.4	1801.161	462334.9	1801.161	433355.2	0.010438	28677.2	302.4998	302.4998	239686.4	0.118383	0.165289	0.716215	28374.7	411516.1
403	363	303	82544.28	1131.622	1131.622	494060.3399	222345.9	222648.4	1815.235	467971.8	1815.235	438505.9	0.010266	29163.45	302.4998	302.4998	245323.4	0.117645	0.165289	0.711749	28860.95	411516.1
373	368	303	82544.28	1131.622	1131.622	558274.1786	222345.9	222695.6	1722.76	433964.4	1722.76	406088.4	0.012544	27526.27	349.6823	349.6823	211268.7	0.128635	0.17663	0.728273	27176.59	475729.9
378	368	303	82544.28	1131.622	1131.622	558274.1786	222345.9	222695.6	1736.981	439304.6	1736.981	410853.5	0.012291	28101.47	349.6823	349.6823	216609	0.128119	0.17663	0.725352	27751.78	475729.9
383	368	303	82544.28	1131.622	1131.622	558274.1786	222345.9	222695.6	1751.17	444703.2	1751.17	415687.7	0.012052	28665.85	349.6823	349.6823	222007.6	0.127546	0.17663	0.722106	28316.16	475729.9
388	368	303	82544.28	1131.622	1131.622	558274.1786	222345.9	222695.6	1765.342	450166.8	1765.342	420596.5	0.011825	29220.65	349.6823	349.6823	227471.2	0.126921	0.17663	0.71857	28870.97	475729.9
393	368	303	82544.28	1131.622	1131.622	558274.1786	222345.9	222695.6	1779.514	455701	1779.514	425584.4	0.011611	29766.9	349.6823	349.6823	233005.4	0.126251	0.17663	0.714776	29417.22	475729.9
398	368	303	82544.28	1131.622	1131.622	558274.1786	222345.9	222695.6	1793.698	461310.7	1793.698	430655.6	0.011407	30305.49	349.6823	349.6823	238615.1	0.12554	0.17663	0.710751	29955.81	475729.9
403	368	303	82544.28	1131.622	1131.622	558274.1786	222345.9	222695.6	1807.905	467000.4	1807.905	435813.6	0.011212	30837.16	349.6823	349.6823	244304.8	0.124793	0.17663	0.706519	30487.47	475729.9
378	373	303	82544.28	1131.622	1131.622	628639.0262	222345.9	222747.3	1728.481	437787.4	1728.481	407995.7	0.013473	29390.34	401.3781	401.3781	215040.1	0.134807	0.187668	0.71833	28988.96	546094.7

