Ministry of Higher Education and Scientific Research

University of Monastir

THESIS

Presented to fulfill the doctor degree requirements from the

National Engineering School of Monastir

In Energy Engineering

By Hela GUESMI

Study of a Solar Air Conditioning System with Variable Refrigerant Flow

Publicly defended on 24 January, 2026

Jury Members

Mr. Abdallah MHIMID	**Emeritus Professor, ENIM**	**Chair**
Mr. Ammar ABASSI	**Assist. Pr, ENIGA**	**Reviewer**
Mr. Walid HASSEN	**Assist. Pr, ENIM**	**Reviewer**
Mr. Med Naceur BORJINI	**Pr, ENIM**	**Examinator**
Mr. Hacen DHAHRI	**Pr, ENIM**	**Supervisor**

Laboratory for the Study Thermal & Energy Systems (LESTE) LR99ES31

Dedication

A special thanks to my family, words cannot express how grateful I am to my parents **Mouldi** and **Rasmia** for unconditional support, prayers for me all the time and encouragement to pursue my interests. This thesis is dedicated to them. No dedication can express the love, esteem, dedication and respect that I have always had for you. Nothing in the world is worth the efforts provided day and night for my education and my well-being. This work is the fruit of your sacrifices that you have made for my education and training.

I extend my heartfelt gratitude to my husband **Nabil** for his constant support throughout this work. I also dedicate my deepest love to my children **Myla**, **Ahmed**, and **Yasmine** whose smiles and innocence have been a profound source of joy and unwavering motivation during this journey.

Without family kind support, it would be impossible for me to complete my PhD.

Special Dedication

To my brother and spiritual father, Dr. Marwen

You have been my pillar, my guide, and my protector since we were children.
You stepped into a fatherly role early on caring for me, guiding me, and paving the way for my success.
Simply...
Thank you, from the bottom of my heart.

Acknowledgement

I wish to express deep gratitude to my supervisor **Hacen Dhahri**, Professor at ENIM University of Monastir, Tunisia, for his invaluable supervision and insight throughout the research process and for all the patience and support you gave me since the first day of my thesis completion. His consistent trust during my thesis work is greatly appreciated.

I would like to thank **Abdallah Mhimid**, Emeritus Professor at ENIM, University of Monastir, who has kindly accepted to be the president of the jury evaluating my thesis work.

I would thank also my committee members **Abassi Med Ammar** Associate-Professor at National Engineering School of Gafsa, University of Gafsa, and **Walid Hassan** Associate-Professor at ENIM, University of Monastir, for accepting to review my thesis. Their critical reviews and evaluations of my work resulted in the success of this PhD thesis.

Many thanks are also addressed to **Borjini Med Naceur**, Professor at ENIM, University of Monastir, Tunisia, for accepting to examine this thesis.

SUMMARY

General introduction.....1
Chapter 1.....7
1. Introduction.....7
2. Global demand for cooling and energy implications.....7
3. Conventional air conditioning systems.....10
   3.1. Historical background of cooling technologies.....10
   3.2. Vapor compression air conditioning system.....10
   3.3. Absorption cooling systems.....11
   3.4. Desiccant cooling systems (solid and liquid).....12
   3.5. Evaporative cooling systems.....13
   3.6. Thermoelectric and magnetic cooling systems.....13
   3.7. Comparative discussion.....14
4. Solar assisted air conditioning systems.....15
   4.1. Introduction and classification.....15
   4.2. Solar thermal sorption systems.....16
   4.3. Solar PV driven compression systems.....19
   4.4. Comparative summary and research trends.....19
   4.5. Solar variable refrigerant flow system.....20
5. Variable refrigerant flow (VRF) air conditioning systems.....21
   5.1. Historical background and principle of operation.....21
   5.2. Types of VRF configurations.....22
   5.3. Performance advantages and control strategies.....23
   5.4. Environmental and operational limitations.....24
   5.5. Summary and comparative insights.....24
6. Solar VRF hybrid systems: attempts and limitations.....25
7. Analysis and research motivation.....28
8. Conclusion.....29

References.....31

Chapter 2.....34
1. Introduction.....34
2. Description of the system.....34

3. SDPHEX system…36
3.1. Geometrical and physical configuration …36
3.2. Governing equations…39
4. MPHEX system…41
4.1. Geometrical and physical configuration …41
4.2. Boundary conditions…45
5. System modeling using LBM method …45
5.1. LBM formulation for temperature …46
5.2. Implementation of LBM boundary conditions…47
5.3. Validation…49
6. Conclusion …49
Reference…50
Chapter 3…51
1. Introduction…51
2. System and mathematical formulation…53
2.1 Physical model …53
2.2 COP of SDPHEX…55
3. Grid check and numerical model validation…55
3.1 Grid check…55
3.2 Validation of numerical models…56
4. Results and discussion…58
4.1. Dynamic and thermal behaviors: case of one porous medium, SPHEX…58
4.2. Dynamic and thermal behavior: two porous mediums-case of DPHEX…59
4.2.1. Dynamic Study…61
4.2.2. Thermal Study…63
4.2.3. Energy storage…68
4.2.4. Performance study …71
5. Conclusion…76
Reference…78
Chapter 4…81
1. Introduction…81
2. Methodology…85
2.1 Schematic Description of the MPHEX …85

2.2 Main Assumptions……………………………………………………………..88
2.3 Numerical Method: Lattice Boltzmann Method (LBM)………………………....89
3. Results and discussion…………………………………………………………..89
3.1 Influence of the First Medium on Flow, Thermal, and Exergy Performance…….89
3.2 Comparison Between MPHEX and VRF Systems ……………………………….96
4. Conclusion………………………………………………………………..….101
Reference………………………………………………………………………………104
General conclusion…………………………………………………………………109

NOMENCLATURE

Symbol	Signification	Unit
A	Acceleration	$m.s^{-2}$
Ap	Pore surface area	m^2
AT	Total surface area	m^2
Cp	Specific heat at constant pressure	$J.Kg^{-1}.K$
ci	Discretized velocity	-
dp	Mean pore diameter	m
D	Spatial dimension	-
E	Stored energy	-
ε	Porosity:	-
F	Maxwell–Boltzmann distribution function	-
Fi	External force in the direction of ci	N
fi	Distribution function in direction ci	-
feq	Local equilibrium distribution function	-
H	Height	m
$\bar{h}$	Enthalpy	$J.Kg^{-1}$
kB	Boltzmann constant	J
L	Length	m
M	Mass of a particle	Kg
K	Permeability	m^2
P	Pressure	$Kg.m^{-1}$
Da	Darcy number	-
Ha	Hartmann number	-
Ec	Eckert number	-
Pr	Prandtl number	-
ρ_0	Density	s

Re	Reynolds number	-
Rk	Thermal conductivity ratio	-
Rc	Heat capacity ratio	-
t	Time	s
T	Temperature	K
Θ	Dimensionless temperature	-
$\bar{u}$	Internal energy	$J.mol^{-1}$
VT	Total volume	m^3
Vp	Pore volume	m^3
Vs	Solid skeleton volume	m^3
u,v	Transverse and axial velocity components	$m.s^{-1}$
x,y	Transverse and axial coordinates	m
τ	Dimensionless time	-
U,V	Dimensionless velocity components (axial and transverse)	-
X,Y	Dimensionless axial and transverse coordinates	-

Greek Letters

Symbol	Signification	
α'	Specific surface area	-
W	Collision frequency	$m^2.s^{-1}$
ρ	Mass density	$Kg.m^{-3}$
Ω	Collision operator	-
υ	Kinematic viscosity	$m^2.s^{-1}$
Φ	Viscous dissipation term	-
α	Thermal diffusivity	$m^2.s^{-1}$
λ	Thermal conductivity	$W.m^{-1}.K$
wi	Weight factor in a given direction	-
Δt	Time step	s

Δx, Δy	Spatial step	m

Subscript

Subscript	**Meaning**
eff	Effective
ref	Reference
in	Inlet
out	Outlet
S	Solid
F	Fluid
W	Wall
A	Ambient
Fs	Fluid–Solid

General introduction

The global demand for cooling and air conditioning has shown a sudden and steady increase over the past decades, mainly because of population growth, urbanization, rising living standards, and most importantly, climate change. According to International Energy Agency (IEA), space cooling energy demand, has triple since 1990 and it is projected to see more than a double increase by 2050 if the trend continues. This rising demand creates a severe energy problem worldwide, especially where hot climates are dominant and the energy infrastructure is not fully developed. In fact, cooling technology not only consumes a large amount of energy, but it also relies heavily on power generated from fossil fuel sources. Hence, a large amount of GHG emission is caused, especially when carbon-rich energy is consumed. Moreover, conventional air conditioners use refrigerants like R-410A and R-134a, having a High Global Warming Potential, thus worsening the problem. Unless a radical change takes place, the emission from cooling can offset the hard-earned results of other sectors' decarbonization. On the other hand, cooling is turning out to be a necessity, not an indulgence anymore since it is essential for health (during heat waves), food, vaccines, and productivity of a work place. Therefore, nowadays, a low energy cooling technology is a global need. To address these issues, a budding technology of solar-assisted air conditioning (SAAC) systems is also coming forward. Solar energy comes with a natural peak that exactly meets the peak cooling demand, and thus, it is the most appropriate renewable energy source that can be employed as a supplementary energy source with cooling technology. However, two most important demerits prevent it from widespread use, namely, the intermittency of sun rays and a lack of feasibility of efficient integration of storage and control units of the system. Almost all designs of most of the solar cooling systems use separate thermal energy storage systems and also use abundant numbers of active control units,

Variable Refrigerant Flow (VRF) systems, are currently very common due to high efficiency as well as high levels of control. VRF systems are refrigerant flow rates controlled in real time by inverter driven compressors with electronic expansion valves. VRF systems offer up to 30% more energy efficiency than conventional HVAC systems. However, their high susceptibility to faults due to the use of advanced electronics, control algorithms, and precise components mitigates the effectiveness and efficiency of VRF systems, especially in off-grid applications. These constraints have fueled the search for passive thermal methods that do not require any external energy employment. In this category, porous media show great promise. Because of their internal properties, these media can handle both heat and mass transfer processes concurrently. They can thus function as thermal energy storage and heat exchange equipment, making compact and maintenance free cooling solutions feasible. Nevertheless, present day cooling methods, for the most part, continue to use active components and fossil fuels for electricity generation. VRF conditioning, for instance, although more energy efficient than conventional HVAC systems, use sophisticated electronic controls and high GWP refrigerants; hence, there are great concerns regarding their cost effectiveness and environmental integrity and sustainability. Similarly, any kind of solar assisted cooling methods are generally made up of various subsystems like solar collectors, storages, and cooling units; thus, there are high thermal losses, installation complexities, and expenses in these setups too. To grasp the limitations of sustainable cooling methods better, there are four general limitations that can be pointed out:

- ✓ High energy consumption for flow control: VRF systems rely on compressors, control valves, and sensors to control the flow of the refrigerant fluid. This kind of control consumes a lot of energy and cannot easily be applied in low-energy or off-grid situations.
- ✓ Thermal storage with physical separation: In the case of solar assisted systems, thermal storage is usually performed in external tanks involving the use of water or phase change materials. This process involves the use of intermediate heat transfer, hence resulting in lower efficiencies and higher spatial requirements.
- ✓ Lack of integration between solar capture and refrigerant control: Most systems consider solar energy collection and refrigerant management in a separate way without exploiting the opportunity of some materials like porous media for passive integration.
- ✓ Absence of compact, fully passive architectures: There has been progress in this area, but it has not been possible to integrate solar energy storage and flow regulation within a compact, passive architecture yet. An active system has to be used to achieve control, hence impacting autonomy.

These issues promote the need for the design of integrated cooling solutions that are free from compressors, tank separation, and electronic controls. In particular, regions such as South Asia, the Middle East, and Sub-Saharan Africa where demand for cooling are in a greatest need of such technologies, as discussed above.

In these regards, among other forms of alternative energy, solar energy is easier and more predictable to use: There are three ways of using solar energy presently with cooling systems:

- ✓ Solar thermal cooling: These systems use solar collectors to drive thermally activated cycles such as absorption or adsorption. Although they reduce electricity use, they remain costly and complex.
- ✓ Water current powered systems: Solar energy can be used for the production of electricity in these applications. The existing infrastructure for these applications is in abundance, and thus there is no need for extensive implementation.
- ✓ Hybrid systems with storage: In such systems, thermal storage materials, are paired with solar energy input.

Recent research has indicated that the integration of solar energy with thermal materials has the potential to increase the efficiency levels of such systems. These systems would also be able to improve energy access in off grid communities.

VRF and solar solutions still suffer from critical limitations:

- ✓ Traditional VRF units provide precise adaptive cooling but are associated with high electronic complexity, constant electricity use, environmentally destructive refrigerants, and vulnerability to malfunctions in damaging environments.
- ✓ Traditionally, solar cooling systems generally involve bulky storage tanks of thermal energy, suffer losses of heat during every transfer operation, and consist of a number of synchronized components. They do not make use of the potential of passive materials for the generation of storage and control functionalities.

In conclusion, although VRF and solar assisted technologies have partial solutions, neither of them is capable of providing a level of integration, compactness, and passivity that is required for next generation sustainable cooling solutions. In light of the global challenge of environmental degradation, there is a need for a paradigm shift towards material driven and self-governed designs. For that reason, as a global response to the problem of environmental degradation, air conditioner requires more than a mere innovation of current solutions. This research stems from the hypothesis that passive porous media structures, when carefully designed, can replace both the storage tanks and the variable speed regulation mechanisms found in modern systems, thus providing a new class of low energy, solar powered and autonomous air conditioning systems.

The proposed concept, combine two innovative modules:

- ✓ A solar double porous heat exchanger (SDPHEX)**,** which integrates 2 functions; solar thermal storage and thermal heat exchanger into one component using two porous media. First, solar energy is stored in the solid matrix; then, it is transferred to a heat transfer fluid supplying the cooling system. This removes the need for external storage tanks and improves energy compactness.
- ✓ A multi porous heat exchanger (MPHEX)**,** capable of emulating the behavior of a VRF system without electronics. By changing the permeability of the porous branches, which can be identified with the Darcy number.

In such application, solar cooling systems require neither external storage units or PCMs to balance the impact of solar intermittency, thereby increasing bulk, thermal losses, and system level inefficiencies. The SDPHEX embodies storage and heat exchange within a single structure, where fewer components eliminate heat recovery loops entirely. Moreover, distributed storage within the porous matrix enhances thermal stability and responsiveness. In parallel, VRF systems, though efficient, depend on electronic valves, variable speed compressors, and control logic, raising energy demand and reducing reliability in harsh environments. For the MPHEX, superposed porous media with spatially varied permeability modulate the passive flow of the refrigerant as a function of the intrinsic permeability, pressure gradient. In fact, passive mechanical actuation or electrical power input becomes unnecessary under such configurations, thus allowing for robustness and low maintenance operation, VRF control, in off grid systems or those with solar drives. The combined system offers:

- ✓ Passive operation: no electrical control components;
- ✓ High energy efficiency: minimized losses due to structural integration;
- ✓ Compact design: less space than systems with independent storage tanks;
- ✓ Solar compatibility: designed to operate optimally under solar input profiles;
- ✓ Robustness: suitable for deployment in remote or off grid areas.

Main objectives of this thesis are thus:

A: Fulfill these requirements (below) via the combined employment of porous media, solar energy, and passive flow modulation towards low carbon and autonomous climate control. B: Show a new systemic approach for solar cooling, in which the foundation is justified because of the limitations posed by current systems with high energy inputs in Variable Refrigerant Flow (VRF), and solar cooling.

To achieve these objectives, our efforts will be focused on:

- Design an integrated solar air conditioning system that replaces conventional flow control and storage subsystems with passive, porous-media based components.
- To develop, with numerical simulation techniques adapted to porous materials, detailed thermal and fluidic models of the system.
- To compare thermal performance and energy efficiency of the proposed designs with conventional VRF and solar systems.
- Develop a parametric and sensitivity analyses to determine how variables such as porosity, permeability gradients, and layers affect system performance.
- To estimate the power saving and environmental benefits of the combined system concerning the reduction of the refrigerating agent, emissions of CO_2, and enhancement of the Coefficient of Performance (COP) value.

The overall structure of this thesis has been laid out to take the reader on an odyssey from the broad scenario of worldwide energy and cooling issues to specific modeling, simulation, and analysis associated with the proposed solar air conditioner. After the **General Introduction**, **Chapter 1** provides a state-of the art review of air conditioning techniques. This chapter discusses the conventional vapor compression technique, solar assisted cooling methods, Variable Refrigerant Flow (VRF) technology, and highlights the role of porous materials in thermal energy storage and passive flow regulation. This chapter will offer a review of the literature to identify the limitations of current air conditioning techniques to lay the groundwork for the innovative porous hybrid design described in the thesis.

Chapter 2 discusses the thermal and energy analysis of the conceptualized SDPHEX – MPHEX system. This chapter introduces the concept and equations that define the two main systems: the Solar Double Porosity Heat Exchanger and the Multi Porosity Heat Exchanger, as far as the geometric parameters are concerned. Justification for the use of the Lattice Boltzmann Method in the process of heat transfer and fluid dynamics within porous media is also covered in the chapter.

Chapter 3, "Improving Solar Air Conditioning Efficiency through Double Porosity Heat Exchanger Design: Numerical Insights ", carries forward the simulation study and numerical discussion of the SDPHEX. The chapter discusses the effect of various parameters such as Darcy number, thermal conductivity ratio, and heat capacity ratio, among others, on flow, temperature, and storage behavior. The chapter also covers validation, grid independence, and subsequent discussions on dynamics for both single and double porosity systems.

Chapter 4, "A Numerical Case Study on the Design of a Multi Porosity Heat Exchanger for VRF air conditioning applications" explores the MPHEX concept developed to mimic the performance of VRF systems. By employing the LBM model, Chapter 4 examines the effect of the Darcy number on the velocity and temperature distributions with the help of structural configuration adjustment for the creation of variable refrigerant flow without the use of any actuator. The performance comparison of MPHEX with the conventional VRF system shows the enhanced efficiency and reliability of the proposed design.

Ultimately, the thesis **concludes** by pointing out the highlights of the major findings, underlining the significance of the integration of SDPHEX-MPHEX in the development of next generation autonomous and solar powered air conditioning systems.

Chapter **1**

STATE OF THE ART AND LIMITATIONS OF COOLING SYSTEMS

1. Introduction

The cooling demand around the world has risen sharply over the last few decades due to the increase in worldwide warming, urbanization, and economic growth. What was a luxury a few decades back: air conditioning, has now become a necessity. Nonetheless, the use of traditional cooling systems is not only a major factor in electricity demand, which is mostly from fossil fuels, but also involves chemical refrigerants with a large global warming potential. There seems to be a paradox here with cooling required to counteract heat stress, which in turn helps to climate change. In view of these issues, considerable efforts have been seen in technology and research to identify more sustainable cooling solutions. Some of these alternatives may include solar assisted air conditioning and variable refrigerant flow. While solar cooling use alternative energy sources, thus decreasing reliance on power grids, variable refrigerant flow technology is more energy efficient due to its abilities to accurately control refrigerant flow rates.

The aim of this chapter is to shed light on the status in air conditioning technology: conventional vapor compression air conditioning systems, solar assisted air conditioning and VRF technology. Then there is a critical analysis of the limitation of those technologies in relation to air conditioning. Finally, we present the importance of porous materials in heat transfer.

2. Global demand for cooling and energy implications

Air conditioning technology began with the idea that surfaced at the start of the 20th century. In the past few decades, air conditioning has become an essential utility for both residential and commercial purposes. Notably, air conditioning is presently regarded as "one of the fastest growing uses of energy in buildings." **Fig.1.1** shows the global cooling degree days data along with the adaptation metric corresponding to the region's solar potential.

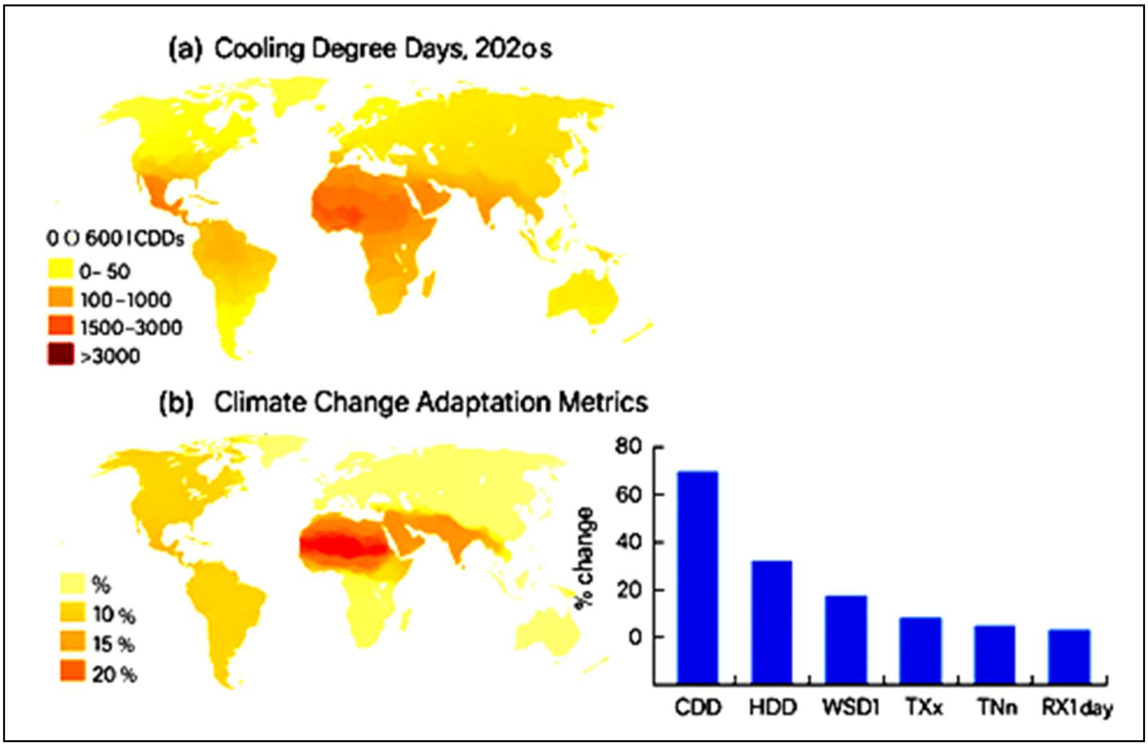


Fig.1.1. Cooling demand and climate change adaptation metrics [1].

The rise is important, especially in tropical climates such as Southeast Asia, the Middle East, and Africa. This is especially because space cooling is critical for maintaining health, work, and quality life. Moreover, space cooling already contributes close to 10% to the global electricity consumption, accompanied by an increase during peak seasons. **Fig.1.2**, present the regional share of space cooling energy consumption, emergence of new economies is dominating the growth:

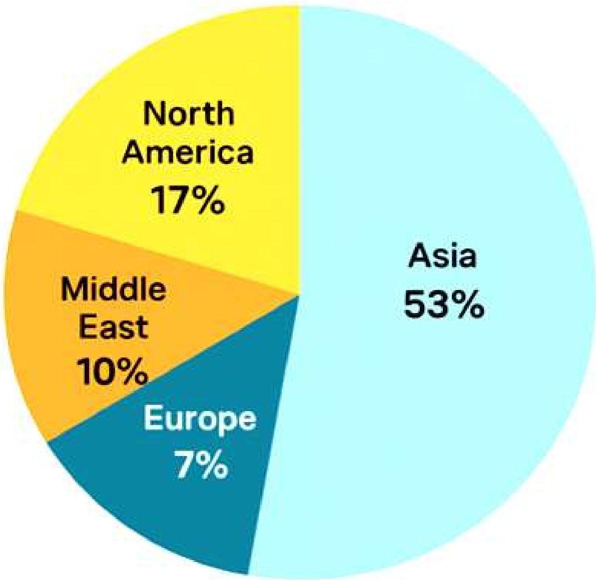


Fig.1.2. Global electricity uses for space cooling by region (2022) [1].

Air conditioners contribute considerably to the stress on the power grid in many rapidly growing economies.

The top ten countries with the highest cooling-related electricity use are shown in **Table 1.1.**

In tropical regions, countries use much more of their electricity for cooling than countries in temperate regions. This is the situation worldwide regardless of the level of economic development.

Table 1.1. Top 10 Countries by cooling electricity use (in TWh/year) [1].

Rank	Country	Cooling Electricity Use (TWh/year)	Share of Total Electricity (%)
1	China	600	16
2	United States	500	15
3	India	220	10
4	Indonesia	95	9
5	Brazil	80	8
6	Saudi Arabia	75	40
7	Japan	70	7
8	Mexico	60	6
9	Egypt	55	12
10	Pakistan	50	13

Moreover, most traditional air conditioners are still employing hydrofluorocarbons, or HFCs, as their refrigerants, giving them high global warming potential. The problem is, then, two-fold: it is necessary to ensure the universal achievement of thermal comfort, while, at the same time, reducing the negative environmental impacts associated with cooling. This is requiring a transition towards cooling solutions adapted to the global environment.

3. Conventional air conditioning systems

3.1 Historical background and early cooling technologies

The idea of artificial cooling dates back to ancient times, where cooling systems were used by ancient cultures through passive cooling techniques. The initial mechanical cooling systems were realized in the 19th century through the concept of ice storage and gas expansion cooling machines for industrial purposes [2]. However, modern air conditioning began with the work of Willis Carrier in 1902, who designed a vapor compression system to control humidity in a printing facility [3]. Since then, air conditioning technologies have evolved into several distinct families, depending on the operating principle and energy source. These include:

- ✓ Mechanical vapor compression systems, which dominate the residential and commercial markets;
- ✓ Absorption and adsorption cooling systems, which use thermal energy to drive the cooling cycle;
- ✓ Desiccant systems, relying on moisture removal to produce a cooling effect;
- ✓ Evaporative and thermoelectric systems, applied in niche or low-energy applications.

Each of these technologies has its own advantages, limitations, and historical context. The following sections present these systems in detail, with supporting technical figures and references to previous work.

3.2 Vapor compression air conditioning systems

Vapor compression systems operate on the principle of refrigerant phase change (**Fig1.3**).

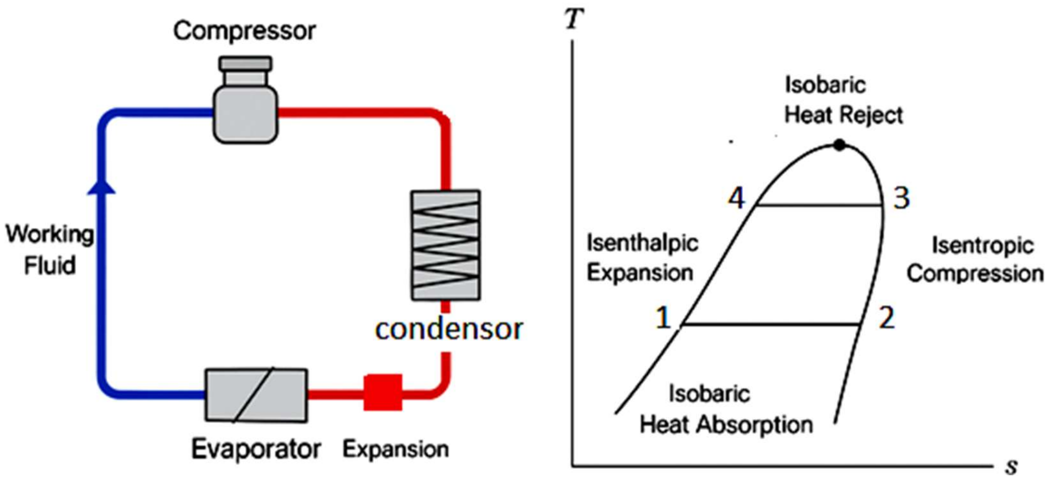


Fig.1.3. Schematic diagram and temperature/entropy chart of the vapor compression refrigeration cycle [4].

They involve a cycle comprising four main components: compressor, condenser, expansion valve, and evaporator. These systems are widely used due to compactness, performance, and commercial availability [5]. It is based on the principles of phase change thermodynamics to reach effective temperatures differential action involving relatively small equipment. The temperature entropy (T-s) diagram demonstrates the major processes: isentropic compression, constant pressure cooling, isenthalpic expansion, and isobaric heat absorption. These cycles are designed to work at certain ambient conditions and load requirements. Several authors have analyzed the performance and optimization of vapor compression units: examined the effect of ambient temperature on COP [6], assessed the influence of refrigerant types on system efficiency [7] and developed application of advanced control methods to lower cycle losses in inverter systems [8].

3.3 Absorption cooling systems

Absorption systems replace the mechanical compressor with a thermal compression process using a refrigerant absorbent pair. The most common pair is water/lithium bromide for cooling applications and ammonia/water for refrigeration. Heat is applied in the generator to separate the refrigerant, which is then condensed, expanded, and evaporated as in a classic cycle [9]. This process is illustrated in **Fig.1.4,** which presents a schematic diagram of a typical absorption cooling system using a LiBr/H_2O solution [10].

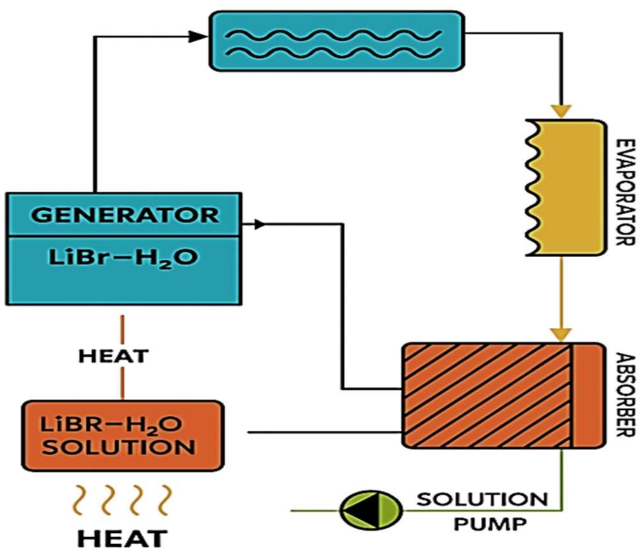


Fig.1.4. Absorption cooling system using LiBr/H_2O solution [10].

These systems are driven by heat sources such as natural gas, waste heat, or solar collectors. Many researchers provided a comprehensive review of absorption systems [11], examined their integration into building energy systems [12] and compared single and double effect absorption systems under various operating conditions [13].

3.4 Desiccant cooling systems (solid and liquid)

Desiccant cooling systems work by removing moisture from air, followed by sensible cooling. In solid desiccant systems, materials like silica gel or zeolites adsorb moisture, which is later regenerated using low temperature heat. Liquid desiccant systems use hygroscopic solutions such as lithium chloride or calcium chloride to absorb water vapor directly [14]. This configuration is illustrated in **Fig.1.5**, showing a hybrid desiccant system with a regeneration unit and cooling coil.

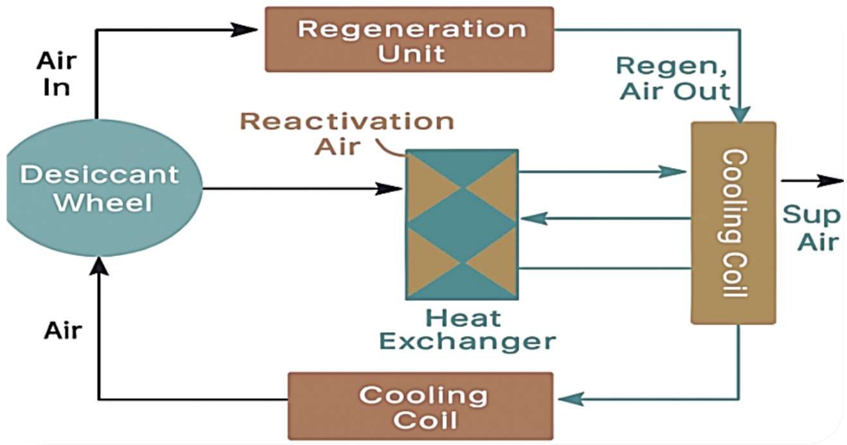


Fig.1.5. Hybrid desiccant system coupled with a regeneration unit and cooling coil [15].

Worek and Lavan [16] were among the earliest researchers who came up with theoretical models that presented the thermal behavior of super fluids, and mass transfer phenomena in solar regenerated desiccant wheel systems. Their research provided a basis for understanding the correlation between solar energy input and desiccant regeneration, and system performance, which allows for further optimization and experimental validation in later studies. Henning [17] brought forward a relevant review encompassing the integration of solid desiccant cooling systems into building applications. He identified the areas of desiccant and heat key design parameters, strengths, and weaknesses of desiccant based technologies and highlighted the ability to lower electrical load and enhance air conditioning in humid climates.

3.5 Evaporative cooling systems

Evaporative cooling is a passive system in which air is cooled because of the evaporation of water inside, by using the latent heat of vaporization. In direct evaporative cooling systems, the water is injected into the air stream, while in indirect systems the heat exchangers keep the humidity from increasing (**Fig.1.6**).

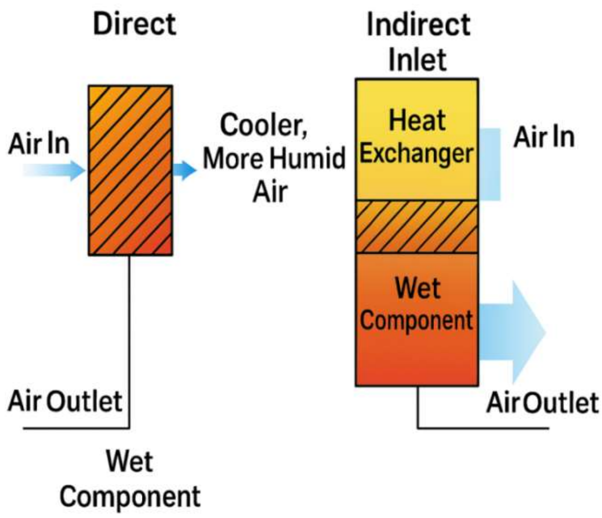


Fig.1.6. Basic direct and indirect evaporative cooling concepts [18].

Although these systems have a low consumption of energy, they are effective only in dry climates. Boukhanouf et al. [19] presented experimental and simulation investigations that showed solar desiccant cooling systems can significantly reduce electrical peak loads in north African climates. Their work provided real performance data under natural weather conditions. This will help prove the feasibility and economic interest in such systems for regions with high solar. irradiance and cooling demand. This was further complemented by Gvoni [20] when he made practical design guidelines suited for desert arid environments, tackling different aspects like air humidity control and sizing of solar collectors and system durability. His contribution helped to bridge the gap between theoretical design and real world, facilitating the deployment of solar assisted cooling systems in harsh climates

3.6 Thermoelectric and magnetic cooling systems

Thermoelectric cooling is based up on the Peltier effect where electric current provides a temperature gradient across semi-conductor junctions. Magnetic systems use magnetocaloric materials that change temperature when exposed to magnetic fields.

These technologies are compact and free of vibration, but also suffers from low energy efficient setup configuration (**Fig.1.7**).

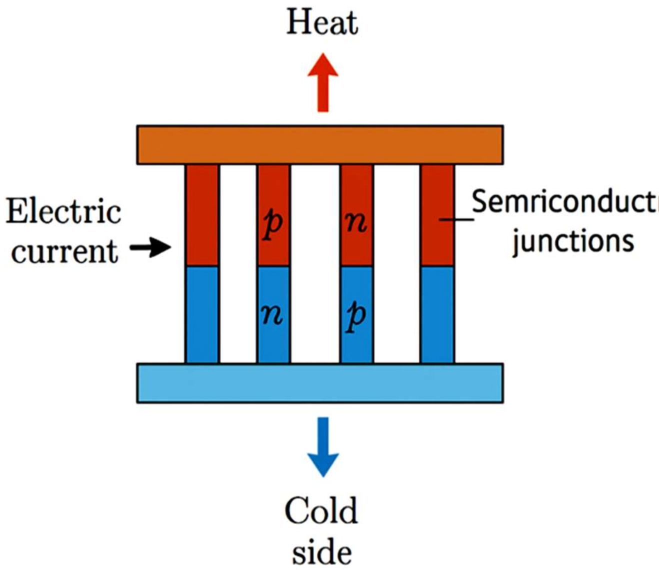


Fig.1.7. Thermoelectric cooling module configuration [21].

Rowe and Velázquez et al. [22-23] analyzed the application of thermoelectric modules for small scale air conditioning applications, with capacity to be compact, noiseless, and environmentally friendly cooling systems. Their work helped establish the efficiency limitations of thermoelectric devices and approaches to improve performance by means of optimized module design and heat exchanger integration. On the other hand, Tegus et al. [24] extended the research frontier by exploring the viability of magnetic refrigeration for domestic cooling systems.

3.7 Comparative discussion

Table 1.2 provides a comparative overview of the major conventional air conditioning technologies, highlighting their operating principles, energy sources, advantages, and limitations.

Table 1.2. Comparative overview of the major conventional air conditioning technologies.

Technology	Principle	Energy Source	Efficiency (COP)	Suitability	Limitation	[Ref]
Vapor Compression	Phase change	Electricity	3 – 4.5	Widely used	High GWP, grid dependence	**[4]**
Absorption Cooling	Thermal compression	Waste/solar heat	0.6 – 1.4	Buildings with thermal recovery	Large size, slow dynamics	**[12]**
Solid Desiccant	Moisture adsorption	Solar/gas heat		Humid climates	Requires regeneration	**[16]**
Liquid Desiccant	Moisture absorption	Solar/gas heat		Precise humidity control	Corrosion, crystallization	**[17]**
Evaporative Cooling	Water evaporation	Ambient air		Dry climates	Not suitable for humid areas	**[20]**
Thermoelectric	Peltier effect	Electricity	<1.0	Electronics, compact systems	Low efficiency	**[23]**

4. Solar assisted air conditioning systems

4.1 Introduction and classification

Solar assisted air conditioning (SAAC) systems use solar energy as a primary or auxiliary source to drive cooling processes. These technologies address the growing demand for sustainable space cooling while taking advantage of the natural synergy between high cooling loads and peak solar radiation (**Fig.1.8**):

- ✓ Solar thermal systems (sorption based), where solar heat is used to activate a thermodynamic or sorption cooling cycle.
- ✓ Solar photovoltaic (PV) systems, where solar electricity powers conventional compression-based air conditioning.

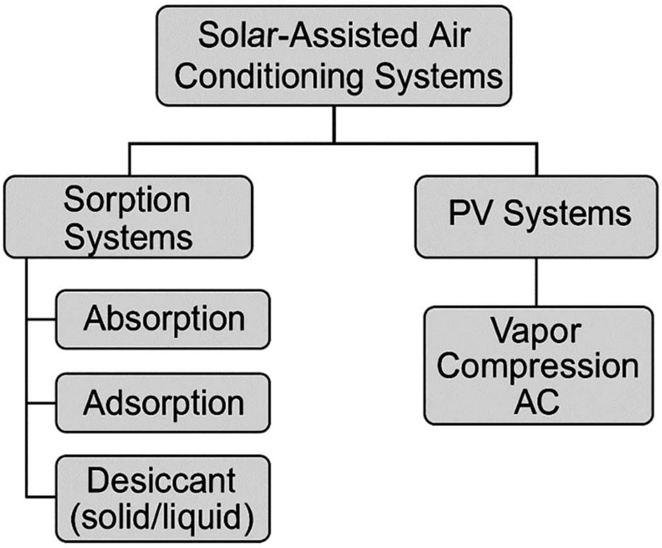


Fig.1.8. Classification of solar-assisted air conditioning systems.

4.2 Solar thermal sorption systems

(a) Absorption cooling systems

Solar absorption chillers use thermal energy typically from flat plate collectors to drive a closed loop cycle based on $LiBr/H_2O$ or NH_3/H_2O pairs. In single effect systems, heat enables refrigerant desorption, followed by condensation, expansion, and evaporation to produce cooling, while the absorbent is recirculated. These systems operate efficiently at moderate temperatures (**Fig. 1.9**).

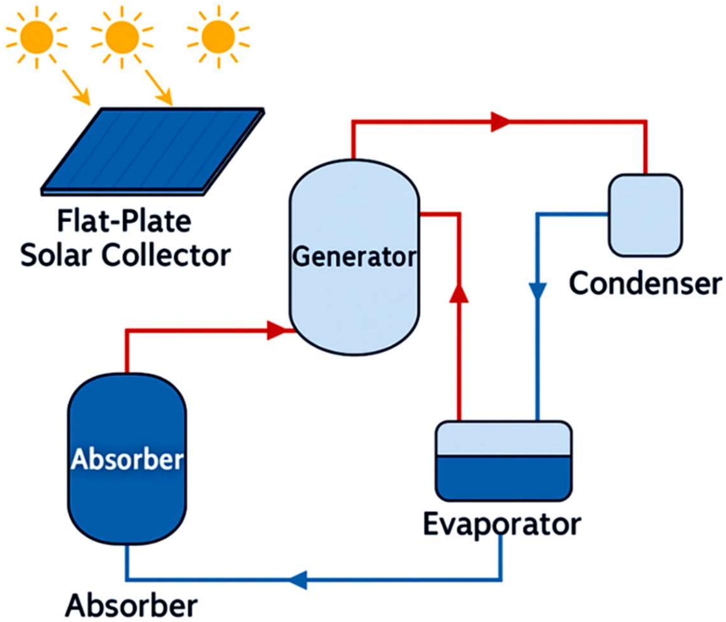


Fig.1.9. Single effect solar absorption cooling system [25].

Grossman [25] conducted early studies on single effect LiB/H_2O absorption systems for building cooling, establishing their technical feasibility. He created a foundation for the advancements that occurred in solar-assisted absorption technology. Although Henning [26] gave an implementation of solar driven absorption chiller cycles in Europe, focusing on their practical performance. System integration and operating performance were given specific emphasis by him conditions for improvement in reliability. The work of Florides et al. [27] has proved the seasonal performance of solar absorption systems in the Mediterranean context of Cyprus. The results confirmed that such systems could be viable in regions of high solar availability and double effect chillers coupled with high temperature solar collectors were investigated by Molina et al. [28], proving their potential application in improving thermal efficiency. It helped their research because the development of high-performance solar cooling systems. Despite the fact that absorption systems are wide commercialized, these devices still need constant heating and are often characterized by excessive footprint, slow response time, and tight operating conditions (crystallization risk for LiBr).

(b) Adsorption cooling systems

Adsorption chillers employ a solid adsorbent such as silica gel, zeolite, or carbon. refrigerant vapor, usually water. Then solar heating creates cycles in the solid adsorbent enabling cooling production without mechanical compression (**Fig.1.10).**

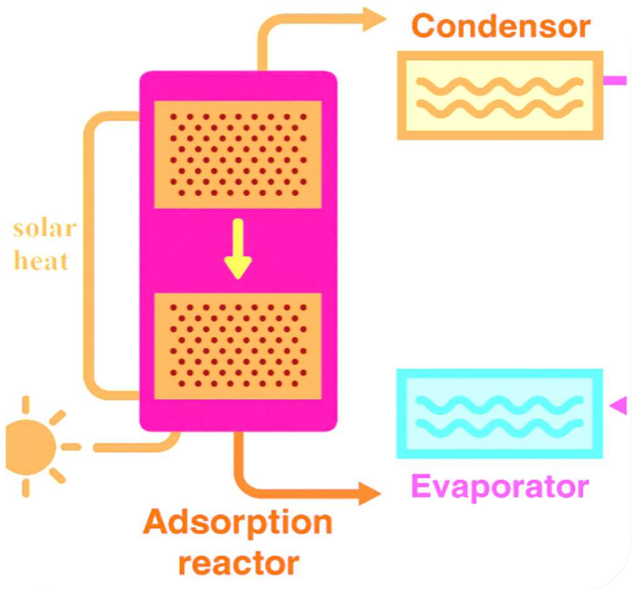


Fig.1.10. Two bed solar adsorption cooling system [29].

The use of silica gel-based water adsorption systems was pioneered by Wang et al. [29] for solar cooling. This was an important step in the development of solid/state adsorption technology. Sorption chillers employ a solid adsorbent such as silica gel, zeolite, or carbon, refrigerant vapor, usually water. Then solar heating creates cycles in the solid adsorbent enabling cooling production without mechanical compression This was improved by Restuccia et al. [30] with the application of innovative heat transfer technologies, exchangers, thus leading to more efficient and lighter/weight designs. Anyanwu [31] studied combinations of activated carbon and methanol for different solar radiation rates, including their flexibility to adjust the changing circumstances. Besides, adsorption systems are known for their high reliability and low maintenance needs, although these are constrained by their low COP (0.3-0.6) and long cycle durations.

(c) Desiccant based solar cooling

Desiccant systems regenerate materials that dehumidify the air by means of solar heat. These materials can be either solid (usually desiccant wheels) or liquid (silica gel, such as LiCl or Ca Cl_2 solutions). This regeneration is coupled with a process of moisture removal, where, after the removal of moisture, evaporative cooling or indirect cooling takes place. **Fig.1.11**, Hürner et al.[32], investigate how varying regeneration temperatures influence the efficiency of the desiccant wheel, and point to ways of optimizing the use of regeneration energy. Ge et al. [33], on the other hand, analyzed hybrid systems combining desiccant dehumidification with evaporative cooling and attained better performance in humid climates. Zhou and Zhang [34] also proposed the use of low temperature solar collectors for liquid desiccant regeneration, enhancing the feasibility under moderate solar conditions.

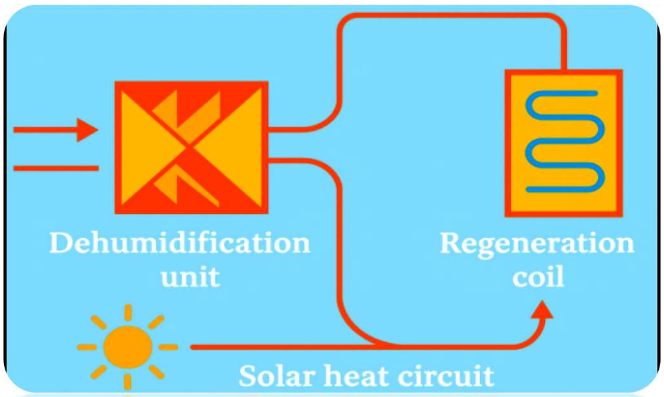


Fig.1.11. Solar regenerated desiccant cooling system [32].

4.3 PV Solar driven compression systems

Fig.1.12 presents a solar photovoltaic panel that generate electricity to power a conventional vapor compression air conditioner (VCAC). The system is often connected to the grid (or batteries) to ensure continuous operation.

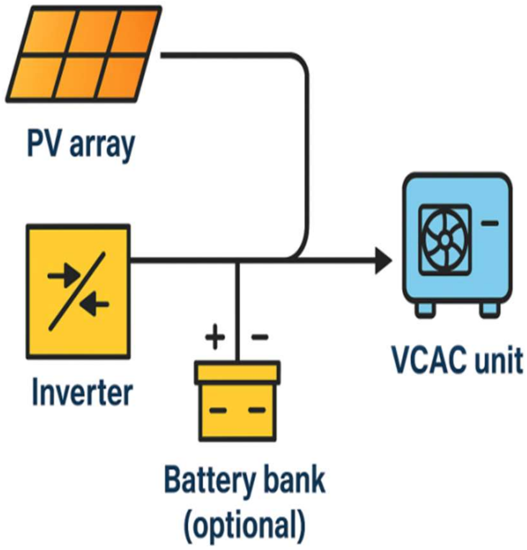


Fig.1.12. Solar PV compression cooling system [35].

Tian and Chai [35] modeled grid connected PV–VC systems with performance tracking. Radermacher and Hwang [36] assessed the seasonal efficiency of off grid PV cooling in remote zones. Belayachi et al. [37] integrated maximum power point tracking (MPPT) and energy storage to improve continuity. PV driven AC systems are modular, scalable, and benefit from declining PV costs. However, they remain sensitive to solar intermittency, require energy storage, and lack thermal inertia.

4.4 Comparative summary and research trends

Solar assisted systems offer promising solutions for reducing peak grid loads and integrating renewable energy. **Table 1.3** compares key solar cooling technologies by energy source, COP, operating complexity, and climate suitability.

Table 1.3. Comparison of Solar assisted cooling technologies.

Technology	Energy Source	COP	Climate Suitability	Maturity	Key Limitation	[Ref]
Solar Absorption	Thermal (hot water)	0.7–1.2	Sunny, dry climates	High	Bulky, slow dynamics	**[25]**
Solar Adsorption	Thermal (low temp)	0.3–0.6	Hot and humid	Medium	Low efficiency	**[29]**
Desiccant Cooling	Thermal (low temp)	–	Humid climates	Medium	Regeneration complexity	**[32]**
PV–Compression	PV electricity	2.5–4.5	All climates	High	Needs batteries/grid	**[35]**

4.5. Solar variable refrigerant flow systems

In recent years, a few research initiatives have explored the integration of solar energy with VRF systems **(Fig.1.13)**. The objective of these hybrid configurations is to reduce grid dependency while maintaining the zoning flexibility and efficiency of VRF technology.

Kim et al. [38] developed a grid connected PV VRF system for a medium sized office building in South Korea. The solar PV panels supplied part of the electricity to the outdoor VRF unit, while the rest was supplemented by the grid. The study reported up to 18% energy savings annually. However, the system remained vulnerable to solar intermittency, and its economic performance relied heavily on local electricity tariffs and feed in policies. Another method proposed in a study by Karagiorgas et al. [39] involved a solar assisted VRF system with a flat plate solar collector and a thermal buffer tank. This study demonstrated minimal energy savings (3-5%) but introduced difficulties with the cooling load ratio not matching the thermal load ratio.