Properties of working fluid SES36 — continued

T_{sc} (K)	T_{evap} (K)	T_{cond} (K)	P_{cond} (Pa)	S_1 (J/kg/K)	S_2 (J/kg/K)	P_{evap} (Pa)	h_1 (J/kg)	h_2 (J/kg)	S_4 (J/kg/K)	h_4 (J/kg)	S_5 (J/kg/K)	h_5 (J.kg)	Y	W_{exp} (J/kg)	W_{pump} (J/kg)	$W_{turbine}$ (J/kg)	Q_{in} (J/kg)	η_{th}	η_{carnot}	η_{II}	W_{cycle} (J/kg)	ΔP (Pa)
383	373	303	82544.28	1131.622	1131.622	628639.0262	222345.9	222747.3	1742.938	443288.3	1742.938	412873.3	0.013197	30013.61	401.3781	401.3781	220541	0.134271	0.187668	0.715472	29612.23	546094.7
388	373	303	82544.28	1131.622	1131.622	628639.0262	222345.9	222747.3	1757.345	448841.9	1757.345	417816.6	0.012937	30623.93	401.3781	401.3781	226094.6	0.133672	0.187668	0.712282	30222.56	546094.7
393	373	303	82544.28	1131.622	1131.622	628639.0262	222345.9	222747.3	1771.722	454456.2	1771.722	422831.9	0.012692	31222.9	401.3781	401.3781	231708.8	0.133018	0.187668	0.708798	30821.52	546094.7
398	373	303	82544.28	1131.622	1131.622	628639.0262	222345.9	222747.3	1786.087	460137.5	1786.087	427924.4	0.01246	31811.79	401.3781	401.3781	237390.2	0.132316	0.187668	0.705053	31410.41	546094.7
403	373	303	82544.28	1131.622	1131.622	628639.0262	222345.9	222747.3	1800.454	465891.7	1800.454	433098.6	0.01224	32391.7	401.3781	401.3781	243144.4	0.131569	0.187668	0.701076	31990.32	546094.7
383	378	303	82544.28	1131.622	1131.622	705509.4289	222345.9	222803.8	1734.31	441626.7	1734.31	409952.1	0.014455	31216.77	457.846	457.846	218823	0.140565	0.198413	0.708449	30758.92	622965.2
388	378	303	82544.28	1131.622	1131.622	705509.4289	222345.9	222803.8	1749.021	447298	1749.021	414950.5	0.014154	31889.62	457.846	457.846	224494.2	0.140011	0.198413	0.705658	31431.77	622965.2
393	378	303	82544.28	1131.622	1131.622	705509.4289	222345.9	222803.8	1763.661	453014.8	1763.661	420010	0.013872	32547	457.846	457.846	230211.1	0.13939	0.198413	0.702526	32089.15	622965.2
398	378	303	82544.28	1131.622	1131.622	705509.4289	222345.9	222803.8	1778.255	458786.6	1778.255	425137.9	0.013607	33190.92	457.846	457.846	235982.9	0.13871	0.198413	0.699096	32733.08	622965.2
403	378	303	82544.28	1131.622	1131.622	705509.4289	222345.9	222803.8	1792.823	464621.1	1792.823	430340.3	0.013356	33823.02	457.846	457.846	241817.4	0.137977	0.198413	0.695403	33365.17	622965.2
388	383	303	82544.28	1131.622	1131.622	789248.2838	222345.9	222865.3	1740.229	445477.3	1740.229	411952.9	0.015492	33004.99	519.3506	519.3506	222612	0.145929	0.208877	0.698637	32485.64	706704
393	383	303	82544.28	1131.622	1131.622	789248.2838	222345.9	222865.3	1755.217	451330.1	1755.217	417081.5	0.015164	33729.29	519.3506	519.3506	228464.9	0.145361	0.208877	0.695917	33209.94	706704
398	383	303	82544.28	1131.622	1131.622	789248.2838	222345.9	222865.3	1770.108	457219.3	1770.108	422264.8	0.014858	34435.08	519.3506	519.3506	234354	0.14472	0.208877	0.692847	33915.73	706704
403	383	303	82544.28	1131.622	1131.622	789248.2838	222345.9	222865.3	1784.932	463156.2	1784.932	427511.9	0.01457	35124.96	519.3506	519.3506	240291	0.144015	0.208877	0.689474	34605.61	706704
393	388	303	82544.28	1131.622	1131.622	880229.2011	222345.9	222932.1	1746.22	449332.7	1746.22	413992.3	0.016586	34754.28	586.1639	586.1639	226400.6	0.150919	0.219072	0.6889	34168.11	797684.9
398	388	303	82544.28	1131.622	1131.622	880229.2011	222345.9	222932.1	1761.511	455380.2	1761.511	419261.7	0.016229	35532.33	586.1639	586.1639	232448.2	0.15034	0.219072	0.686256	34946.17	797684.9
403	388	303	82544.28	1131.622	1131.622	880229.2011	222345.9	222932.1	1776.672	461452.1	1776.672	424577.7	0.015896	36288.21	586.1639	586.1639	238520	0.149682	0.219072	0.683252	35702.05	797684.9
398	393	303	82544.28	1131.622	1131.622	978839.7476	222345.9	223004.5	1752.262	453185.4	1752.262	416063.2	0.017741	36463.68	658.5679	658.5679	230180.9	0.155552	0.229008	0.679244	35805.11	896295.5
403	393	303	82544.28	1131.622	1131.622	978839.7476	222345.9	223004.5	1767.887	459443	1767.887	421486.1	0.01735	37298.36	658.5679	658.5679	236438.6	0.154965	0.229008	0.676682	36639.8	896295.5