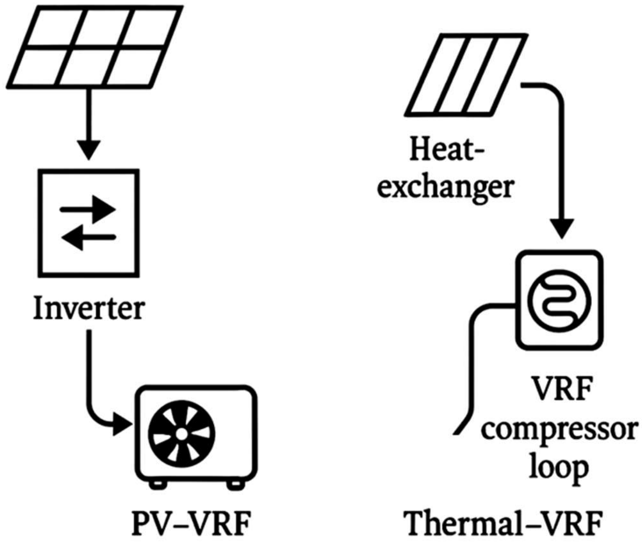


Fig.1.13. PV–VRF and thermal–VRF hybrid systems [38].

Despite their potential, the above SOLAR VRF systems have some significant limitations:

- ✓ They are still dependent on the electrical grid to function continually,
- ✓ Solar PV integration does not solve the problem of the lack of thermal storage capacity of VRF systems,
- ✓ could still work, is technically challenging, and not scalable,
- ✓ There is no passive modulation capability in these systems. They cannot be used in autonomous or off-grid systems.

These findings tend to prove that the mere integration of solar inputs and VRF technology alone will not prove adequate to transcend the limitations posed by traditional air conditioners. The existing gap opens avenues for innovative ideas based on passive cooling and storage systems, which will be explored throughout the dissertation

5. Variable refrigerant flow- air conditioning systems

5.1 Historical background and principle of operation

VRF technology was originated in Japan, in the early 1980s, primarily developed by Daikin industries. It was introduced as an evolution of multi split systems, offering enhanced zoning, better part load performance, and reduced energy consumption. Since then, VRF systems have gained widespread use in Asia, Europe, and North America, particularly in commercial buildings, hotels [40]. VRF systems operate on the vapor compression principle but allow the refrigerant flow rate to vary according to real time thermal demand in different zones. This is achieved through inverter driven compressors and electronic expansion valves (EEVs) that regulate the flow to multiple indoor units (**Fig 1.14**)

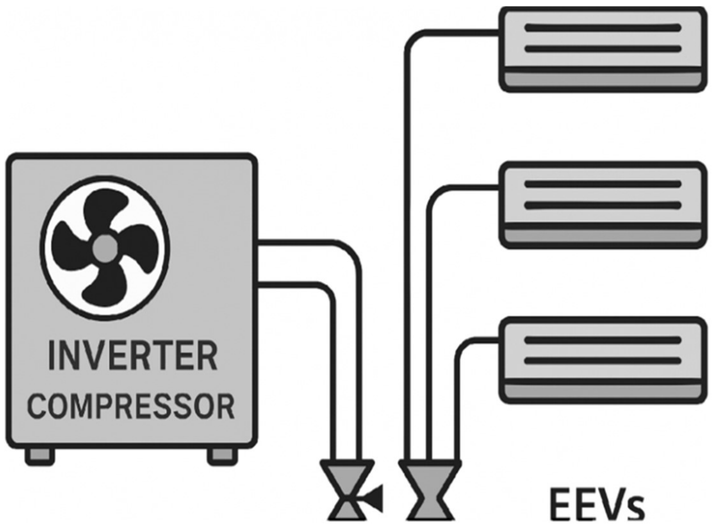


Fig.1.14. Basic architecture of a VRF system with multiple indoor units [40].

Unlike traditional direct expansion systems, VRF systems can operate in cooling, heating, or simultaneous cooling/heating modes using heat recovery configurations. The refrigerant piping network can extend over large distances, making the system flexible for complex building layouts.

5.2 Types of VRF configurations

VRF systems are available in different configurations based on energy source and heat distribution (**Fig.1.15)**:

- ✓ Air to air VRF: Most common type, where both condenser and evaporator circuits use air as the medium heat exchanger,
- ✓ Water-cooled VRF: The outdoor unit rejects heat to a water loop, allowing indoor units to function independently of outdoor air conditions,
- ✓ Heat pump VRF: Provides either heating or cooling to all zones simultaneously,
- ✓ Heat recovery VRF: Allows different zones to be heated or cooled at the same time by transferring internal energy between zones.

The dynamic performance of air-to-air VRF air conditioners, in a subtropical climate, has also been analyzed by Yang et al. [41]. Zhou et al. studied water cooled VRF systems in high rise office buildings. They proved the increased efficiency and compactness of these systems in high environments [42]. Jeong and Kim reported that a simulation model for three-pipe heat recovery VRF systems has been developed for the purpose of optimizing performance and designing controls during partial loads [43].

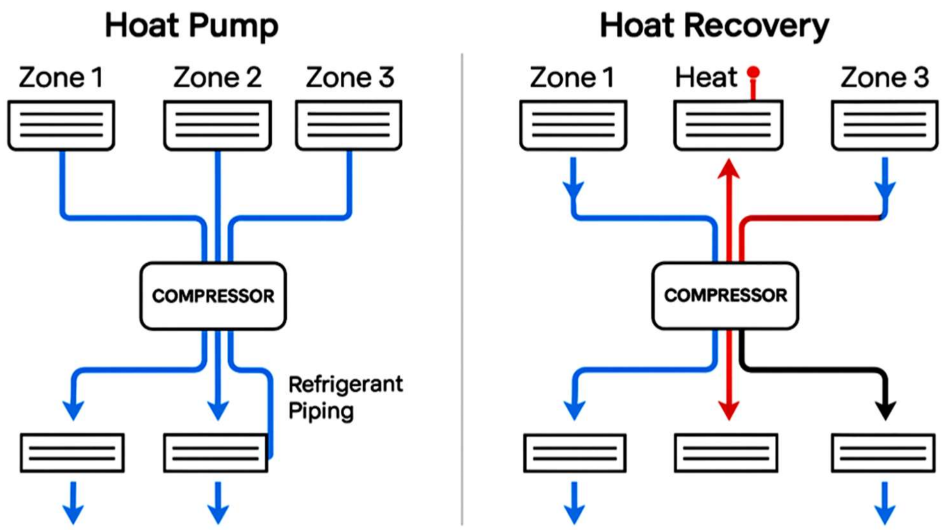


Fig.1.15.VRF types: heat pump and heat recovery [43].

5.3 Control and performance advantages strategies

VRF systems are renowned for their efficiency, especially when working under partial loads, where they are more effective compared to constant speed compression systems. The use of variable speed drives in these systems, along with zonal temperature control, results in energy savings that are often over 30% compared to traditional multi-split systems (**Fig1.16**).

Li and Wu have proved the significance of the need for advanced control algorithms, such as fuzzy logic and model predictive control, for the optimal operation of VRF [44]. Katsura et al., in their study, observed a long-term energy saving of 25-35% in educational buildings equipped with centralized VRF air-conditioning systems [45]. In addition, it should be pointed out that the VRF system has the ability to reduce the losses associated with the ducts to a negligible extent, work silently, and provide thermal comfort inside the space with a minimal temperature difference.

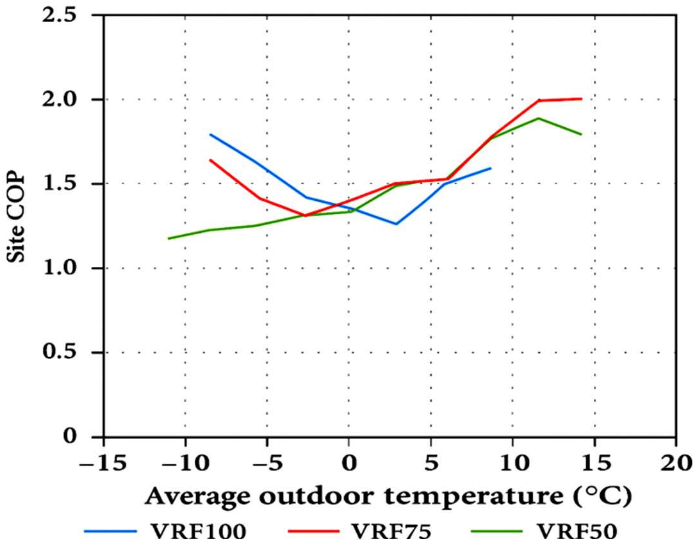


Fig. 1.16: Seasonal COP variation of VRF [45] **.**

5.4 Environmental and operational limitations

Despite VRF advantages, those systems present several critical limitations:

- ✓ Dependence on electricity: They rely entirely on electrical energy, often from nonrenewable sources,
- ✓ Use of high GWP refrigerants: Common refrigerants include R410A and R407C, which have significant environmental impact,
- ✓ High initial cost and installation complexity: The system requires precise refrigerant charge calculation, specialized installation, and advanced diagnostics,
- ✓ Control sensitivity: Performance can degrade without proper zoning, control logic, or maintenance.

Hwang and Radermacher [36] emphasized the importance of refrigerant charge management in large VRF systems, underlining its role in maintaining optimal performance and safety. Whereas Rasti and Amidpour [46], have modeled the effects of partial refrigerant leakage on system efficiency and reliability, highlighting the necessity of regular monitoring and leakage detection.

5.5 Summary and comparative insights

Table 1.4 present a comparison between VRF systems and other conventional air conditioning systems in terms of flexibility, energy performance, environmental impact, and maintenance requirements.

Table 1.4: Comparison between VRF and conventional air conditioning systems

Feature	VRF Systems	Split Systems	Chilled Water Systems	[Ref]
Load Modulation	Inverter-based	Limited	Good with VFD pumps	**[41]**
Zonal Control	Excellent	Limited (by unit)	Moderate	**[44]**
Energy Efficiency (SEER/COP)	High (up to 6)	Medium (3–4)	Medium	**[45]**
GWP of Refrigerant	High (R-410A, R-407C)	High	Low (water circuit)	**[46]**
Installation Complexity	High	Low	High	**[47]**
Maintenance requirement	High	Low	Medium to High	**[46]**

Although VRF systems are being widely used in large and complex buildings because of their performance, their environmental impact, high cost, and dependence on electronic control systems are some drawbacks that restrict their use in low resourcing or off grid settings. It is because of these limitations and taking into consideration future sustainability requirements that the use of VRF systems cannot be considered as the final solution.

6. Solar VRF hybrid systems: attempts and limitations

Recently, there have been attempts to integrate solar energy with Variable Refrigerant Flow (VRF) systems to enhance the energy autonomy and environmental characteristics of the latter. Such hybrid systems are, in most cases, based on photovoltaic VRF systems or, to a lesser extent, solar thermal assisted VRF units. Nevertheless, available literature suggests that these configurations provide minimal gains, particularly in relation to energy independence and efficiency.

Figs 1.17 and **1.19** are from selected case studies and scientific literature. Every figure shows a typical problem or outcome that frequently occurs in PV-VRF hybrid systems, but they do not originate from the same experimental arrangement. Their use is, accordingly, representative. and comparative, with the purpose of emphasizing the general limitations found in the literature.

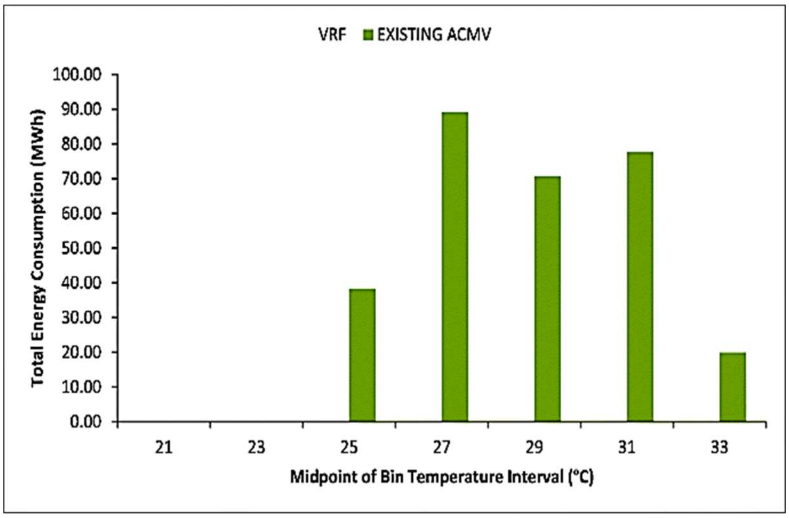


Fig.1.17: Annual contribution of PV electricity to meet the VRF demand [38]

In a case study conducted by Kim et al. [38], it was found that in a PV/powered VRF system, only 18% of solar irradiation was achieved on an annual basis. Similarly, in a study carried out by Karagiorgas et al. [39], it was found that in a solar/assisted VRF system, with thermal preheating, there were marginal efficiency gains (below 5%).

Fig.1.18 represent the effect of outdoor temperature on performance of a conventional ACMV system and the VRF system. In both configurations, the cooling capacity decreases as the ambient temperature rises, while the power input increases. Within this context, the VRF system shows a remarkable cooling output compared with the conventional system with better adaptability to outdoor temperature fluctuations. This proved performance under partial loads, and the superior energy management of VRF technology. Such systems still remain much dependent on the electrical grid, do not offer inertial thermal, and does not provide load modulation at thermal levels. Moreover, increased complexity of control and installation costs often exceeds the benefits derived from such systems.

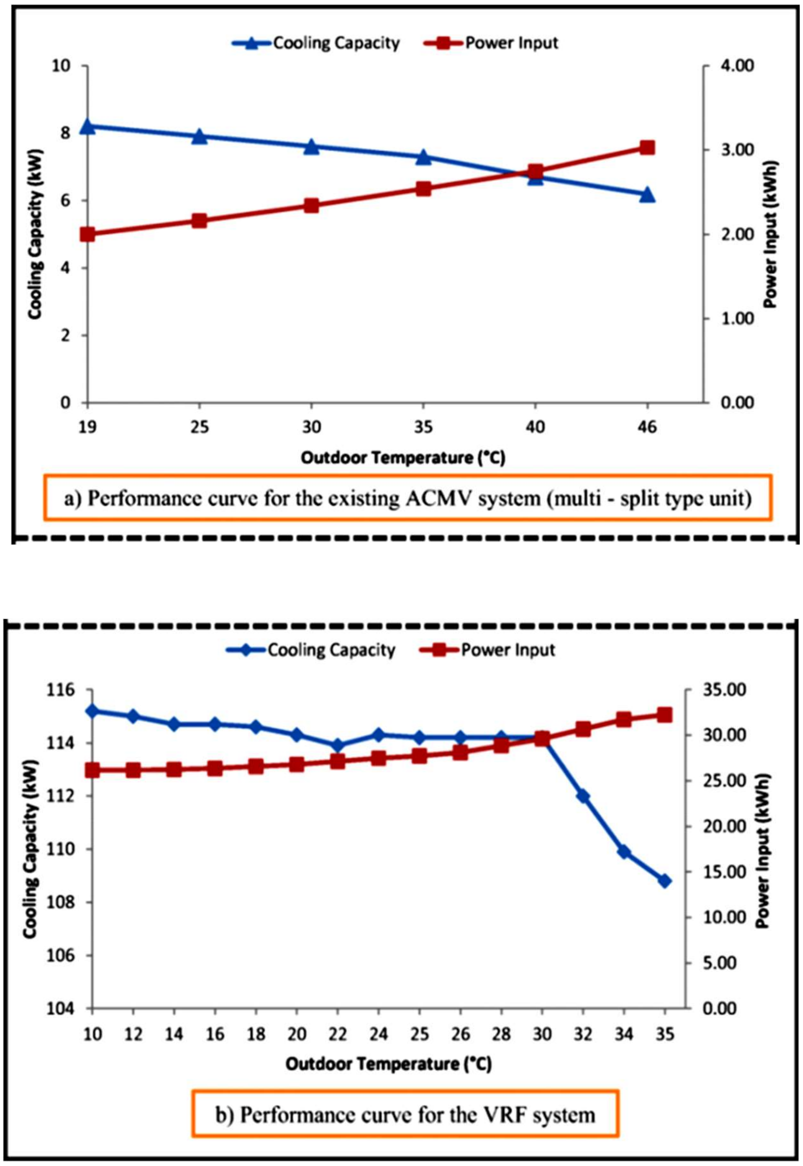


Fig. 1.18. Daily mismatch for solar irradiance and cooling load [38]

These limitations clearly indicate that adding solar input to the VRF systems does not solve the problem of structural constraints in conventional air conditioning. This logically leads to the motivation for a fundamentally different approach that allows for passive flow regulation, thermal storage, and autonomous operation, as it is introduced in this work

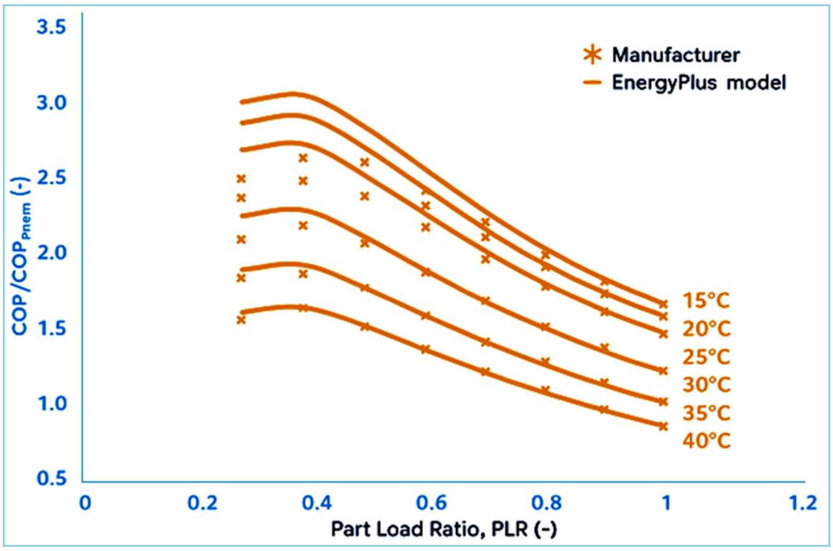


Fig.1.19. COP variation for VRF and standard solar assisted AC [39]

7. Analysis and research motivation

The review of conventional, solar assisted, and VRF air conditioning systems reveals significant advances in cooling technologies, but also exposes persistent technical and environmental limitations (**Table 1.5**).

Table.1.5: Summary of advantages and limitations of existing cooling technologies

Technology	Advantages	Limitations	[Ref]
Vapor Compression	High COP, compact, well-known	High electricity use, GWP, poor part load performance	**[6]**
Absorption Cooling	Renewable driven, GWP-free refrigerants	Bulky, low COP, slow response	**[25]**
Adsorption Cooling	Low temperature heat use, no moving parts	Low efficiency, long cycle time	**[29]**
Desiccant Systems	Effective in humid climates	Complex control, need for continuous regeneration	**[32]**
Evaporative Cooling	Low-cost, passive	Limited to dry climates	**[20]**
Thermoelectric	Compact, silent	Very low efficiency	**[23]**
PV–VRF	Renewable-powered, modular	Grid-dependent, needs storage, no thermal buffering	**[38]**
Thermal–VRF	Some energy savings possible	Technically complex, marginal efficiency gain	**[39]**

From this comparative analysis, several key research gaps emerge:

- ✓ None of the systems analyzed offer simultaneous energy autonomy**,** flow modulation and thermal storage,
- ✓ VRF systems are efficient but fully grid dependent, and solar coupling has shown limited benefit without buffering**,**
- ✓ Solar thermal systems can store heat, but respond slowly and require large equipment**.**
- ✓ Passive regulation and load adaptive operation remain underexplored.

These gaps justify the need for a new generation of hybrid systems capable of:

- ✓ Operating without electrical compressors **;**
- ✓ Ensuring passive flow regulation according to thermal demand;
- ✓ Storing thermal energy to bridge solar availability and load mismatch;
- ✓ Providing a compact and efficient solution suitable for hot climates with limited infrastructure.

The following chapters will detail the development, modeling, and performance analysis for an integrated system incorporating Solar Double Porous Heat Exchanger, energy storage, and Multi-layer Passive Heat Exchanger to accomplish above stated aims.

8. Conclusion

This chapter offers a comprehensive review of air conditioning technologies, their diversity, and the limitations intrinsic to all available methods. Vapor compression systems are currently the most popular and extensively used technologies across the global marketplace, but they have critical environmental impacts associated with their use. Solar assisted air conditioning technologies have the potential but pose challenges related to efficiency and control. VRF air conditioning technologies have the most advanced modulation but are anticipated to have critical energy consumption impacts and associated challenges of decarbonizing. Attempts at combining VRF with solar energy have been of limited success, thus emphasizing the need for more innovative solutions. This study argues in favor of the need for passive autonomous cooling systems.

The research proposed in this thesis has been aimed at meeting this challenge with a novel hybrid design of the proposed system that incorporates and use porous media, solar thermal energy, and passive flow control in order to provide efficient and autonomous cooling.

References

[1] International Energy Agency (IEA). The Future of Cooling: Opportunities for Energy-Efficient Air Conditioning. IEA, Paris, 2018. DOI: 10.1787/9789264301993-en.

[2] Burstall, A. F. A History of Mechanical Engineering. MIT Press, Cambridge, 1965.

[3] Carrier, W. H. Apparatus for Treating Air. U.S. Patent 808,897, 1906.

[4] Stoecker, W. F., & Jones, J. W. Refrigeration and Air Conditioning. McGraw-Hill, New York, 1982

[5] Moran, M. J., Shapiro, H. N., Boettner, D. D., & Bailey, M. B. Fundamentals of Engineering Thermodynamics, 8th ed. Wiley, 2014

[6] Dincer, I., & Rosen, M. A. Thermal Energy Storage: Systems and Applications. Wiley, 2011.

[7] Calm, J. M. The next generation of refrigerants – Historical review, considerations, and outlook. *International Journal of Refrigeration*, 31(7), 2008, pp. 1123–1133.
DOI :10.1016/j.ijrefrig.2008.01.013

[8] S. Srikhirin, S. Aphornratana, and S. Chungpaibulpatana, "A review of absorption refrigeration technologies," *Renewable and Sustainable Energy Reviews*, vol. 12, no. 9, 2008, pp. 200–215.

[9] G. Grossman, "Absorption refrigeration systems," *International Journal of Refrigeration*, vol. 22, 1999, pp. 111–124.

[10] D. Herold, et al., "Comparison of single and double effect absorption chillers," *ASHRAE Transactions*, vol. 102, no. 1, 1996, pp. 778–789.

[11] Srikhirin, P., Aphornratana, S., & Chungpaibulpatana, S. A review of absorption refrigeration technologies. Renewable and Sustainable Energy Reviews, 5(4), 2001, pp. 343–372. DOI : 10.1016/S1364-0321(01)00003-X

[12] Henning, H.-M. Solar assisted air conditioning of buildings – An overview.
Applied Thermal Engineering, 27(10), 2007, pp. 1734–1749. DOI :
10.1016/j.applthermaleng.2006.07.021

[13] Ziegler, F. State of the art in sorption heat pumping and cooling technologies.
International Journal of Refrigeration, 25(4), 2002, pp. 450–459. DOI : 10.1016/S0140-7007(01)00022-8

[14] B. Givoni, *Passive and Low Energy Cooling of Buildings*, Wiley, 1994.

[15] Henning, H.-M. Solar desiccant cooling systems: State of the art and future trends. Renewable Energy, 23(3–4), 2001, pp. 493–511. DOI : 10.1016/S0960-1481(00)00160-9

[16] M. Velázquez, et al., Thermoelectric modules for small-scale air conditioning, *Applied Energy*, vol. 190, 2017, pp. 100–110.

[17] Henning, H.-M**.** *Solar desiccant cooling systems: State of the art and future trends.* Renewable Energy, 23(3–4), 2001, 493–511. DOI: 10.1016/S0960-1481(00)00160-9

[19] Boukhanouf, R., Alharbi, A., Ibrahim, H. G., & Kanzari, M. (2015). *Experimental and numerical study of a heat pipe based indirect porous ceramic evaporative cooler.* International Journal of Environmental Science and Development**,** 6(2), 104–110. DOI : 10.7763/IJESD.2015.V6.707

[20] Givoni, B. Passive and Low Energy Cooling of Buildings. *John Wiley & Sons, 1994.*

[22] Rowe, D. M. Thermoelectrics Handbook: Macro to Nano. *CRC Press, 2006.*

[23] Velázquez, N., García-Valladares, O., Sauceda, D., & Beltrán, R. (2010). *Numerical simulation of a Linear Fresnel Reflector Concentrator used as direct generator in a Solar-GAX cycle*. Energy Conversion and Management, 51 (3), 434–445. https://doi.org/10.1016/j.enconman.2009.10.005

[24] O. Tegus, et al., Magnetic refrigeration technologies, *International Journal of Refrigeration*, vol. 67, 2016, pp. 68–77.

[25] H. Grossman, Solar absorption refrigeration, *Solar Energy*, vol. 24, no. 2, 1980, pp. 131–140.

[26] H.-M. Henning, Solar driven absorption chillers: A review, *Solar Energy*, vol. 80, no. 9, 2006, pp. 1135–1153.

[27] G. Florides, et al., Seasonal performance of solar cooling systems in Cyprus, *Renewable Energy*, vol. 35, no. 9, 2010, pp. 2237–2247.

[28] A. Molina, et al., Double-effect absorption chillers with high-temperature collectors,*Energy*, vol. 69, 2014, pp. 121–130.

[29] R. Wang, et al., Development of silica gel adsorption chillers, *Energy Conversion and Management*, vol. 50, no. 5, 2009, pp. 1313–1320.

[30] G. Restuccia, et al., Compact adsorption cooling systems, *Applied Thermal Engineering*, vol. 109, 2016, pp. 772–781.

[31] E. E. Anyanwu, Activated carbon-methanol adsorption cooling, *Renewable Energy*, vol.

67, 2014, pp. 218–224.
[32] C. Hürner, et al., Effect of regeneration temperature on desiccant wheel efficiency, *Solar Energy*, vol. 85, no. 12, 2011, pp. 3035–3044.
[33] Y. Ge, et al., Hybrid desiccant and evaporative cooling systems, *Energy and Buildings*, vol. 137, 2017, pp. 33–41.
[34] N. Zhou and Y. Zhang, Low-temperature solar collectors for desiccant regeneration, *Renewable Energy*, vol. 113, 2017, pp. 1233–1242.
[35] Z. Tian and W. Chai, Grid-connected PV–VC system modeling, *Solar Energy*, vol. 148, 2017, pp. 120–132.
[36] R. Radermacher and Y. Hwang, Seasonal efficiency of off-grid PV cooling, *International Journal of Refrigeration*, vol. 91, 2018, pp. 1–11.
[37] A. Belayachi, et al., PV-powered VRF systems with MPPT and storage, *Energy Reports*, vol. 5, 2019, pp. 839–849.
[38] D. Kim, et al., Grid-connected PV VRF system performance, *Energy and Buildings*, vol. 231, 2021, 110594.
[39] C. Karagiorgas, et al., Solar thermal assisted VRF systems, *Renewable Energy*, vol. 120, 2018, pp. 400–407.
[41] J. Yang, et al., Dynamic performance of air-to-air VRF systems, *Applied Thermal Engineering*, vol. 142, 2018, pp. 152–161.
[42] Z. Zhou, et al., Water-cooled VRF for high-rise buildings, *Energy and Buildings*, vol. 189, 2019, pp. 123–134.
[43] J. Jeong and S. Kim, Simulation and optimization of three-pipe heat recovery VRF systems under partial load conditions, *Energy*, vol. 183, 2019, pp. 356–365.
[44] X. Li and J. Wu, Application of advanced control algorithms in VRF air conditioning systems, *Energy and Buildings*, vol. 198, 2019, pp. 25–34
[45] T. Katsura, et al., Energy savings in buildings with VRF, *Energy and Buildings*, vol. 183, 2019, pp. 377–386.
[46] M. Rasti and M. Amidpour, Impact of refrigerant leakage on VRF efficiency, *Energy Conversion and Management*, vol. 184, 2019, pp. 110–118.

Chapter 2

Analyses and modeling of the SDPHEX–MPHEX system

1. Introduction

Energy system modeling is an important task in the assessment of theoretical performance, optimal design, and prediction of the behavior of the system under a set of practical operating conditions. In this chapter, there is a detailed mathematical model of the hybrid solar cooling system. This is accomplished by starting with a description of the system in order to obtain the model equations according to the laws of thermodynamics in porous media. Special focus will be put on the Lattice Boltzmann Method, which is used due to its stability in simulating coupled heat and mass transport in porous media.

2. Description of the system

The cooling system design integrates two kinds of porous heat exchangers namely, Solar Double Porosity Heat Exchanger (SDPHEX) and Multi Porosity Heat Exchanger (MPHEX) to give a passive and solar-powered variable refrigerant flow system. The hybrid design allows it to operate without using control devices like electronic expansion valves and variable-speed compressors. This offers it the ability to operate independently and, in an energy, saving way, especially in remote or hot zones (**Fig. 2.1**).

The system consists of the following functional units:

a. Solar energy input and thermal storage (SDPHEX):

This particular system functions on the platform of the first energy interface. This process absorbs sunlight and then saves the generated thermal energy through a solid porous medium. The energy exchanger has two parts:

- An upper porous layer designed to optimize solar absorption and storage properties, commonly consisting of high-specific-heat-materials of high surface area,
- A lower porous zone through which a heat transfer fluid (HTF) passes in order to harvest the stored energy through the process of conduction as well as convection.

The design enables the system to operate during the solar charging process and the subsequent phases after irradiation, thus serving as a heat buffer.

b. Refrigerant circulation and modulation (MPHEX):

After the thermal input part, it passively controls the refrigerant flow according to the system pressures and temperature differences. It is made up of a number of layers, which are either porous with different permeability and porosity to ensure that the system is capable of:

- Adapt flow rate dynamically without sensors or control logic,
- Provide efficient heat transfer between the refrigerant and the environment or working fluid,
- Stabilize flow velocity profiles to prevent flow oscillations

Loop configuration and working principle:

The two exchangers are connected in a loop which includes a compressor substitute or pressure-driving mechanism and this may be powered intermittently eg solar powered pump or gravity feed. Energy is absorbed by the working fluid or refrigerant from the SDPHEX and is conducted through the MPHEX to complete the thermal cycle.

The system can be configured as:

- A DX refers to a direct expansion cycle where the refrigerant acts directly.
- Secondary loop system: A heat transfer fluid, circulating among components coupled through thermal interfaces.

Auxiliary components (Minimal):

Because this system uses embedded storage and relies on passive modulation, it keeps auxiliary parts like sensors, controllers, and actuators to a minimum. Inlet and outlet manifolds, flow direction check valves, and insulation layers are included only for maintaining structural integrity and thermal efficiency.

Operation modes:

The system works in two different yet interconnected phases:

- The solar collection and charging phase in which the solar energy will be harnessed and stored in the SDPHEX.
- Cooling phase: a phase during which the refrigerant flow is passively modulated through the MPHEX and thermal energy is delivered to the conditioned space or load.

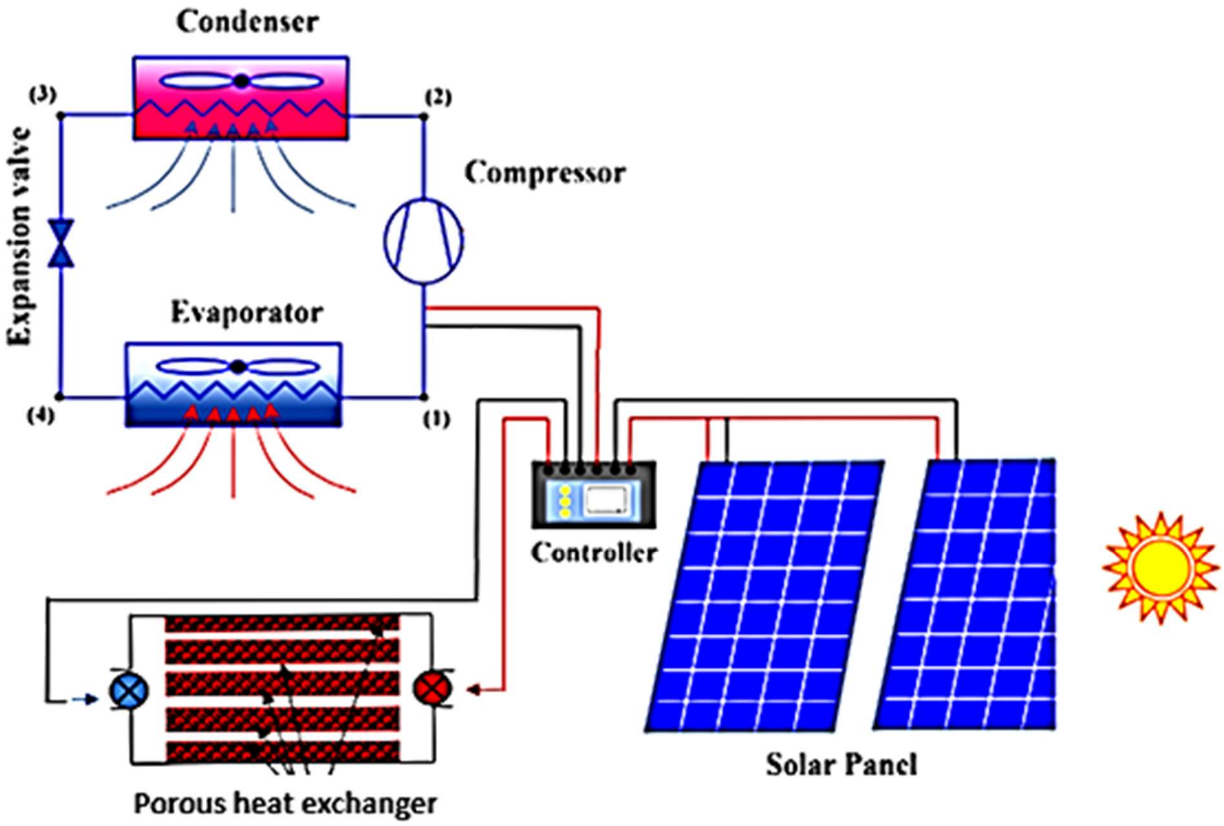
This will, therefore, be a dual-functionality system that provides both, hence allowing precise temperature control with minimum energy input. The module can be designed for deployment in compact form and is therefore quite apt for applications related to remote areas, mobile units, or energy-autonomous buildings

3. SDPHEX System

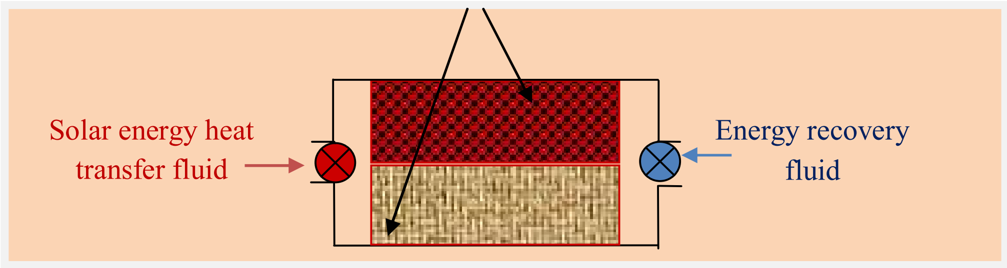
The Solar Double-Porosity Heat Exchanger (SDPHEX) integrates solar absorption, thermal storage, and heat transfer into a unified porous structure. To accurately model its performance, it is necessary to represent the energy transport within the dual-porosity medium, the fluid-solid interactions, and the transient thermal behavior due to solar radiation variability.

3.1 Geometrical and physical configuration

A porous exchanger, a compressor, a solar panel, an evaporator, a condenser and a thermostatic expansion valve are the main components of the considered system: SDPHEX : Solar AC with double Porous Heat Exchanger.



(a)



(b)

Fig.2.1. Physical model of the solar air conditioner (a: General system; b: Double porous heat exchanger).

The fluid flow in DPHEX is controlled by a 4-way solenoid valve placed just upstream of the exchanger. To transfer solar energy to the solid phase up to a high-pressure HP, the valve slide swings between two positions. In the first position, the fluid from the solar panel passes through the heat exchanger; this is the storage circuit. The second position: allows the fluid from the evaporator to pass through the DPHEX and absorb the previously stored solar energy up to a low-pressure LP, along this last circuit the enthalpy of the refrigerant varies (H1,H2…H8); this is the transfer circuit.

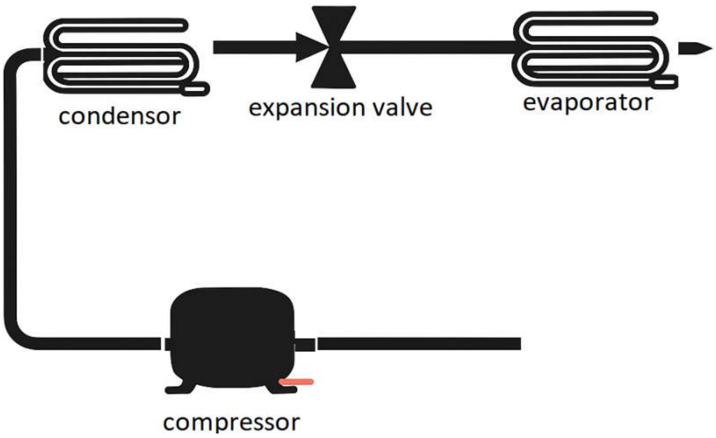
The technical function of each component is described in follow table:

Table.2.1. Technical function of components

Component	Technical Function
Evaporator	Absorbs ambient heat at low temperature and pressure. The refrigerant evaporates (liquid → vapor).
Thermostatic Expansion Valve (TXV)	Reduces pressure and temperature of the refrigerant before entering the evaporator.
Condenser	Rejects heat to the ambient; refrigerant condenses (vapor → liquid).

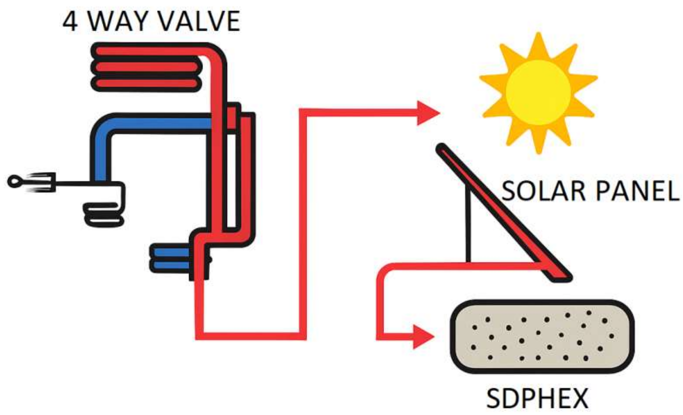
Compressor	Compresses low-pressure refrigerant vapor to high pressure and temperature for recirculation.
Solar Thermal Collector	Converts solar energy into thermal energy; heats the fluid before it enters the DPHEX.
Double Porous Heat Exchanger)	Dual-purpose unit: (1) stores thermal energy in its porous solid matrix, and (2) transfers stored heat to the refrigerant.
4-Way Solenoid Valve	Switches between storage mode (solar loop) and transfer mode (refrigeration loop).

The proposed solar-assisted cooling system consists of three interconnected subsystems, each represented by a distinct circuit: the conventional refrigeration loop (black, **Fig2.2**), the solar thermal storage loop (red, **Fig2.3**), and the thermal energy transfer loop (blue, **Fig2.4**).



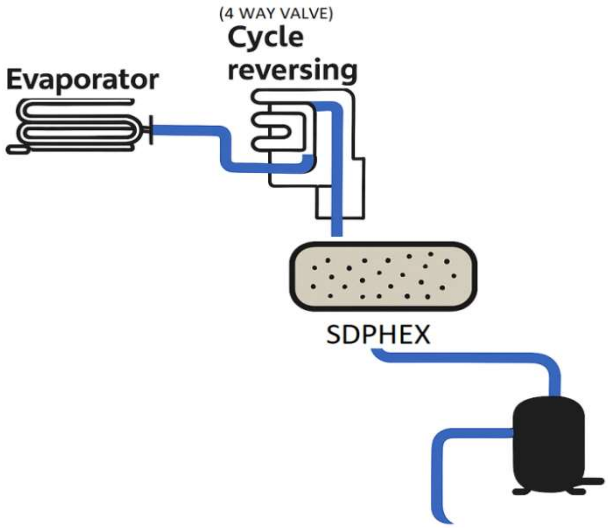
The refrigerant is compressed, condensed, expanded, and evaporated. This loop provides conventional cooling.

Fig2.2. Main vapor compression refrigeration cycle of the SDPHEX AC system.



Hot fluid from the solar collector enters the DPHEX (T_0, U_0) to store energy in the porous solid. No phase change occurs; energy is stored in the matrix.

Fig2.3. Solar thermal storage circuit of the SDPHEX AC system.



Cold refrigerant passes through the DPHEX and absorbs stored heat before compression. This improves system performance.

Fig 2.4 Thermal transfer circuit via DPHEX of the SDPHEX AC system

3.2 Governing equations

The following theories are presented to appropriately characterize the problem's mathematical formulation: the flow is thought to be laminar, incompressible, and viscous. Additionally, the solid and fluid phases are in local thermal equilibrium condition. The homogeneity and isotropy of the porous matrix's thermo-physical characteristics are unaffected by temperature. Furthermore, the homogenization of the governing equations in the REV approach reflects the porous media impact. Thus, the Navier-Stokes equations in the fluid domain and the Darcy-Brinkman- Forchheimer equations in the porous medium model the flow.

According to the abovementioned assumptions, the transient macroscopic governing equations at the REV scale, can be recast using the canonical dimensional form that follows. For more details, one can refer to **Dhahri,** [1-3].

$$\nabla.\vec{u}=0 \tag{1}$$

$$\frac{\partial \vec{u}}{\partial t}+(\vec{u}.\nabla)(\varepsilon_k^{-1}\vec{u})=-\nabla(P)+v_f\nabla^2\vec{u}+\varepsilon_k\vec{F}_k \tag{2}$$

$$[\varepsilon_k(\rho C_p)+(1-\varepsilon_k)(\rho C_p)]\frac{\partial T}{\partial t}+(\rho C_p)\vec{u}.\nabla T=\nabla.(\lambda_{eff,f}\nabla T) \tag{3}$$

The velocity vector, porosity, pressure, porous medium temperatures, density, kinematic viscosity, thermal capacity, and equivalent thermal conductivity are represented by the variable $\vec{u}$, $\mathcal{E}_k$ P, T_f, ρ,v_f, $C_p$and $\lambda_{eff,f}$, respectively. The solid and fluid phases are indicated by subscripts *s* and *f*, respectively. k designates 1 if the sold point belongs to porous media 1 and 2 if the solid point belongs to porous media 2.

The total body force caused by the presence of porous media is indicated by$\vec{F}_k$(Eq. (2)) and it can be written as [4]:

$$\vec{F}_k=-\left(\frac{V_f}{K_k}+\frac{F_{\varepsilon k}}{K_k}|\vec{u}|\right)\vec{u} \tag{4}$$

The permeability and the Forchheimer' s form coefficient $K_k$and $F_{\varepsilon k}$, are often not universal. They are stated here as [5]:

$$K_k=\varepsilon_k^3 d_{pk}^2(150(1-\varepsilon_k)^2)^{-1} \tag{5}$$

$$F_{\varepsilon k}=\frac{1.75}{\sqrt{150\varepsilon^3}} \tag{6}$$

Boundary and initial conditions

The following are the related initial conditions (IC) and boundary conditions (BCs) required for the process to finish the issue formulation:

▪$u=u_0$; v=0

;$T_f=T_0$, at $x=0$ and $0\leq y\leq H$ (left boundary);

▪$\nabla_x u=0$; v=0; at x=L and $0\leq y\leq H$ (right boundary);

▪u=0; v=0 and $\nabla_y T_f=\nabla_y T_s=0$ (perfect-insulated) at $0\leq x\leq L$ and $y=H$ (upper boundary);

▪ $u=0$; $v=0$ and $\nabla_y T_f = \nabla_y T_s = 0$ (perfect-insulated) at $0 \le X \le L$ and $y=0$ (lower boundary);

▪ $u=0$; $v=0 T_f = T_0$ and at $t=0$ for $0 \le x \le L$ and $0 \le y \le H$

▪ $u=0$; $v=0$ and $\nabla_y T_f = \nabla_y T_s = 0$ (perfect-insulated) at $0 \le x \le L$ and $y = \frac{1}{2}H$ (interface between two porous mediums)

The following are the main dimensionless variables and parameters:

$$\bar{x}=\frac{x}{H},\quad \bar{y}=\frac{y}{H},\quad \bar{u}=\frac{u}{U_0},\quad \bar{v}=\frac{v}{U_0},\quad \tau=\frac{tu_0}{H};\quad \theta_{f,s}=\frac{T_{f,s}}{T_0},$$

$$R_{c,k}=\frac{\rho C_{ps,k}}{\rho C_{pf}},\ R_{k,k}=\frac{\lambda_{s,k}}{\lambda_f}\quad R_e=\frac{\rho_f U_0}{\mu_f H}\qquad Pr=\frac{\mu_f C_{Pf}}{\lambda_f}\qquad Da_k=\frac{K_k}{H^2}\quad P=\frac{p}{\rho U_0{}^2}$$

Then, Eqs. (1) - (3) are transformed into a dimensionless format as

$$\frac{\partial U}{\partial X}+\frac{\partial V}{\partial Y}=0 \tag{7}$$

$$\frac{\partial U}{\partial \tau}+\frac{1}{\varepsilon_k}\left(\frac{\partial U^2}{\partial X}+\frac{\partial UV}{\partial Y}\right)=-\frac{\partial \varepsilon_k P}{\partial X}+\frac{1}{Re}\left[\frac{\partial^2 U}{\partial X^2}+\frac{\partial^2 U}{\partial Y^2}\right]-\varepsilon_k\left(\frac{1}{ReDa_k}+\frac{F_{\varepsilon k}}{\sqrt{Da_k}}|U|\right)U \tag{8}$$

$$\frac{\partial V}{\partial \tau}+\frac{1}{\varepsilon_k}\left(\frac{\partial UV}{\partial X}+\frac{\partial V^2}{\partial Y}\right)=-\frac{\partial \varepsilon_k P}{\partial Y}+\frac{1}{Re}\left[\frac{\partial^2 V}{\partial X^2}+\frac{\partial^2 V}{\partial Y^2}\right]-\varepsilon_k\left(\frac{1}{ReDa_k}+\frac{F_{\varepsilon k}}{\sqrt{Da_k}}|U|\right)V \tag{9}$$

$$\left(\varepsilon_k+(1-\varepsilon_k)R_{C,k}\right)\frac{\partial \theta_f}{\partial \tau}+\left(U\frac{\partial \theta_f}{\partial X}+V\frac{\partial \theta_f}{\partial Y}\right)=\frac{1}{R_e P_r}\left(\varepsilon_k+(1-\varepsilon_k)R_{k,k}\right)\left(\frac{\partial^2 \theta_f}{\partial X^2}+\frac{\partial^2 \theta_f}{\partial Y^2}\right) \tag{10}$$

The corresponding dimensionless BC and IC are converted as follows:

▪ $U=1$; $V=0$; $\theta_f = 1$, at $X=0$ and $0 \le Y \le 1$;

▪ $\nabla_X U = 0$; $V=0$; at $X=L/H$ and $0 \le Y \le 1$;

▪ $U=0$; $V=0$ and $\partial_y \theta_f = 0$ at $0 \le X \le L/H$ and $Y=1$;

▪ $U=0$; $V=0$ and $\partial_y \theta_f = 0$ at $0 \le X \le L/H$ and $Y=0$;

▪ $U=0$; $V=0$ and $\partial_y \theta_f = 0$ at $0 \le X \le L/H$ and $Y=1/2$;

4. Thermodynamic model of the MPHEX

4.1 Geometrical and physical configuration

The Multi-Porous Heat Exchanger (MPHEX) introduced in this work is a novel thermal distribution system composed of two vertically arranged porous layers. The lower layer consists of multiple horizontal branches each characterized by a distinct Darcy number while the upper layer is a common porous domain through which the refrigerant flows (**Fig.2.5**). When a specific branch in the lower porous layer is selected via an electronic distributor, the permeability associated with that path directly governs the velocity and heat transfer in the upper layer. As a result, the thermal output to the corresponding indoor zone is passively adjusted, without mechanical regulation or variable-speed components. This passive tuning of refrigerant velocity and cooling capacity offers a robust, modular, and low-energy alternative to conventional electronically controlled system.