Abstract

This thesis explores a novel configuration of a thermohydraulic machine that employs a liquid piston driven by low-temperature heat sources. The concept, which targets mechanical power generation, has been patented by the Laboratory of Mechanical Engineering, Materials and Structures at the University of Tissemsilt. The main goal is to evaluate the performance of the proposed concept through a comprehensive thermodynamic analysis using various working fluids, in order to identify the most appropriate one for the cycle. In parallel, a hydraulic model of the machine has been developed to improve the understanding and prediction of the behavior of all system components. Ultimately, this work seeks to provide a valuable tool for the design and optimization of thermohydraulic systems, enabling engineers to make informed decisions regarding component selection, working fluids, and operational strategies.

Keywords: Thermohydraulic machine, power mechanical generation, liquid piston, low temperature working fluid.

Résumé

Ce travail de thèse porte sur une nouvelle configuration de machine thermo-hydraulique utilisant un piston liquide entraîné par des sources de chaleur à basse température. Ce concept, destiné à la production d'énergie mécanique, a été breveté par le Laboratoire d'Ingénierie Mécanique, Matériaux et Structures (LIMMaS) de l'Université de Tissemsilt. L'objectif principal est d'évaluer les performances de ce système à travers une analyse thermodynamique approfondie, en considérant différents fluides de travail afin d'identifier celui qui convient le mieux au cycle. Parallèlement, un modèle hydraulique de la machine a été développé pour mieux comprendre et prédire le comportement de l'ensemble des composants du système. Ce travail vise en définitive à fournir un outil pertinent pour la conception et l'optimisation des systèmes thermo-hydrauliques, afin d'aider les ingénieurs à faire des choix éclairés en matière de composants, de fluides et de paramètres de fonctionnement.

Mots clés: Machine thermohydraulique, production de la puissance mécanique, piston liquide, basse température, fluide de travail.

الملخص

يتناول هذا العمل ضمن أطروحة الدكتوراه تصميماً جديداً لآلة حرارية-هيدروليكية تعتمد على مكبس سائل يتم تشغيله بواسطة مصادر حرارية ذات درجة حرارة منخفضة. وقد تم تسجيل هذا المفهوم، الموجه لإنتاج الطاقة الميكانيكية، كبراءة اختراع من طرف مخبر الهندسة الميكانيكية والمواد والهياكل (LIMMaS) بجامعة تسمسيلت. يتمثل الهدف الرئيسي من هذا العمل في تقييم أداء هذا النظام من خلال تحليل ديناميكي حراري معمق، مع دراسة مجموعة من الموائع العاملة لتحديد الأنسب منها لهذا النوع من الدورات. وبالموازاة مع ذلك، تم تطوير نموذج هيدروليكي للآلة بغرض فهم أفضل وتنبؤ أدق بسلوك مختلف مكونات النظام. ويسعى هذا العمل في نهايته إلى تقديم أداة فعالة لتصميم وتحسين الأنظمة الحرارية-الهيدروليكية، مما يساعد المهندسين على اتخاذ قرارات مدروسة تتعلق باختيار المكوّنات والموائع ومعايير التشغيل.

الكلمات المفتاحية : الالة الحرارية الهيديروليكية، توليد الطاقة الميكانيكية، مكبس سائل، درجة حرارة منخفضة، سائل العمل.