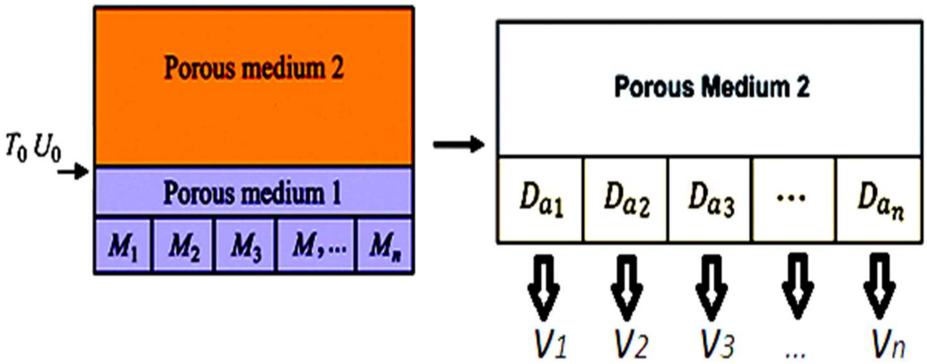


Fig.2.5. Schematic of the multi-porous heat exchanger (MPHEX).

Where :

M_1, M_2, M_3… M_n: Medium1, Medium 2, Medium 3…Medium n

D_{a1}, D_{a2}, D_{a3}… D_{an}: Darcy Number for Medium1, Medium2, Medium 3…Medium n

V_1, V_2, V_3… V_n: Velocity of refrigerant flow at outlet of Medium1, Medium2, Medium 3…Medium n

The associated permeability is able to adjust flow and heat transfer in the upper layer. To illustrate the relevance of the MPHEX to general cooling systems, the functional relationship between the MPHEX and the VRF system is provided below in **Fig.2.6**:

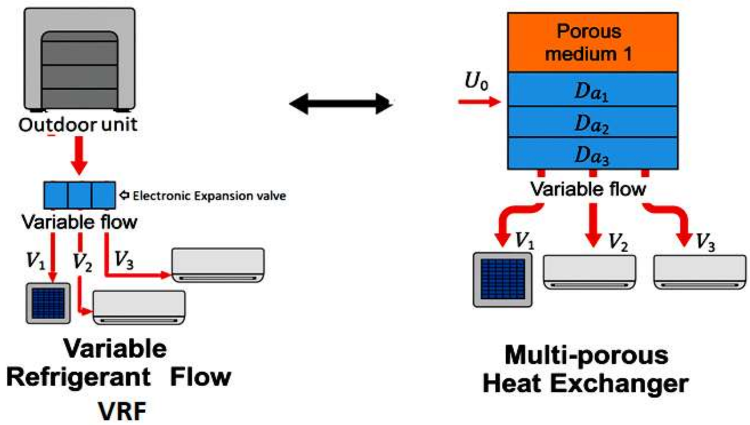


Fig.2.6. Analogy between MPHEX and VRF.

Whereas VRF controls the flow of the refrigerant actively using variable speed compressors and expansion valves, the MPHEX does so passively by varying the permeability values of the branches. In the MPHEX, the VRF functionality is replicated by using the porous branches aligned in parallel within the lower porous sub-layer. Every branch is supposed to represent the space, as well as have a unique permeability factor (Da1, Da2, ., Dan), which enables the selective control of the fluid speed and the heat transfer. This fluid is supplied to one branch using a low-power electronic distributor depending on the feedback information from the indoor temperature sensors.

This helps to improve robustness and reliability, especially when working offline, and becomes an alternative for sustainable and economical air-conditioning systems. Comparison between traditional VRF systems and MPHEX designs has been provided in **Table 2.1**, which highlights various differences between these two systems based upon control, complexity, requirement for energy, and suitability.

Tab2.1: Comparison analysis between VRF and MPHEX.

	VRF System	**MPHEX**
Flow Control	Active control using electronic expansion valves and variable-speed compressors	Passive control via permeability variation (Darcy number) in the porous medium
Electrical Consumption	Significant due to electronics, sensors, and continuous regulation	Very low; flow is regulated structurally, without electronics.
System Complexity	High: requires advanced algorithms, multiple sensors, and electronic actuators	Simplified architecture: relies on geometric and material configuration for flow regulation
Installation Cost	High initial cost due to electronic components and control systems	Lower investment: reduced number of active components, passive design adaptable to solar systems

Maintenance Requirements	Requires specialized technicians, frequent calibration, sensitive to electronic failures	Minimal maintenance: mechanically robust with no active control parts
Reliability & Robustness	Generally reliable but susceptible to electronic failures	Highly robust and durable, less sensitive to environmental and operational conditions
Suitability for Remote Areas	Limited applicability in off-grid or resource-constrained environments	Ideal for off-grid use: passive, low-energy, solar-compatible.

This thermodynamic model of the MPHEX thus provides the basic platform for simulating refrigerant dynamics within the context of passive flow regulation. **Fig.2.7**: Conceptual representation of the dual paradigms of flow regulation: Electronic regulation in existing VRF technology vs Permeability-based passive regulation in the MPHEX design. This representation conceptually highlights radical divergences in the strategies of the two paradigms. While in the existing technology based on VRF architecture, compressors, inverter drives, or so-called electronic expansion valves play a critical dynamic feedback role in regulating target state flow regimes in accordance with system requirements, in the innovative MPHEX architecture, all these regulatory strategies rely solely on material resistance inherent in inherent geometric properties of the setup. This representation metaphorically captures the dematerialized reasoning of the MPHEX design by emphasizing the dematerialized philosophy behind its design: eliminating all electromechanical elements in favor of more intrinsic reasoning strategies based solely on spatial geometry. While in the existing setup dynamic flux regulation strategies dynamically modify the flow rates based on system feedback in accordance with predefined requirements, in the MPHEX design strategy spatial properties based on inherent permeability modify the dynamics of the existing flow rates in accordance with predefined spatial requirements. This theoretical representation thus captures the genius of an innovative design approach dematerializing existing approaches by relying solely on intrinsic spatial properties to accomplish design requirements.

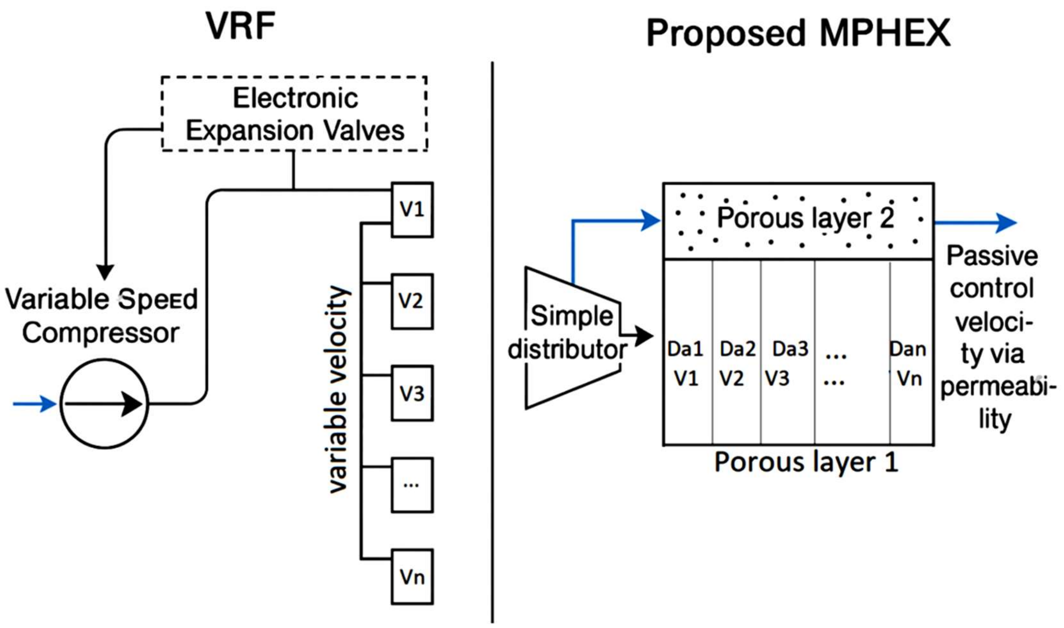


Fig.2.7. Comparison of flow control strategies: active regulation in VRF vs passive permeability-driven control in MPHEX.

4.2 Boundary and initial conditions

Same boundary conditions, used for SDPHEX mentioned in section 3.2, are used for MPHEX and added this condition between Lateral walls of PM1 branches:

$u=0$; $v=0$ and $\nabla_y T_f = \nabla_y T_s = 0$ (perfect-insulated) at $0 \le x \le L$.

5. System modeling using the lattice Boltzmann method (LBM)

The complexity of the proposed system comes not only from the need to deal with flow, energy storage, and thermal exchange within such as heterogeneous and anisotropic environment but also because it proposes an SDPHEX coupled to an MPHEX. These challenges are difficult to overcome using conventional numerical methods such as finite difference or finite volume methods. Thus, LBM is considered in this work to simulate such coupled flow and heat transfer phenomena in porous exchangers. The thermal and hydrodynamic behavior of MPHEX is investigated by using the LBM, a computational technique that already proved its efficiency in simulating flows in complex geometries such as porous media [6,7]. It can perform many calculations at the same time, which makes it particularly suitable for large-scale simulations. In addition, it handles boundary conditions easily, without the need for complex mathematical treatment. These advantages make it a practical and reliable tool for modeling flow and heat transfer in the MPHEX configuration. [8].

The density's distribution equation for incompressible flow is as follows:

$$f_i(x+c_i\Delta t,t+\Delta t)-f_i(x,t)=-\frac{1}{\tau_e}[f_i(x,t)-f_i^{eq}(x,t)]+\Delta tF_{ei} \quad (11)$$

Where τ_e is the dimensionless relaxation time defined by: $\nu=\Delta tc_s^2\,(\tau_e-0.5)$ (12) and $f_i^{eq}(x,t)$, the distribution function is given by: $f_i^{eq}=w_i\rho\left(1+\frac{c_iu}{c_s^2}+\frac{uu:(e_ie_i-c_s^2I)}{2\varepsilon c_s^4}\right)$ (13)

while ρ is the average density of the fluid, u is the average velocity of the fluid, $c_s=\frac{c}{\sqrt{3}}$

The arrangement we will use is D2Q9 (2D and 9 lattice-velocities), in this case, the discrete velocities and their weights are:

$$Ci=\begin{cases}(0,0) & i=0\\ (\cos[i-\pi/2],\ \sin[i-\pi/2])c & i=1,2,3,4\\ (\cos[2i-9\pi/4],\ \sin[2i-9\pi/4])\sqrt{2c} & i=5,6,7,8\end{cases} \quad (14)$$

$$Wi=\begin{cases}4/9 & i=0\\ 1/9 & i=1,2,3,4\\ 1/36 & i=5,6,7,8\end{cases}$$

Finally, the viscosity is expressed using the following relation:

$$\rho u=\sum c_if_i+\frac{\Delta t}{2}\rho F \quad (15)$$

5.1. LBM formulation for temperature

The Boltzmann equation linked to the thermal quantity is

$$g_i(x+c_i\Delta t,\ t+\Delta t)-g_i(x,\ t)=-\frac{1}{\tau_e}[g_i(x,\ t)-g_i^{eq}(x,\ t)] \quad (16)$$

Where $g_i(x,t)$ is the temperature distribution function at point i, $g_i^{eq}(x,t)$ is the local equilibrium temperature distribution function, τ_g is the dimensionless relaxation time taken for energy transport

$$\tau_g=3\ Pr(\tau_e-0.5)C+0.5\quad,\ C=\frac{\varepsilon_k+(1-\varepsilon_k)R_{k,k}}{\varepsilon_k+(1-\varepsilon_k)R_{C,k}} \quad (17)$$

As for velocity, a local equilibrium appears at the point i and it is determined by Zhao (2005) [9]:

$$g_i^{eq}=w_i T\left(1+\frac{c_i u}{c_s^2}+\frac{uu:(e_i e_i-c^2{}_s I)}{2c^4{}_s}\right) \tag{18}$$

For D2Q9, the discrete temperatures and their weights are:

$$Ci=\begin{cases}(0,0) & i=0\\ (\cos[i-\pi/2],\ \sin[i-\pi/2])c & i=1,2,3,4\\ (\cos[2i-9\pi/4],\ \sin[2i-9\pi/4])\sqrt{2c} & i=5,6,7,8\end{cases} \tag{19}$$

$$Wi\quad\begin{cases}2/3 & i=0\\ 1/9 & i=1,2,3,4\\ 1/36 & i=5,6,7,8\end{cases}$$

Finally, the thermal expression is as follows

$$\sigma T_{f,s}=\sum_i g_{if,s}\quad \sigma=\varepsilon+(1-\varepsilon)R_C \tag{20}$$

5.2 Implementation of LBM boundary conditions

For the dynamic boundary conditions, the input velocity is known so the unknown distribution functions (**Fig.2.8**) are deduced from the known ones (input) Zou and He, 1997[10]**:**

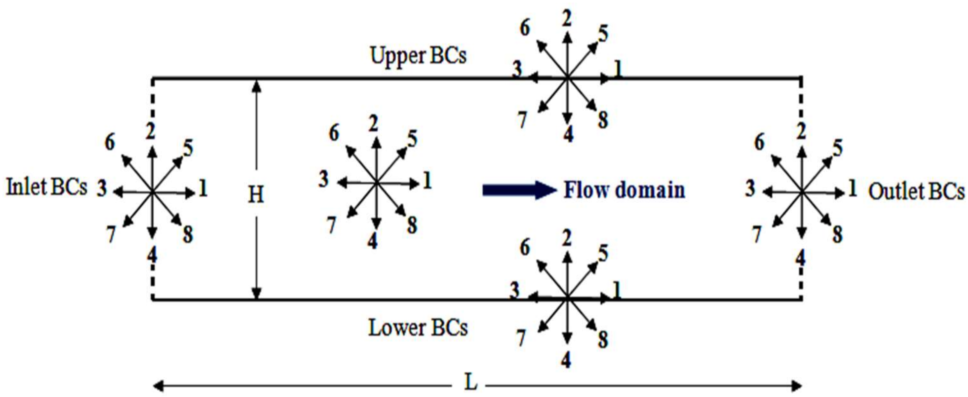


Fig.2.8. D2Q9 velocity and temperature lattice layout within and at domain boundaries.

$\rho_{cal}=\sum_{i=0}^{8} f_i=f_0+f_1+f_2+f_3+f_4+f_5+f_6+f_7+f_8$(20) The projection of eq (25) gives:

$$\text{x-axis } \rho_{cal}u_{in}=\sum_{i=0}^{8} c_{ix}f_i=\sum_{i=0}^{8} ce_{ix}f_i=\sum_{i=0}^{8} e_{ix}f_i\ ;\quad c=1 \tag{21}$$

y-axis (At input, v_{in}= 0)

$\rho_{cal}v_{in}=f_2-f_4+f_5+f_6-f_7-f_8$ so $f_4-f_2-f_6+f_7=f_5-f_8$ (22)

The final equation is,

$f_1=f_3+\frac{2}{3}\rho_{cal}u_{in}$

$f_5=f_7-\frac{1}{2}f_2-f_4+\frac{1}{6}\rho_{cal}u+\frac{1}{2}\rho_{cal}v$

$f_8 = f_6 - \frac{1}{2}f_2 - f_4 + \frac{1}{6}\rho_{cal}u + \frac{1}{2}\rho_{cal}v$ (23)

Besides at the fluid solid boundary, the distribution velocity functions (**Fig.2.9**) belonging to the solid phase are unknown **(**Bounce Back)[11] the velocity distribution functions after contact are reversed in the same direction but in the opposite direction, thus in contact with a solid, the distribution functions of the fluid phase take the values of the distribution functions of the solid phase**.**

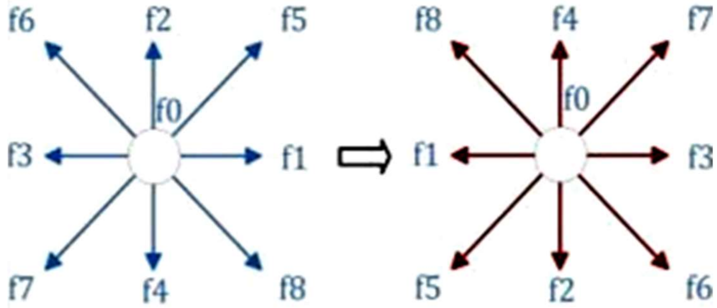


Fig.2.9. Density distribution function at the solid-fluid interface.

So at the lower interface we have:$f_2=f_4$; $f_5=f_7$; $f_6=f_8$ and at the Eastern interface we will have:$f_1=f_3$;$f_6=f_8$;$f_5=f_7$

While temperature at the inlet of the heat exchanger is known: g_1,g_5,g_8 known so

$g_5=w_5+w_7-g_7$ (24)

At the interface of two porous mediums (superimposed vertically or horizontally

inside the exchanger) we have; $f_2=f_4$; $f_5=f_7$; $f_6=f_8$

And $g_2=w_2+w_4-g_4$ (25)

$g_6=w_6+w_8-g_8$

$g_5=w_5+w_7-g_7$

5.3 Validation

To ensure the physical accuracy of the LBM model, simulation results are validated against:

- ✓ Analytical solutions for benchmark porous media problems.
- ✓ Finite volume simulations from literature for equivalent boundary conditions.
- ✓ Experimental results from passive heat exchangers (where available).

Mesh independence, time step sensitivity, and relaxation time tuning are all conducted during a preliminary calibration phase to optimize stability and convergence.

6. Conclusion

This chapter presented a complete mathematical and numerical model of the proposed SDPHEX–MPHEX system. The model integrates porous flow theory, transient thermal storage dynamics, and advanced simulation tools such as the Lattice Boltzmann Method to accurately capture the physical behavior of the hybrid exchanger.

Beginning with a structural and functional description of each component, detailed thermodynamic equations were derived for both the solid and fluid domains. Specific formulations were developed for each exchanger type: LTE modeling for the SDPHEX and MPHEX. A specialized LBM implementation was introduced to handle flow and heat transfer in porous media with varying properties.

Reference

[1] R. Rabhi, B. Amami, H. Dhahri, and A. Mhimid, “Entropy generation for an axisymmetric MHD flow under thermal non-equilibrium in porous micro duct using a modified lattice Boltzmann method,” *Journal of Magnetism and Magnetic Materials*, vol. 419, 2016, pp. 521–532.

[2] B. Amami, H. Dhahri, and A. Mhimid, “Viscous dissipation effects on heat transfer, energy storage and entropy generation for fluid flow in porous channel submitted to uniform magnetic field,” *Transport in Porous Media*, vol. 17, 2014, pp. 841–859.

[3] I. Ginzburg, “LBM in porous media: Theory and applications,” *Physical Review E*, vol. 103, no. 3, 2021, 033305.

[4] D. A. Nield and A. Bejan, *Convection in Porous Media*, 5th ed., Cham: Springer, 2017.

[5] K. Vafai (Ed.), *Handbook of Porous Media*, 3rd ed., Boca Raton: CRC Press, 2015.

[6] I. Ginzburg, “LBM in porous media: Theory and applications,” *Phys. Rev. E*, vol. 103, no. 3, 2021, 033305.

[7] T. S. Zhao, “A lattice Boltzmann method for thermal convective flows in porous media” *Journal of Heat Transfer*, vol. 127, no. 8, 2005, pp. 930–936.

[8] Q. Zou and X. He, “On pressure and velocity boundary conditions for the lattice Boltzmann BGK model,” *Physics of Fluids*, vol. 9, no. 6, 1997, pp. 1591–1598.

[9] S. J. Kim, S. Y. Lee, and S. J. Kim, “Forced convection in microporous media: A lattice Boltzmann study,” *International Journal of Heat and Mass Transfer*, vol. 42, no. 17, 1999, pp. 3609–3620.

[10] A. Mohamed, “Lattice Boltzmann simulation of thermal flow in porous media,” *International Communications in Heat and Mass Transfer*, vol. 34, no. 1, 2007, pp. 1–10.

[11] A. J. C. Ladd, “Numerical simulations of particulate suspensions via a discretized Boltzmann equation. Part 1: Theoretical foundation,” *Journal of Fluid Mechanics*, vol. 271, 1994, pp. 285–309.

Chapter 3

Improving Solar Air Conditioning efficiency through Double-Porosity Heat Exchanger design: Numerical Insights

1. Introduction

The need for comfort has grown in recent years due to climate change. Consequently, increased productivity and air conditioner use lead to increased energy and financial expenses. [1] In 2020, About 226000 GWh of cooling energy were needed globally in the residential sector [2], and by 2030, it is expected that this demand would increase by 72% in Europe [3]. Unfortunately, traditional air conditioners present two problems: bad impact on the environment and important energy consumption. The first problem is the use of CFCs and HFCs as refrigerants. Although HFCs have less impact on the ozone layer than CFCs, they are however, causing the ozone layer [4]. On the other hand, at least 97% of its energy source comes from fossil fuels [5]. This leads to significant environmental contamination and numerous phenomena like global warming [6]. Thus, since the need for air conditioning rises every year fossil fuels' source is decreasing consequently. That is why switch to renewable energy sources from fossil fuels seems imminent [7]. The sun is the main and most accessible renewable energy source[8], and devices that can use solar electricity have been the subject of numerous studies[9]. In fact, the daily energy produced by the sun is 1.1kJ while, annual energy consumed by humans is 4.7kJ [10]. Various investigations have been carried out to provide solutions where renewable power from solar light contributes significantly to air conditioning [11]. These reviews have mostly concentrated on the economic evaluation, optimal design, and energy assessment of different solar systems [12], and a variety of solar thermal collector types [13] for air conditioning production. Numerous studies have contrasted solar and conventional air conditioners in this regard; (Chuang Chen et al.2024) [14] develop a desiccant air conditioner that is driven by solar energy. They show that the system's monthly average coefficient of performance is 5.1 in June, 5.6 in August, 5.5 in September, and 4.8 in July. The new system has a 6.6-year payback period and a 58.4% lower operating cost than the traditional air conditioning system. The new system's CO_2 emission reduction rate is at its lowest in September (62.9%), however, it can rise to 65.1% in August and 65.2% in July. Likewise

(Rebelo et al 2024) [15] compared the conventional air conditioner with the one using renewable energy sources and they prove that the solar photovoltaic air conditioner used roughly 342 kWh during the 30-day experiment. The PV system can save roughly $700.00 on energy costs, and it will pay for itself in 3.7 years.

A long way from using energy, (Adam.et al.2023) [16] focused on the refrigerant fluid type to avoid conventional refrigerant (HFC and HCFC) bad impact on the environment. The system's COP increased by 2.42% when R290 refrigerant was used. This enhancement was supported by a 2.31% reduction in input work and a 2.37% rise in energetic efficiency when a renewable energy source and an eco-friendly air-conditioning cycle were combined. This offers a great way to address the very real issues of high energy use in warm nations. However, (Mukhtar et al. (2022) [17] sought to improve energy efficiency and concentrate on absorption solar air conditioning system design, modeling, and simulation. They indicated that when average heater temperatures rose to 25, energy savings increase. Solar air conditioning is not limited to hot areas, even in countries where it is cold; a lot of research has been done on solar air conditioning. In this framework, (Liu et al., 2020) [18] proposed and evaluated the performance of a solar/air-dual source heat pump system on the Tibetan Plateau, in Qingha. They demonstrated that the system could efficiently provide indoor comfort in extremely cold climates while utilizing all available renewable energy. In the same instance, they created a heat pump using an air-type solar collector with a change phase material that can achieve efficient heating in all weather conditions through the cascading use of thermal energy and developed a vapor injection heat pump that may minimize ventilation heat loss with a waste heat recovery ratio greater than 100% by recovering heat from building exhaust air. While (Shi et al., 2019) [19] studied DX-SAHP (direct expansion solar heat pump) and demonstrated that although it can function effectively in environments with high levels of sun radiation, its effectiveness is inconsistent since sunlight varies. Recent inquiries have besides focused on integrating porous media heat exchangers into solar cooling applications to enhance energy storage and improve heat transfer efficiency. Those findings studied solar energy storage systems, yet no previous theoretical research has been done on the effect of the use of two or more porous mediums for heat exchanger in solar air conditioner [20].

The objective of this chapter is to develop a numerical model to analyze thermal and dynamic behaviors of a double porosity heat exchanger, DPHEX, in a solar air conditioning system. It investigates the effects of parameters such as Darcy number, thermal conductivity ratio and thermal capacities ratio on heat transfer and energy storage using the lattice Boltzmann Method (LBM). It concluded that high permeability and low thermo-physical characteristics promote heat storage which contributes to the development of more efficient and sustainable cooling technologies, aligning with global efforts to reduce energy consumption and environmental impact. The format of this document is as follows: Section 2 describes the problem governing equations and the details of the numerical solution. Section 3 is devoted to discussing the numerical results. Lastly, we finish this investigation and give a summary of the results.

2. System and mathematical formulation

This section provides a concise description of the solar heat exchanger performance as a storage energy material and meanwhile a heat transfer medium in the solar air-conditioner system. The same fluid under some approximation and the interface between the two media is adiabatic. The fluid flow equations and boundary conditions that describe this working are represented in what follows.

2.1. Physical model

A porous exchanger, a compressor, a solar panel, an evaporator, a condenser and a thermostatic expansion valve are the main components of the considered system (SDPHEX): Solar AC with double Porous Heat Exchanger. The two-dimensional heat exchanger filled with two porous mediums is the interest component and the computational domain for this study (as shown in Fig.1). The exchanger of length L and height H is composed of two porous mediums with different characteristics (porosity, thermal conductivity, permeability, etc.). The problem should be 2D since the outlet conditions are completely developed. Note that, to start the first procedure, exchanger is passed through by the fluid coming from the solar collector at an initial temperature T_0, and an initial velocity of component U_0

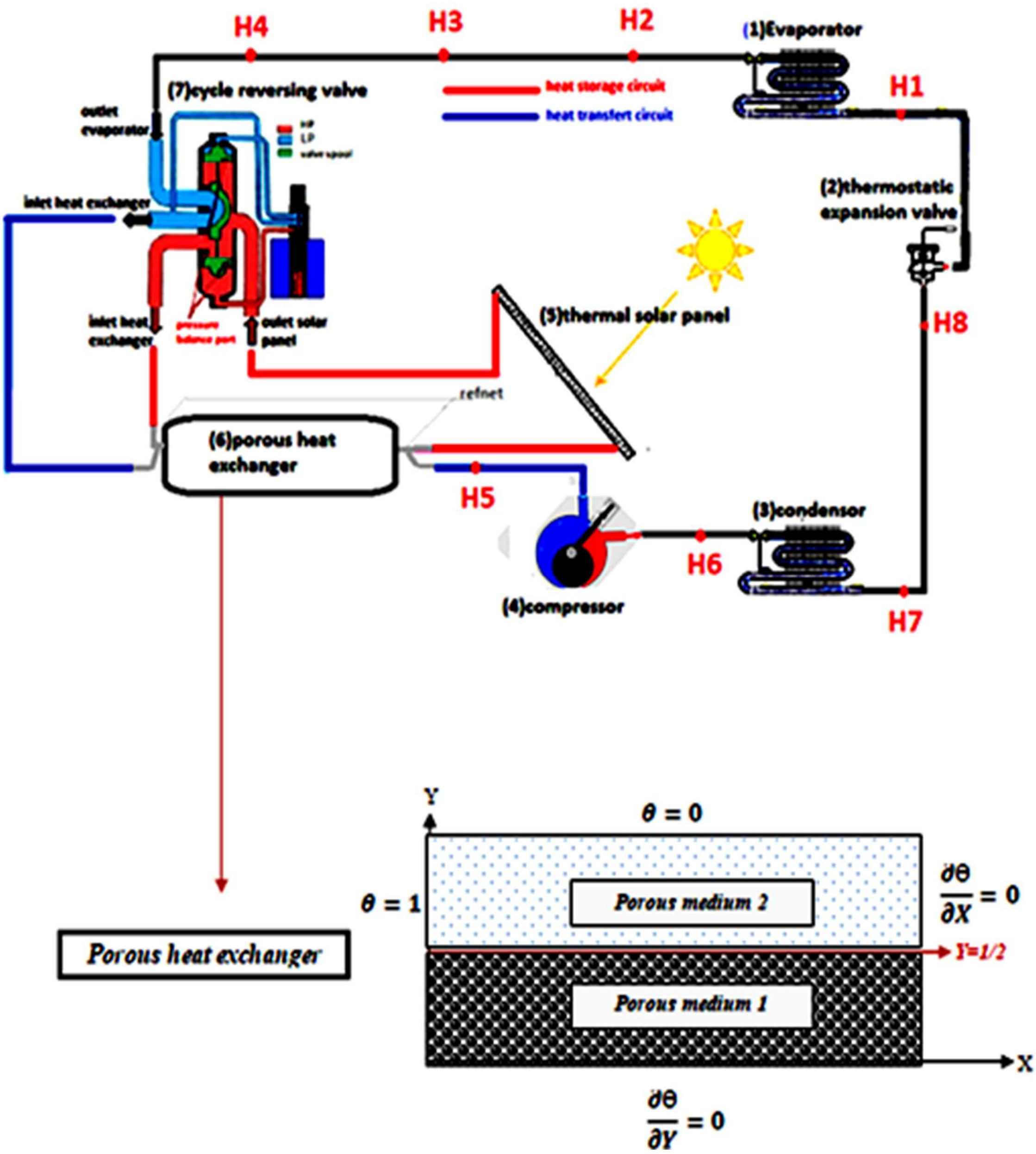


Fig1. Physical model of the solar Double porous heat exchanger (DPHEX).

The fluid flow in DPHEX is controlled by a 4-way solenoid valve placed just upstream of the exchanger as illustrated in Fig.1.To transfer solar energy to the solid phase up to a high-pressure HP, the valve slide swings between two positions. In the first position, the fluid from the solar panel passes through the heat exchanger; this is the storage circuit. The second position: allows the fluid from the evaporator to pass through the DPHEX and absorb the previously stored solar energy up to a low-pressure LP, along this last circuit the enthalpy of the refrigerant varies (H1,H2…H8); this is the transfer circuit.

2.2. COP (performance coefficient) of SDPHEX

The Performance coefficient (COP) of the air conditioning system represents the ratio of the cooling output to the electrical energy input [26]. Typically, AC systems rely entirely on electricity to power the compressor and maintain cooling, resulting in COP equal to ratio of the cooling output to the electrical compressor input [27].In order to compare efficiency of conventional AC and SDPHEX, we need to evaluate the COP of each system respectively COP1 and COP2according to system illustrated in Figure 1 (in the case of conventional AC, we eliminate the solar part; solar panel – four-way valve and DPHEX) and then, the Performance coefficient (COP1) can be given by the following expression:

$$\boldsymbol{COP1} = \dot{m}\,x\frac{H4 - H1}{Wconv} = \dot{m}xC_p\frac{T4 - T1}{Wconv}$$

Where

$$Wconv = \dot{m}\,x\,\Delta H_{COMP} = \dot{m}\,x\,(H6 - H4) = \dot{m}\,x\,C_p(T6 - T4)$$

$$\boldsymbol{COP1} = \frac{T4-T1}{T6-T4} \qquad (1)$$

The same coefficient, COP2, in the case of SDPHEX is given by:

$$\boldsymbol{COP2} = \dot{m}\,x\frac{H4-H1}{W_{SDPHEX}} = \dot{m}xC_p\frac{T4-T1}{\dot{m}\,x\,(H6-H5)} = \frac{T4-T1}{(T6-T5)} \qquad (2)$$

Where

- $\dot{m}$: mass flow
- H1, T1: enthalpy at evaporator inlet respectively
- H4, T4: enthalpy at evaporator outlet respectively
- H5,T5: enthalpy at compressor inlet respectively
- H6,T6: enthalpy at compressor outlet respectively
- W_{SDPHEX}: Electrical compressor input for SDPHEX

3. Grid check and numerical model validation

3.1. Grid check

Trial calculations have been carried out using several mesh sizes, including 80x80, 90x100, 100x100, 110x125, 110x130, and 120x140, to guarantee the grid independence of the answers.

The meshes of 100 100× and 110×125 were found to differ by a maximum of 0.6%. Additionally, we observed that the U-component velocity is independent of grid size beyond the 110x125 grid. In order to achieve the optimal balance between accuracy and computation time, a uniform grid consisting of 110x125 elements was selected for all of the calculations shown below.

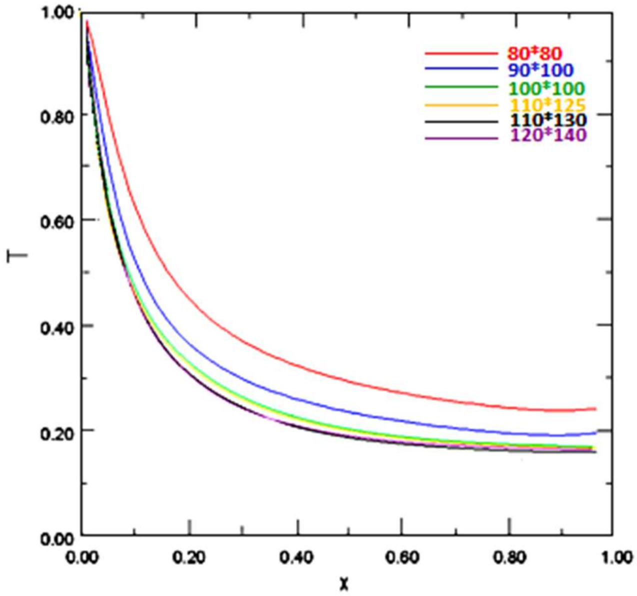


Fig.2. Test mesh independency for Re=70, Pr=0.7.

3.2. Validation of numerical models

Initially, pertinent limiting cases from literature must be used to validate the mathematical model and the numerical approach. The projected velocity profiles from the current study are compared with those of (Kim et al) [33] for various Da numbers, in Fig.3, to illustrate this validity (Da=1e^{-4}, Da=0.024 and Da=0.1). The result reveals the effect of Reynolds number on the axial velocity profile. The parabolic velocity profile is clearly visible; Due to the significant viscosity effect, the velocity is zero close to the walls. It peaks at the center of the channel and less important, farther away from the walls. It portrays that this velocity is strongly affected by Reynolds numbers. The velocity profiles acquired by numerical analysis for various Darcy numbers are compared in Figure 5. It is clear from this figure that the fluid moves through the medium more slowly when the Darcy number is low than when it is high. Similarly, Fig.4, presents the axial variation of temperature (Y=0.6 and Y=0.76) obtained by our developed code and the same obtained by A. Mohamed (2007 and 2011) [34]. It is interesting to note that the temperature passes from a maximum value to zero following a hyperbolic profile. The trend expects a sharp temperature drop because the heat is being rapidly transferred into the medium. The temperature drop would be steeper for smaller media (with a smaller dimension Y) and more gradual for larger media (larger Y), as the heat spreads out over a longer distance. Examining these numbers closely reveals that all our results demonstrate a high degree of agreement with published results for both dynamic and thermal cases.

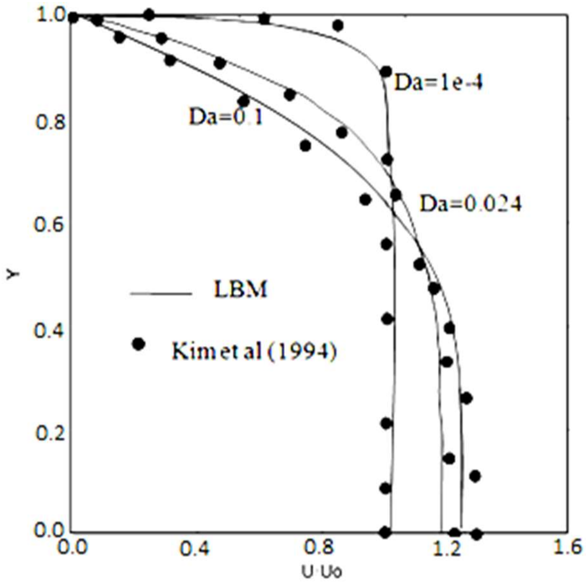


Fig.3. Velocity profile in the fully developed region porous medium for Re=70.

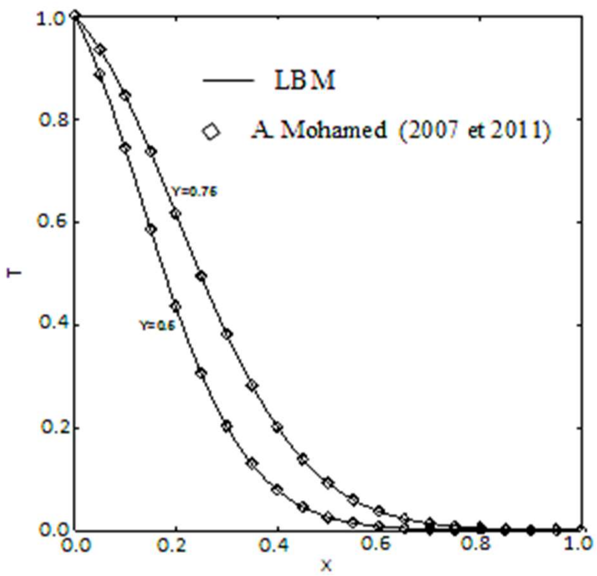


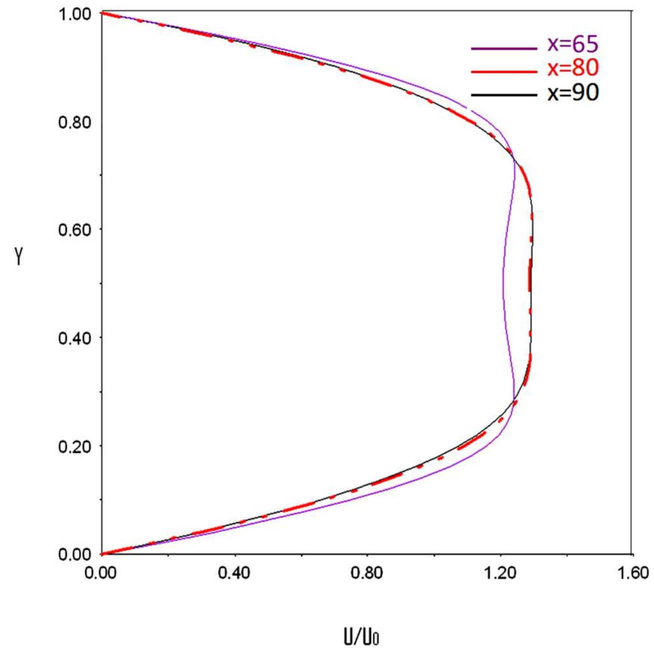
Fig.4. Temperature profile in a saturated and isotropic porous mediumRe=70, Pr=0.7.

4. Results and discussion

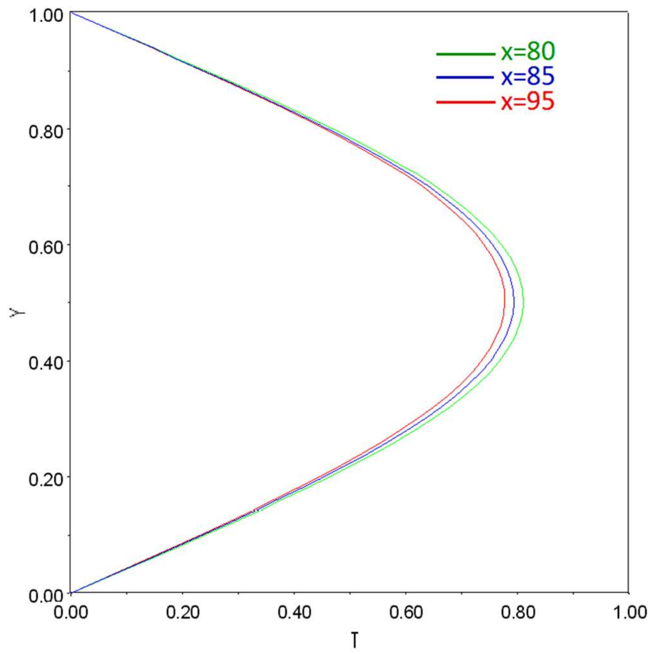
This section investigates the influence of emerging parameters on DPHEX. Some parameters are chosen to be constant such as Re=70 and Prandtl number Pr =0.7. The first porous medium of the DPHEX is between Y=0 and Y=1/2, the second middle is above. Governing equations of flow inside DPHEX have been presented in chapter 2 sections 3 and resolved using the numerical method of LBM detailed in chapter 2 sections 5.

4.1 Dynamic and thermal behaviors: case of one porous medium, SPHEX

The analysis of the heat exchanger with just one porous material inside reveals key insights into fluid dynamics and thermal behavior. Transverse velocity variation (**Fig.5.a**) shows fluid acceleration in the center and deceleration near the walls, with a dynamic boundary layer forming shortly after the inlet. As the fluid progresses, the velocity profile becomes fully developed, indicating stagnant flow. The temperature variation is shown in **Fig.5.b**. It is interesting to observe that the heat loss develops along with the fluid movement to the outlet due to the adiabatic boundary conditions. Such a trend finds confirmation in Nield and Bejan (2017) [35], which underline the key role of permeability in modulating the efficiency of the heat transport mechanism in a porous media. asymptotically decreases the temperature along the channel with a stabilization of the fixed value induced by the transverse position (Y). The temperature variation follows a parabolic profile, with the highest value in the center and a decrease toward the adiabatic walls.



-a-



-b-

Fig.5. Effect of X position for Da=0.02 (a: velocity and b: temperature)

4.2. Dynamic and thermal behavior: two porous mediums case of DPHEX

Despite similar velocity profiles, the second medium (*Da2=0.01*) exhibits a slower flow (Fig.6). A dynamic boundary layer forms, accelerate flow in the center and slowing it near the walls. At the channel inlet, the fluid moves at the same velocity in both porous media as it flows, the velocity in the first medium increases due to its higher Darcy number ($Da1 > Da2$) The velocity is reduced when one porous media is layered over another, leading to the formation of a dynamic boundary layer in both cases. The velocity profile is reduced for the porous medium with a Darcy number (Da2 = 0.01compared to the one with Da1 = 0.1**)**, can be interpreted as a result of the smaller Darcy number corresponding to **a** lower permeability and, consequently, higher flow resistance within the porous medium. As permeability decreases, the fluid encounters more resistance to flow, leading to a reduction in the velocity across the medium. Thus, the velocity is significantly lower in the medium with Da = 0.01, since the flow is more restricted. This demonstrates how permeability plays a crucial part in defining the dynamic fluid flow behavior, with lower permeability resulting in more significant velocity dips within the medium. Thermal effect is shown in Fig.7, the second porous medium retains more heat due to its lower Darcy number (*Da2=0.01,Da1=0.1*) which reduces the heat transfer. Similarly, Mahdi et al. (2020) [36]

demonstrated that a lower Darcy number leads to increased thermal resistance, reducing heat dissipation and prolonging heat retention within the media.

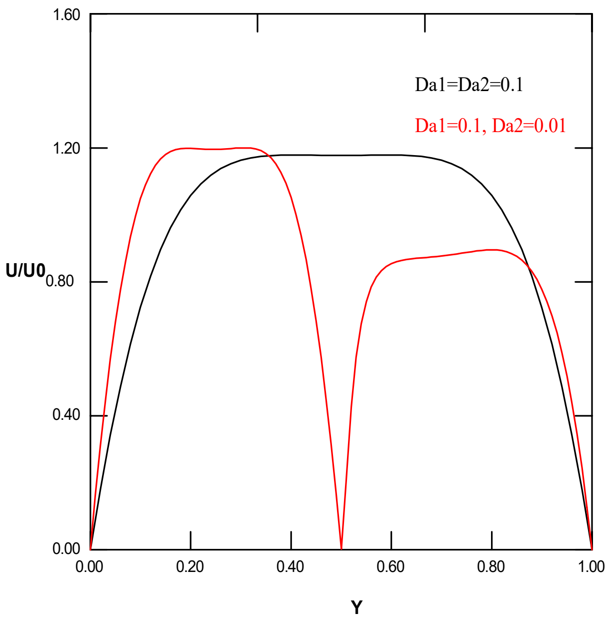


Fig.6. Effect of Darcy number on velocity profile for Re=70

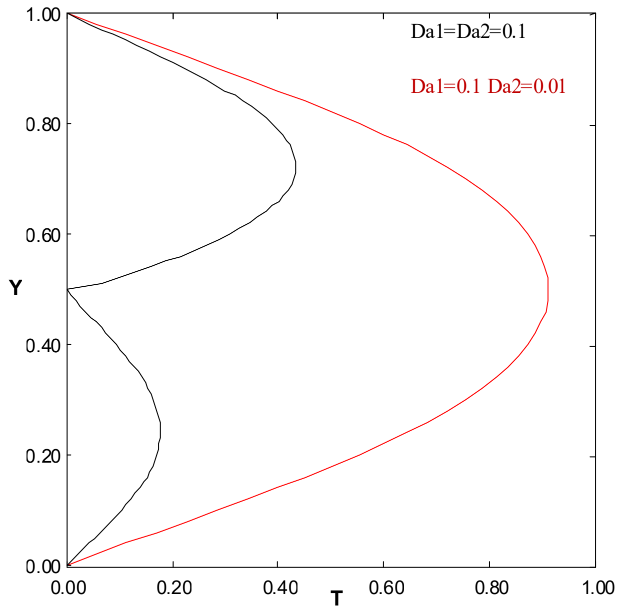


Fig.7. Effect of Darcy number on temperature profile for Pr = 0.7;Rc= 5 and Rk=10.

4.2.1 Dynamic Study

Figs 8 and 9 present the effect of the Darcy number of both used porous mediums on the velocity; higher$Da1$ results in a parabolic velocity distribution similar to Poiseuille flow, while lower Darcy numbers cause a flatter profile due to increased flow resistance. Large value of$Da2$ allows to an acceleration of the fluid in the second medium without impacting the first (Fig.10). When the Darcy numbers of the two media are swapped (Fig.9), the velocity profiles change, reflecting the contrasting hydrodynamic properties of the porous materials. This trend was presented by Wang et al., (2021) [37]. As shown for dynamic behavior Figs (8, 9 and 10), velocity is proportional to the permeability and it is independent of the number of porous media. The velocity distribution in a system composed of two superimposed porous media with distinct Darcy numbers (Da_1 and Da_2) demonstrates a strong sensitivity to permeability variations. As the importance of permeability to the effect of viscosity is reflected in the Darcy number, the greater the value of the Darcy number, the less the resistance to the passage of the fluid through the medium. In the case where $Da_1 > Da_2$, the medium with the higher permeability allows a greater rate of acceleration of the fluid with a greater gradient of the velocity profile especially around the inlet and the boundary of the flow.

On the other hand, when the Darcy number is smaller (Da2), traversing the second medium, where permeability is smaller, increases the fluid flow resistance in that medium. As a result, fluid flows slowly since it is impeded by the reduced pore space and tortuous path offered by the porous medium, hence a lower velocity profile. The fluid flow behavior in the second medium is therefore more dominated by viscosity, and consequently, the fluid velocity is greatly reduced as it moves through the smaller pores. In addition, the interaction between the two mediums is affected by their permeability, hence creating a discontinuity of the velocity profile at the interface. This illustrates how the permeability contrast between two mediums affects fluid flow dynamics and the location of the velocity profile, where the medium that has greater permeability (Da1) controls fluid flow behavior.

This concludes that the role of the Darcy number is important as a tool that determines how fluid flow is affected by medium properties, as illustrated when two superimposed porous media

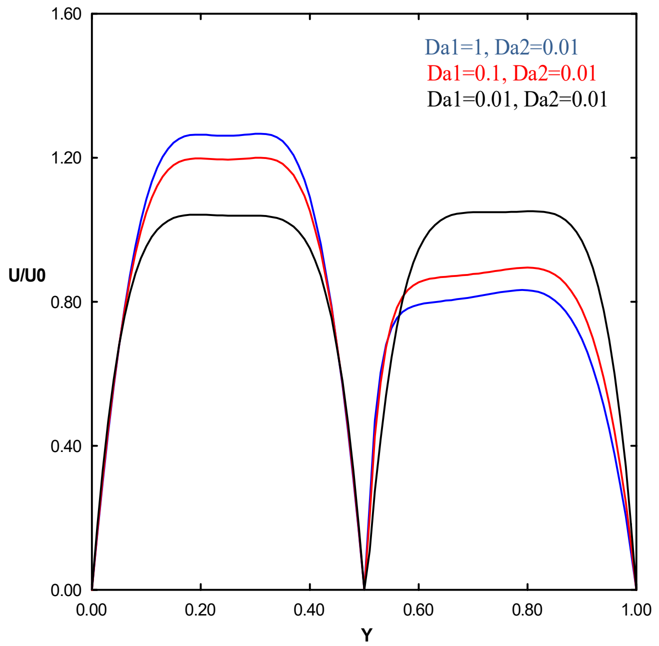


Fig.8. Effect of Da1 on velocity profile for Da2=0.01.

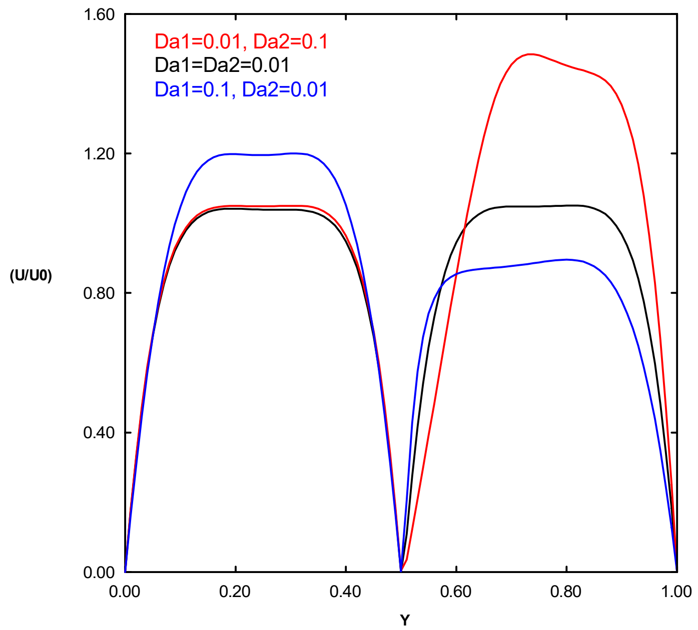


Fig.9. Effect of porous medium location: (case 1: medium with Da =0.1above medium with Da=0.01) - (case2: medium with Da =0.1 below medium with Da=0.01).

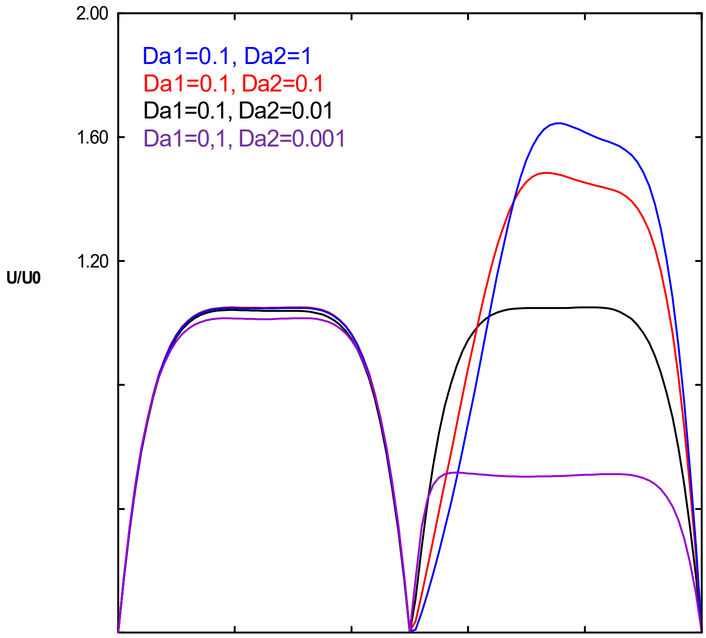


Fig.10. Effect of Da2 on the velocity profile for Da1=0.1.

4.2.2 Thermal Study

The thermal behavior in DPHEX is characterized by a nonlinear interaction between permeability identified as Darcy number (Da), solid to fluid thermal conductivity ratios identified with Rk, and thermal resistance ratios identified with Rc. As highlighted in Figure 11, a high Darcy number significantly improves convective transport, which in turn favors fluid flow in the more permeable region. As a result, there is greater heat transport in the axial direction, and consequently, there is a relatively even temperature distribution. The system changes from diffusion control to advection-dominated transport, where the influence of the fluid inertia begins to dominate the viscous forces, especially in the vicinity of the inlet. **Fig. 12** portrays the influence of the ratio parameters Rk1 and Rk2, representing the ratio of the solid matrix to the fluid phase in each porous medium of the DPHEX on the axial heat conduction in the porous media. A higher value of Rk represents higher solid-phase conduction, enabling the porous medium to act as a heat bridge. The results signify that the higher the solid-phase conduction, the higher the heat transport through the porous media along the axial direction. The results validate the principles of the effective thermal conductivity concept for the porous composites, where the increase in the solid-phase conduction results in the enhancement of the heat transport. **Figs 13** portrays the influence of the heat capacity ratio, Rc, on the heat transport in the double porous heat exchanger. The variation in the ratio parameter Rc1 produces substantial influence on both porous media. The increase in the ratio parameter Rc1 increases the interaction between the solid and fluids in the first porous medium, thus increasing the effect on the fluids entering the second porous medium. As such, the initial condition generated in the first medium varies due to the increase in heat transport due to the increase in solid-fluid interaction in the first medium. On the contrary, the influence brought by the variation in the ratio parameter Rc2 on the first porous medium remains negligible due to the unidirectional flow and adiabatic interface, thus preventing the reverse effect of the heat transport due to the heat exchanger. All of these observations clearly indicate a very strong coupled thermal phenomenon between the two porous media, wherein the properties of one layer are actually influencing the other (Tab1). Such a scenario clearly does not comprise two separate mediums but rather functions as a combined unit with a thermal connection, wherein the associated boundary conditions and characteristics influence the temperature distribution at a local as well as a global level. This basic principle lays the foundation for new and innovative designs wherein the characteristics of the first layer influence and optimize the performance characteristics of the second layer containing the heat exchanger system with layered porous structures.

Effect of Da1, Rc1, Rk1 on Thermal Behavior of the Second Medium

When there is a change in either the Darcy number, heat capacity ratio, or the thermal conductivity ratio in the first porous medium, this greatly affects the second medium's thermal response since there is fluid and thermal current continuity. As Da1 increases, there is greater fluid velocity and greater convective heating transfer, resulting in a better thermally equilibrated fluid that enters the second medium. As Rc1 changes, it affects how well there is energy interaction between or within the solid and fluid phases in the first medium, with greater Rc1 meaning less interaction, and therefore a less thermally equilibrated fluid that enters the second medium. As Rk1 also increases, there are better conductive qualities in the solid phase, and this aids in better heat distribution and greater thermal conditioning of the fluid before it enters the second medium. Such conditions in the second medium are solely dependent on the temperature and heat transfer properties set by these conditions before their initial flow and heating transfer.

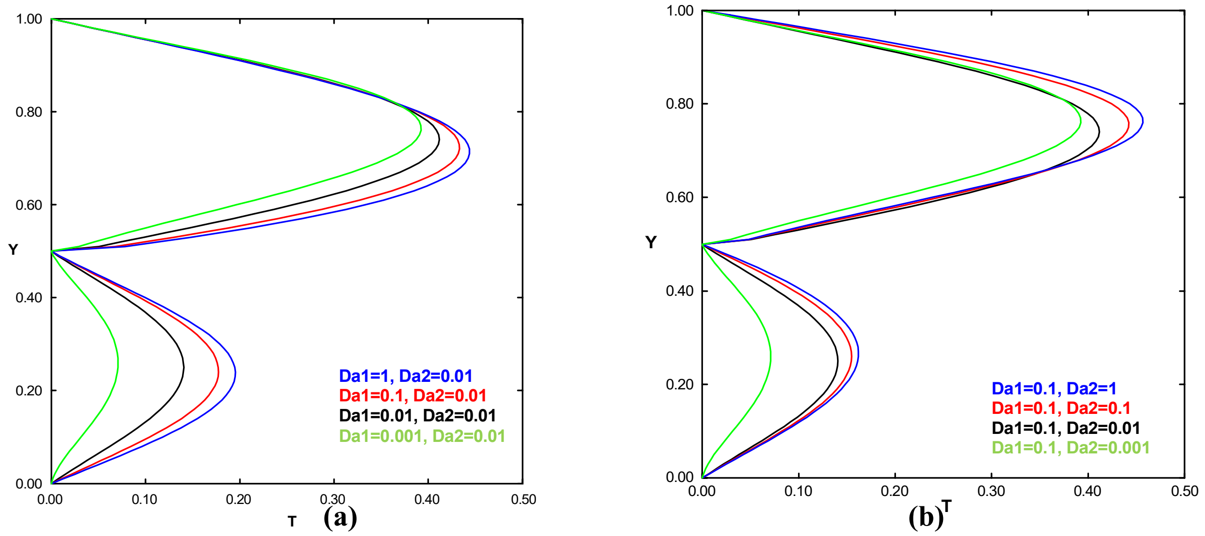
Effect of Da2, Rc2, Rk2 on Thermal Behavior of the First Medium

Conversely, variation in any one of the parameters Da2, Rc2, or Rk2 in the second porous medium does not affect or only slightly affects the behavior of the first porous medium. The lack of effect of the second porous medium on the heat behavior in the first porous medium can be attributed to the one-way nature of the flow of the fluid between the porous media. Because no heat is transferred back to the media in the interface, and the flow is from the first to the second porous media, the heat memory moves forward but not backward. A one-way heat interaction is thus experienced, whereby downstream conditions influence upstream performance but not otherwise. The layout is meant to provide an effective heat conditioning in the first media, which is then responded to in the second media.

In summary, these experiments demonstrate well the significance of modeling flow dynamics in parallel with thermal transport in composite porous media. The flexibility afforded by adjusting parameters such as Da, Rk, and Rc allows for specific thermal functionality to be achieved, either for insulation function, rapid spreading, or specific resistance. This allows for the development of porous heat transfer surfaces in innovative ways that go beyond traditional porous media-based approaches

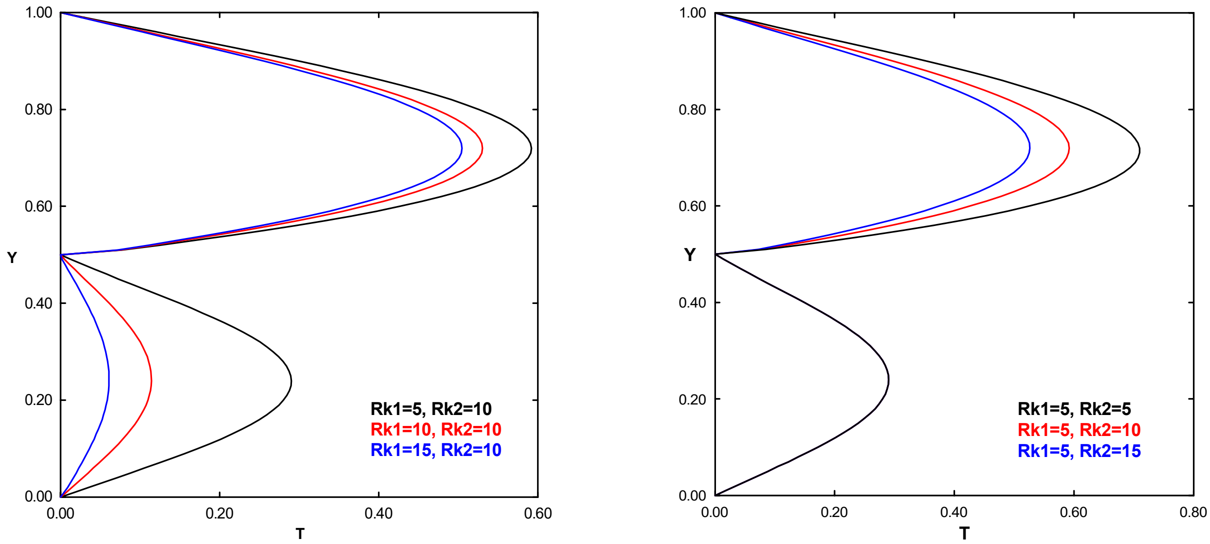
Optimal Parameter Combinations for Enhanced Heat Transfer

In such heat exchangers filled with two porous mediums, a proper selection of the interaction of the upstream and downstream parameters becomes important for optimal thermal performance. For instance, high permeability large Da1 and solid-phase conductivity high Rk1 of the first medium ensure effective energy transport and fluid thermal conditioning before entering the second medium. It is advisable that Rc1 take a moderate value for a proper fluid-solid energy exchange. The properties of the second medium, Da2, Rc2, and Rk2, may be optimized for enhancements in local heat transfer, yet its effect remains confined to the second medium due to the absence of thermal feedback. Therefore, designing the first porous medium as a highly conductive and convectively active zone is critical for improving the overall performance of the exchanger, while the second medium should be tailored to exploit the pre-conditioned thermal field for maximum localized heat transfer.



(a) (b)

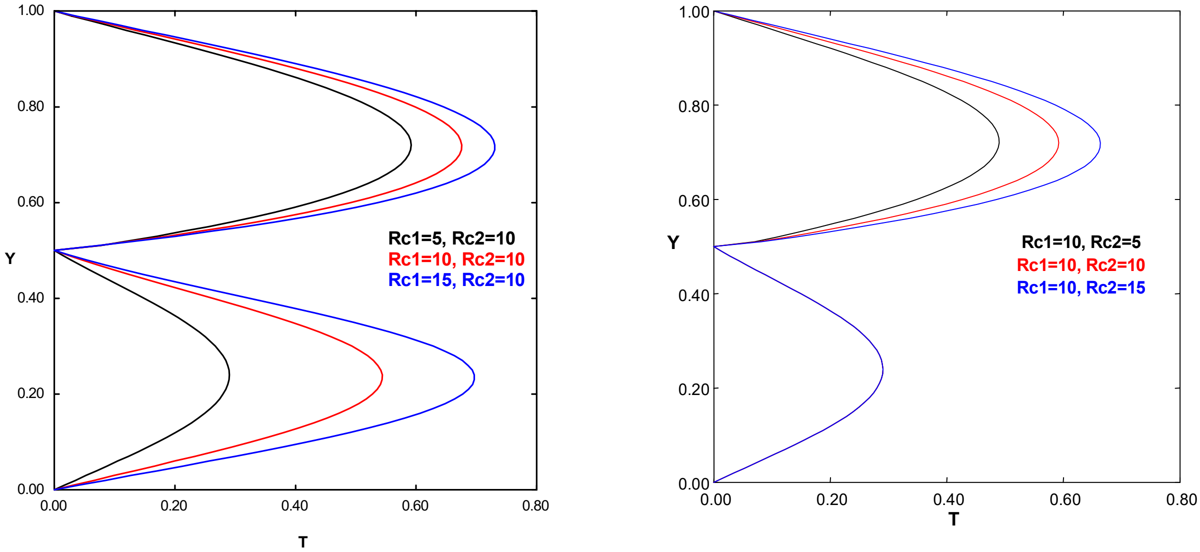
Fig.11.Effect of the Darcy number on the temperature profile for Rc1=5, Rc2=10, Rk1=5, Rk2=10, Pr =0.7 (a: Da2 fixed and Da1 changes, b: Da1 fixed and Da2 changes)



(a) (b

Fig.12. Effect of Thermal conductivity ratio (Rk) on the temperature profile for Pr = 0.7; Da1=0.1; Da2=0.01; Rc1=5; Rc2=10.

(a: Rk2 fixed and Rk1 changes, b: Rk1 fixed and Rk2 changes)



(a) (b)

Fig.13. Effect of the Heat capacity ratio (RC) on the temperature profile for Pr = 0.7; Da1= 0.1; Da2= 0.01; Rk1=5; Rk2=10
(a: Rc2 fixed and Rc1 changes, b: Rc1 fixed and Rc2 changes)

Table 1: Thermal Effect of Da, Rc and Rk

Parameter	***Affects Medium 1***	***Affects Medium 2***	***Explanation***
Da1	☑ Yes	☑ Yes	Strength convective and thermal transport in second medium
Rc1	☑ Yes	☑ Yes	Modifies thermal coupling and output fluid temperature
Rk1	☑ Yes	☑ Yes	Influences thermal diffusion upstream and affects thermal behavior in second fluid
Da2	✗ No	☑ Yes	Downstream permeability does not influence upstream flow or temperature
Rc2	✗ No	☑ Yes	Changes in second medium's convection resistance only affect itself
Rk2	✗ No	☑ Yes	Downstream thermal conductivity doesn't influence upstream due to adiabatic boundary

4.2.3. Energy storage

We consider a DPHEX made up of two porous media with Da1=0.1 and Da2=0.01. The hot fluid enters the DPHEX; a quantity of heat is transmitted to the solid matrix by sensitive transfer. The quantity of energy stored is given by the expression next (Singh et al.2008) [38].

$$E_{Stored} = E_{in} - E_{out}$$
$$E_{Stored} = \iint \dot{m}\, C_P (T_{in} - T_{out}) dS_m$$
$$E_{Stored} = \iint \rho\, C_P ((uT)_{in} + (uT)_{out})$$

The hot fluid transfer heat to the solid matrix, with the stored energy decreasing over time as the temperature gradient decreases, leading to system homogenization. The stored energy inside the DPHEX is higher compared to a single media, with a Darcy number of 0.01, emphasizing the importance of permeability and porosity for better energy storage as illustrated in Fig.14: In DPHEX, the hot fluid transfers heat to the solid structure, and as the temperature difference diminishes over time, the system gradually reaches thermal balance. When two different porous used (Da1 = 0.1 and Da2 = 0.01): The medium of higher Da1, will conduct the fluid to flow fast, hence energy stored is released sooner. While the medium with lower Da2, reduces the velocity of flow, allowing it to retain energy longer and release more slowly. This combination provides a layered energy dissipation profile: a fast release of energy in the more permeable region and extended storage in the less permeable one, enhancing overall system performance compared to a single porous medium.

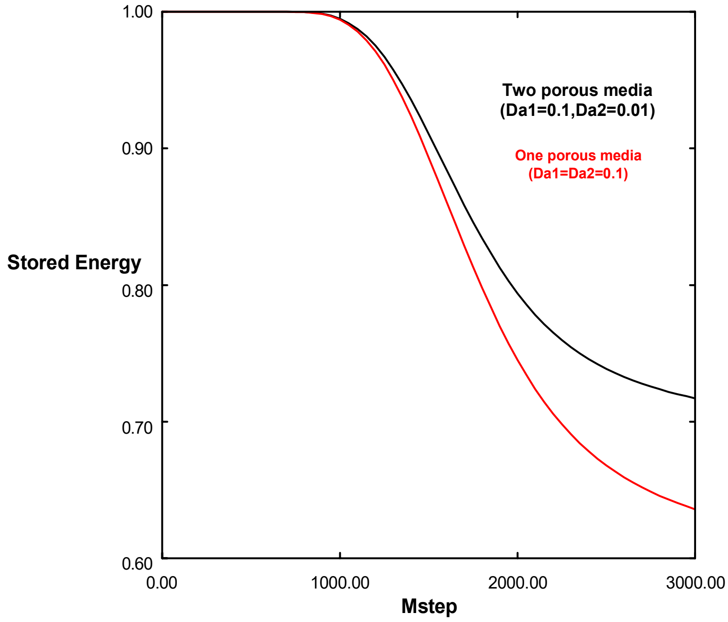


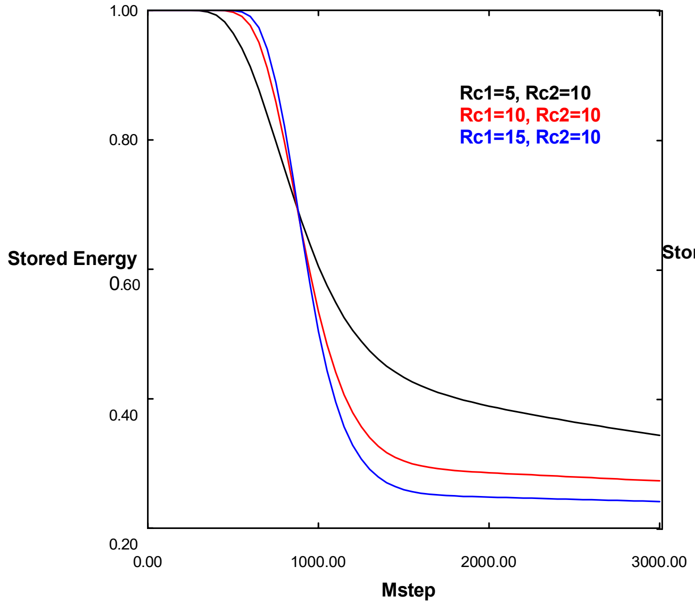
Fig.14. Temporal energy storage for Rc1=5, Rc2=10, Rk1=5, Rk2=10

The energy profile (Fig15), in the DPHEX has a nonlinear curve with the inflection point: Critical point.

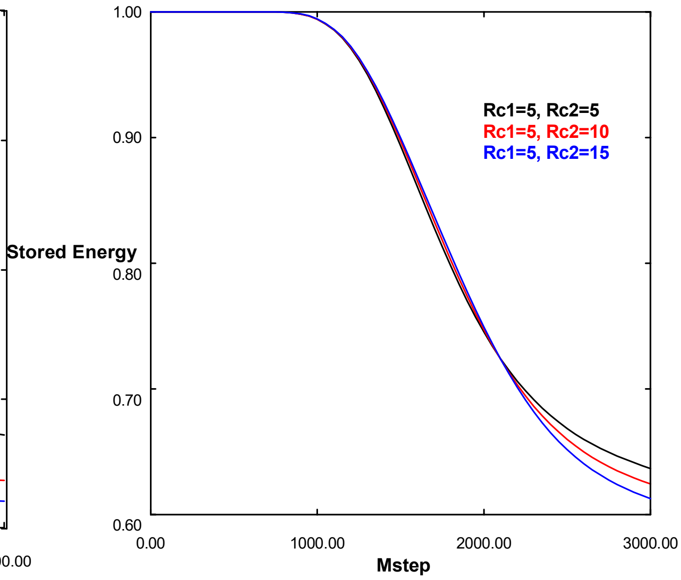
Initial Phase (Decreasing Energy with Higher Rk and Lower RC): In the initial phase, energy remains decreasing as a result of an increase in Rk, or the ratio of thermal conductivity, and a decrease in RC, or the ratio of heat capacity. The increase in Rk enhances conductive transfer, resulting in faster dissipation of heat energy from the porous medium. As a result, since it is able to conduct heat energy better, it also qualifies as a medium that is able to lose energy faster as it rapidly decreases its energy due to efficient dissipation. The decrease in RC causes a reduction in energy ability, as it decreases the ability to store a certain amount of heat energy corresponding to a unit temperature variation. As a result, it also qualifies as a medium that is less capable as it absorbs minimal energy, hence decreasing the energy.

Critical Point: This is the point at which the trend will reverse. Prior to this critical point, because of the increase in Rk while simultaneously reducing RC, there is a net decrease in the stored energy. After the critical point: An increase in Rk values may no longer cause an increase in the heat loss rate. In fact, beyond a critical point, instead of relying on the efficient heat loss, the capability to conduct heat may cause the uniform spreading of energy in the medium, eventually increasing the efficiency of the energy-storing process. An increase in RC values may make the medium less efficient in storing energy; however, beyond a critical point, this may help in effectively storing the energy as the medium will attain a balanced state in managing heat flow as well as storing heat.

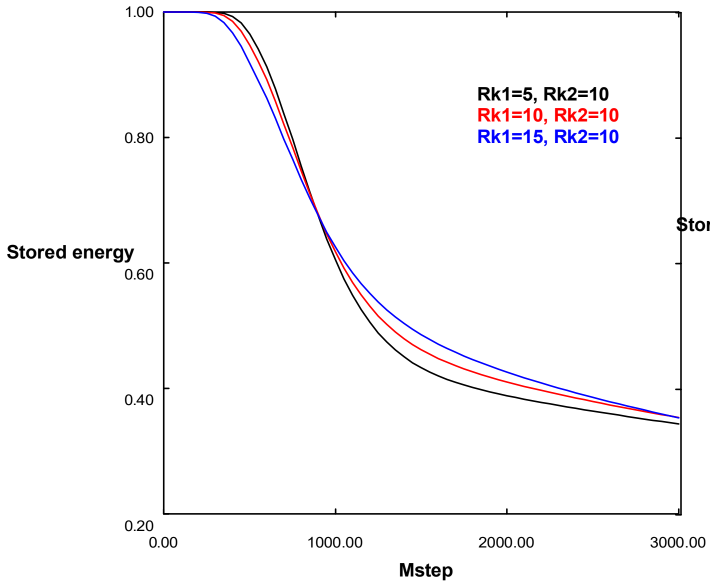
Post-Inflection Phase (Increasing Energy with Higher Rk and Lower Rc): After the inflection point, there is an increase in the energy being stored because of the increase in the value of the thermal conductivity ratio (Rk) and the subsequent reduction of the heat capacity ratio (Rc). A higher value of Rk, which indicates stronger heat conductivity properties, may notably increase the rate of heat transfer, which enables the energy to be transmitted through the medium more efficiently. Rather than there being too much heat being lost, there is an increase in the rate of energy being stored. A low value of Rc would increase the efficiency of energy being stored because the medium would readily take the heat, which would not overload the medium.



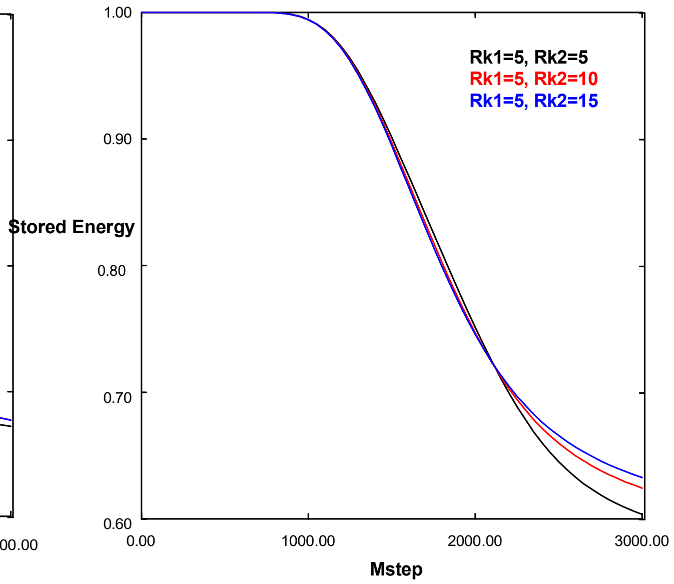
-a- Rc2 fixed



-b-Rc1 fixed



-c- Rk2 fixed



-d-Rk1 fixed

Fig.15. Temporal energy stored (a: different Rc1 value; b: different Rc2 value; c: different Rk1 value; d: different Rk2 value)

4.2.4. Performance study

The solar SDPHEX assist the refrigeration cycle by reducing compressor work great design for energy efficiency and performance improvement. The heat exchanger attributed to the system, the ability to use solar radiation to preheat the working fluid, thereby reducing the electrical load on the compressor. In what follows, we will study the performance of our system (illustrated in Fig.1) and compare it to the conventional model of air conditioner (eliminate porous heat exchanger, the expansion valve and the solar panel from system).

In this section we use RETSCREEN SOFTWARE to visualize the performance of air conditioner's systems.

Considering solar radiation data in Tunisia (Marsa, North of Tunisia) (Fig.16), results clearly prove that the solar AC system with a porous heat exchanger outperforms the conventional AC system in terms of efficiency, especially during months with high solar radiation. The monthly solar radiation peaks during the summer, enabling the solar-assisted system to store more thermal energy and operate at a higher COP (Coefficient of Performance). This stored energy enhances system autonomy and reduces dependence on external power sources. In comparison, the conventional AC system maintains a relatively constant but lower COP throughout the year, as it lacks the benefit of renewable energy input and advanced heat exchange. Notably, while both systems experience reduced performance in winter due to lower solar availability, the solar AC system still maintains competitive efficiency. Fig 17 and 18.

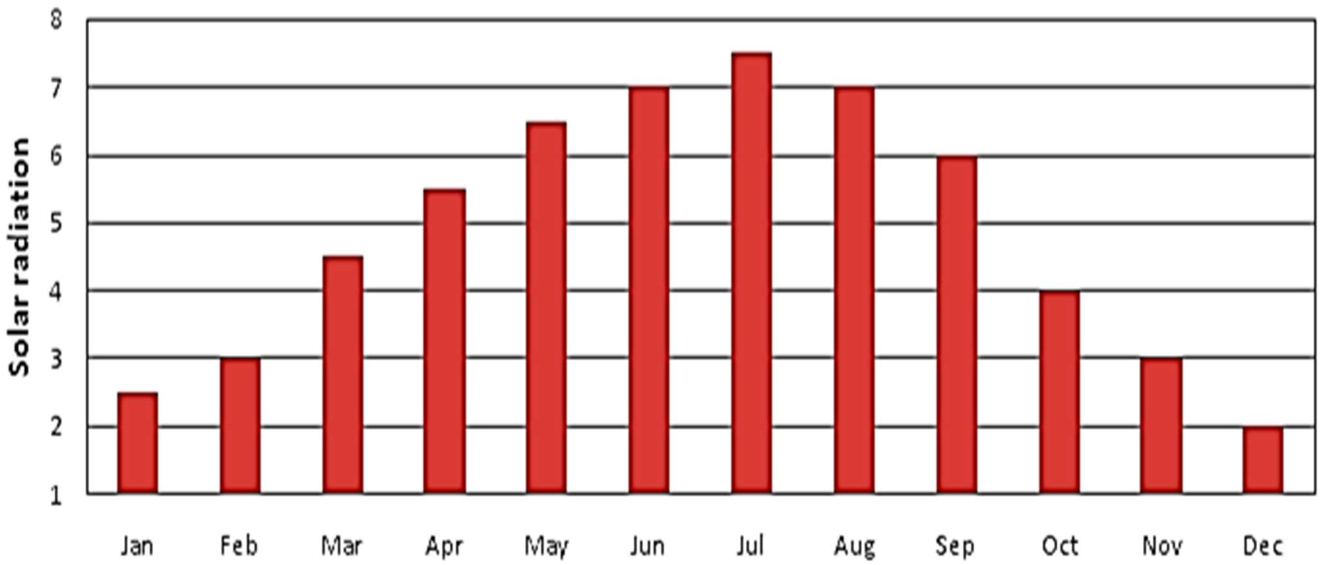


Fig.16. Variation of solar radiation (kWh/m²) in Marsa region-Tunisia [40]

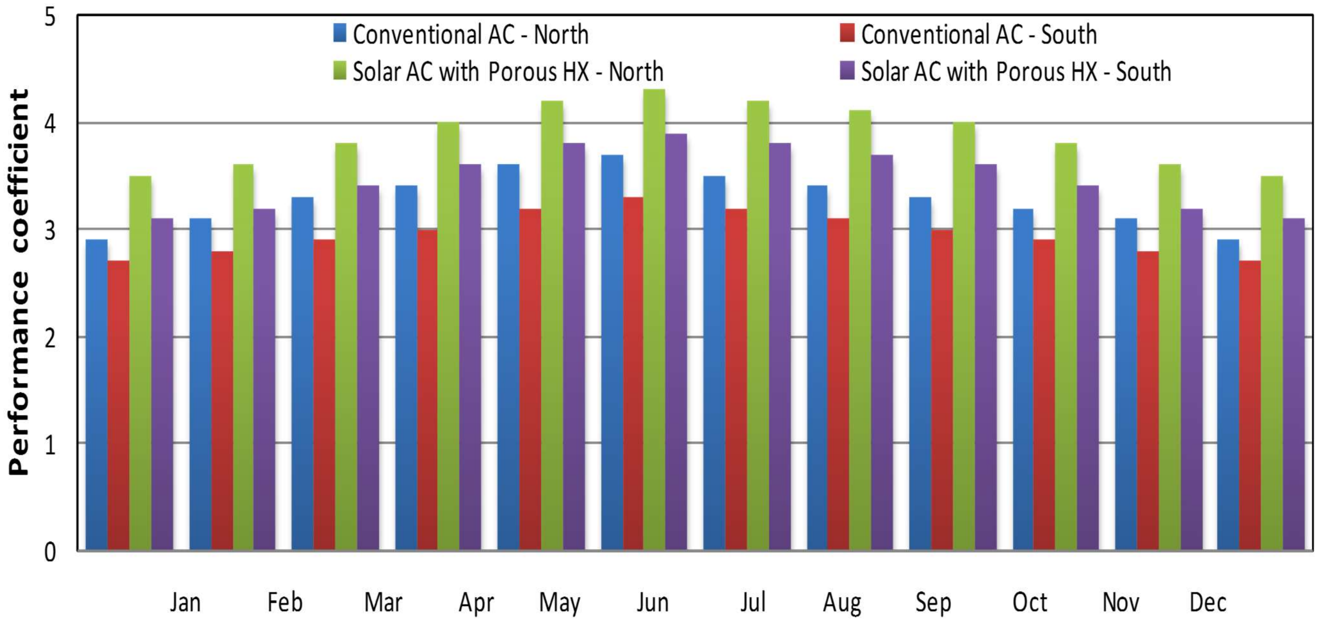


Fig.17. Monthly variation of air conditioning performance coefficient according to type of system and location (North or south) in Tunisia.

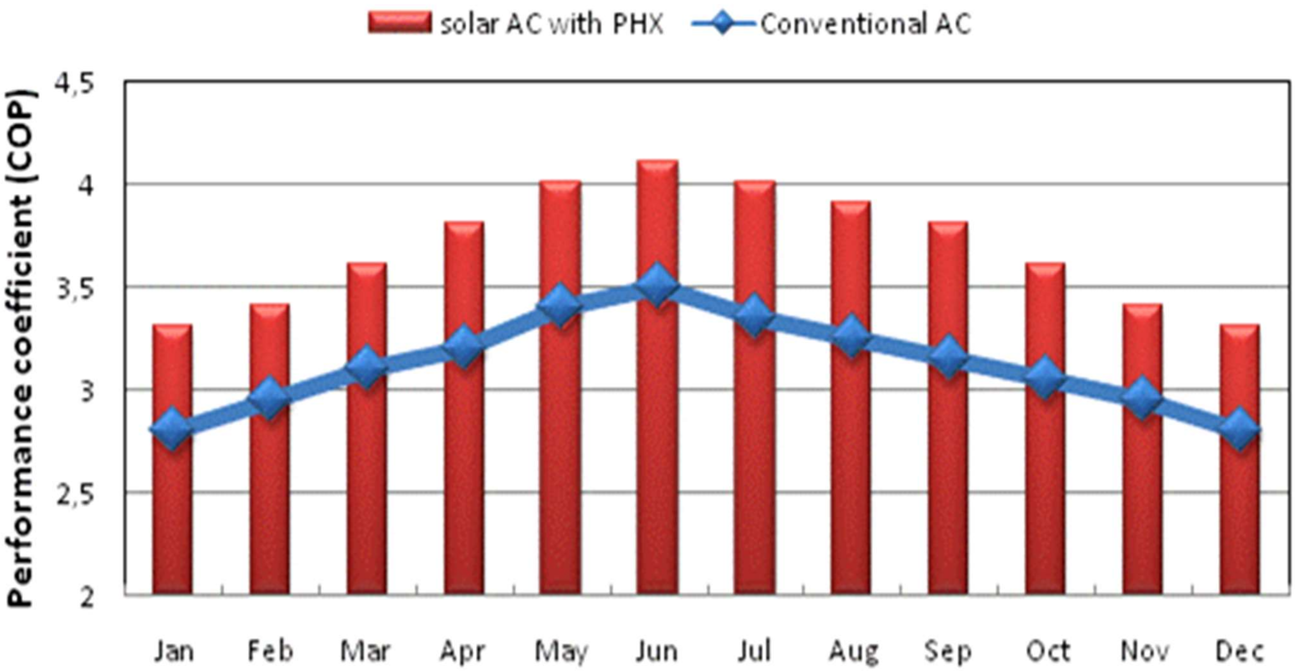


Fig.18. Average (North or south) variation of air conditioning performance coefficient in Tunisia

Based on a monthly comparative analysis using climatic data sourced from NASA Surface Meteorology and Solar Energy database [41], the Solar AC system integrated with a porous heat exchanger (PHX) demonstrated a significant energy advantage over the conventional air conditioning system Fig 19 and 20. The study revealed that the Solar AC with PHX achieved an average energy savings rate of 4–13% depending on the season, with the highest gains observed during peak solar months such as June to August. In terms of Energy gain**,** the solar-assisted system consistently outperformed the conventional AC across all months, particularly in summer, with COP values improving**.** These results highlight the efficiency and sustainability of the Solar AC system, confirming its suitability as a cleaner and more energy-gain (up to 20%) alternative to conventional cooling technologies, especially in regions with high solar availability like Tunisia (in south). Overall, the solar AC system with PHX shows superior seasonal adaptability, greater energy savings, and improved performance compared to the conventional AC system

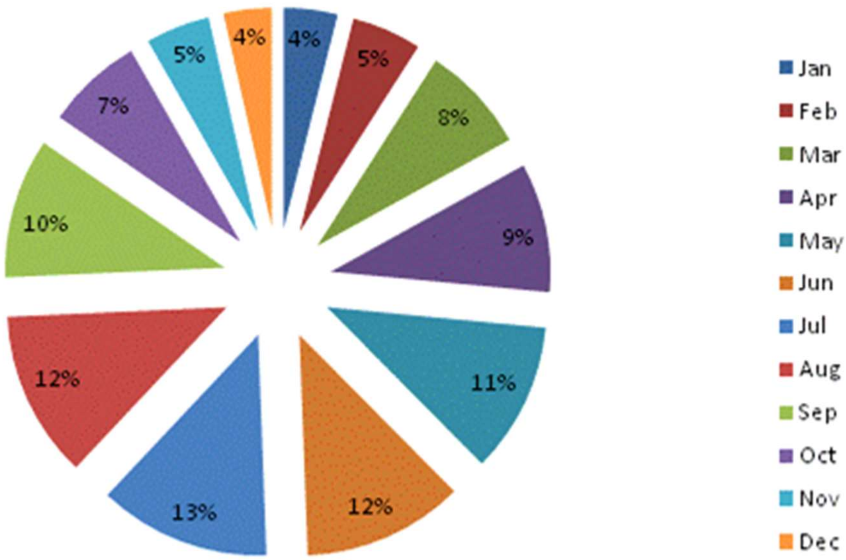


Fig.19. Average contribution of solar energy to total air conditioning consumption - solar AC with PHX in Tunisia (Marsa)

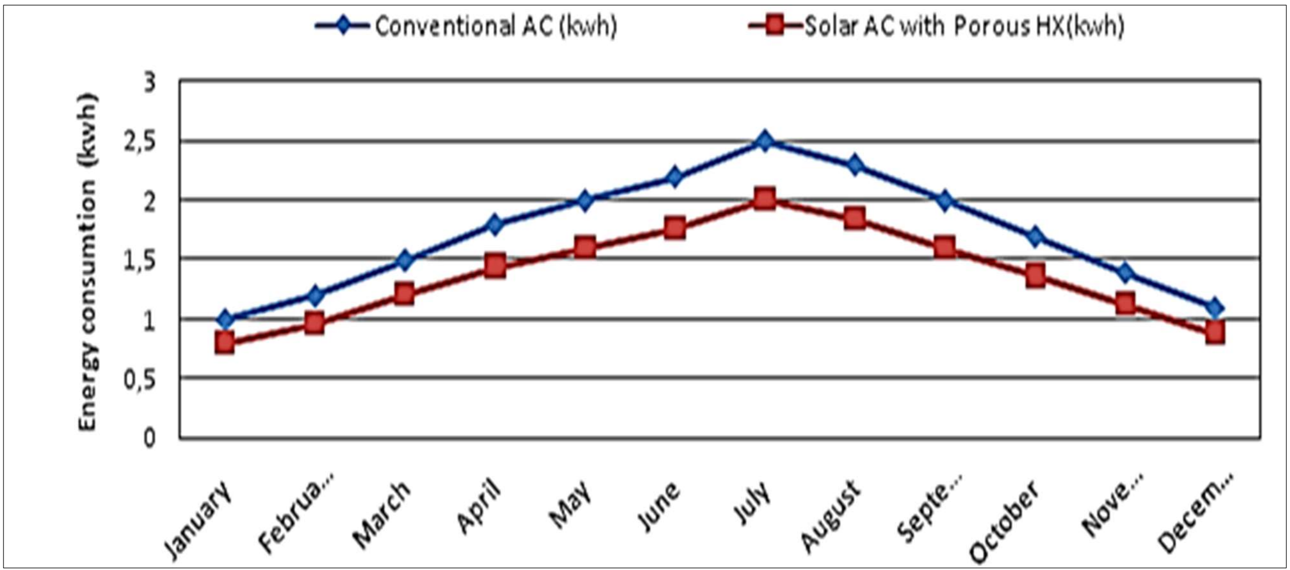


Fig.20. Energy consumption- Conventional air conditioning Vs Solar AC with PHX- Marsa-Tunisia. Cooling capacity 3.5kW

The proposed solar air conditioning system, apart from its performance in terms of energy consumed, presents positive effects on the environment when compared to the conventional solar system as presented in **TAB2**.

Tab2. Environmental effect of conventional AC vs solar SDPHEX

Cooling capacity (kW)	Refrigerant Used(kg) Conventional AC	GWP Conventional AC	GWP Impact(kgCO2-eq) Conventional AC	Refrigerant Used(kg) SDPHEX	GWP SDPHEX	GWP Impact(kgCO2-eq) SDPHEX
2	0.6	2088	1252.8	0.4	2088	835.2
4	1.2	2088	2505.6	0.8	2088	1670.4
6	1.8	2088	3758.4	1.2	2088	2505.6
8	2.4	2088	5011.2	1.6	2088	3340.8
10	3.0	2088	6264.0	2.0	2088	4176

In solar-assisted air conditioning system, the quantity of refrigerant used is reduced compared to a conventional system because the refrigerant is preheated using solar energy before entering the compressor. This reduces the work the compressor needs to do in raising the refrigerant's pressure and temperature, as it starts at a higher temperature thanks to the solar heat stored in the heat exchanger. As a result (Tab.2), the system requires less refrigerant to achieve the same cooling capacity because the refrigerant is already closer to the desired thermodynamic conditions. This leads to a more efficient use of refrigerant, lowering the overall mass needed while maintaining effective cooling performance and reducing GWP [42] impact.

Figs 21-23, presenting environmental impact, clearly shows that the solar AC system with porous heat exchanger significantly outperforms the conventional AC system in terms of sustainability. By utilizing solar thermal energy and improving heat transfer efficiency, the system reduces reliance on electrical power, leading to a notable decrease in CO_2 emissions up to 20% less across various cooling capacities. Additionally, since the solar-assisted design reduces compressor workload, the required refrigerant mass is also lower compared to conventional systems. This not only minimizes the environmental risks associated with refrigerant leaks (which contribute to global warming and ozone depletion) but also enhances the system's overall eco-friendliness. Together, these factors make the system a cleaner, more energy efficient solution with a smaller carbon footprint, aligning better with global environmental goals.

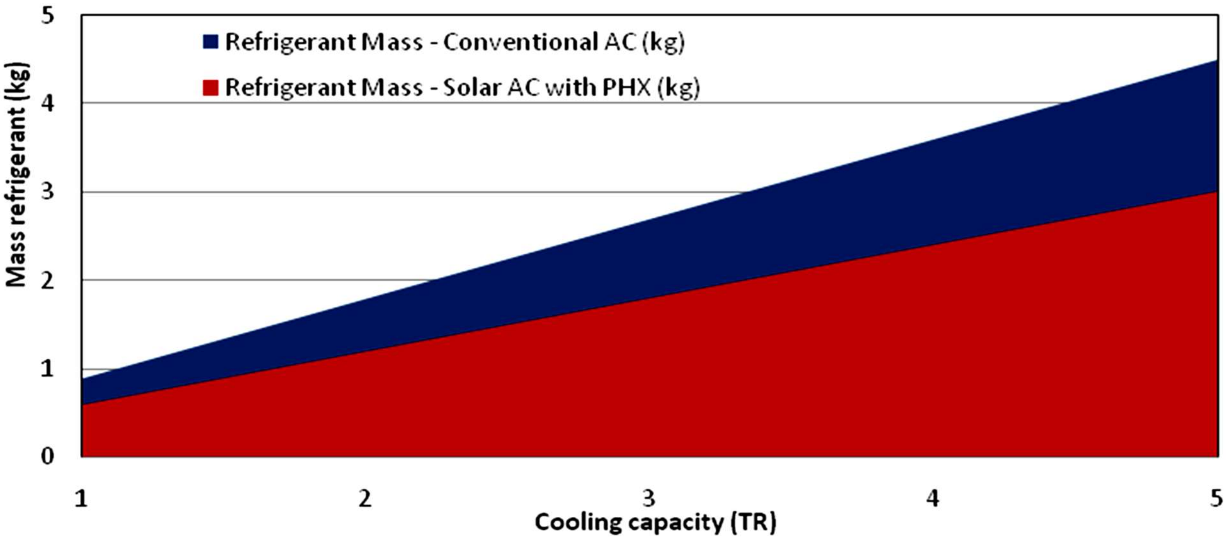


Fig.21. Amount of refrigerant quantity used per system type based on cooling power

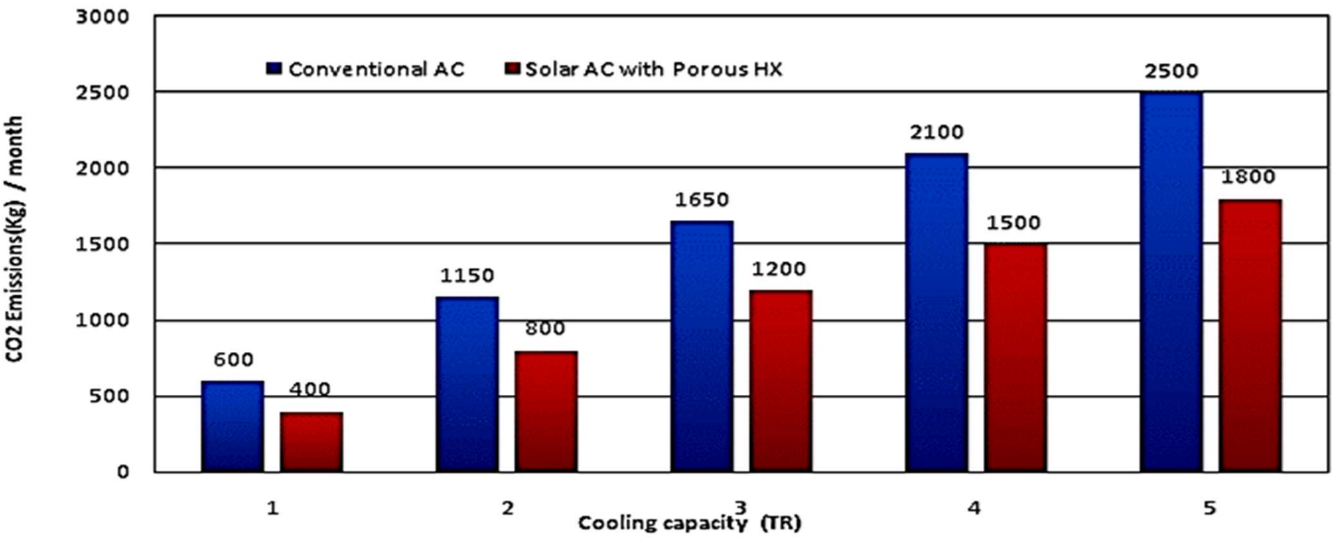


Fig.22. Amount of quantity of CO2 emitted by type of system depending on the cooling power per system type based on cooling power

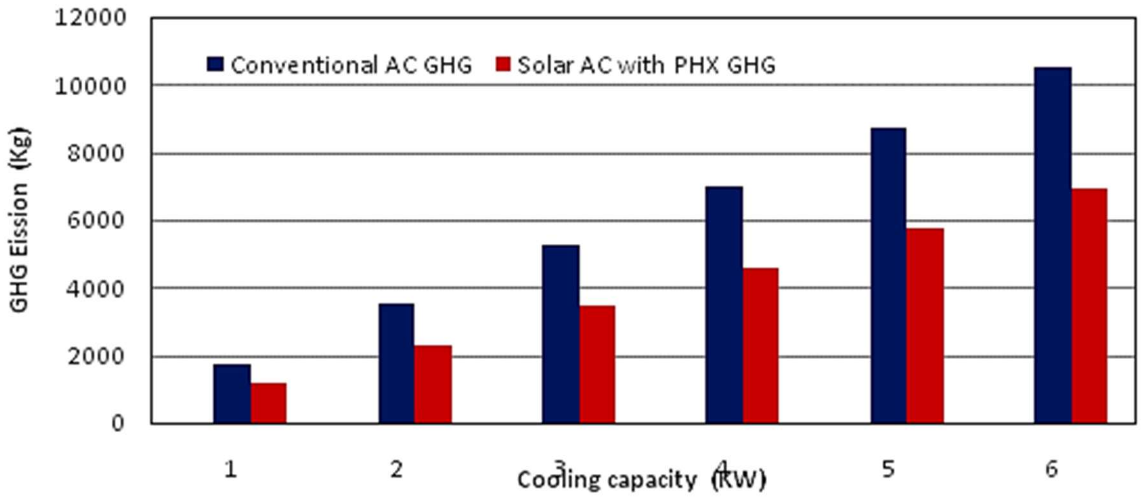


Fig.23. Amount of quantity of CO2 emitted by type of system depending on the cooling power per system type based on cooling power

5. Conclusion

In the present study, a numerical simulation was performed for fluid flow and heat transfer phenomenon of a solar heat exchanger involving two porous mediums, SDPHEX. This paper focuses on the effect of variables like Darcy number, thermal conductivity ratio, and thermal capacities ratio. The behavior will be examined using the thermal Lattice Boltzmann approach. The following are the most important conclusions of the present study as have been obtained by the numerical solutions:

• The use of two porous media of different permeability (Darcy numbers) results in a dynamic system where the quicker fluid flow in the porous medium (higher Darcy number) can be controlled or retarded by the other porous medium with lower Darcy numbers. This multi-medium system enables the efficient flow regulation of fluid flow, thus improving the efficiency of fluid flow. The quicker fluid flow in the porous medium is easily controllable by the other fluid flow.

• For optimal performance of a heat exchanger involving two superposed porous media, it is critical to optimize both downstream and upstream conditions. Higher permeability (Da1) and solid conductivity (Rk1) of the first medium aid convective transport and pre-condition the fluid going into medium 2. Moderately large convective resistance (Rc1) is also desirable to facilitate efficient energy transfer between the fluid and solids, where there is no delay in temperature variations. Even though parameters Da2, Rc2, and Rk2 in medium 2 influence local temperature distributions, they do not contribute to upstream conditions, as medium 2 is adiabatically contacted, and fluid flow is unidirectional. The first medium is, therefore, dominant in global heat transfer, and medium 2 optimizes local heat transfer performance. Optimization of the first medium's ability to pre-condition temperature is, therefore, critical for efficient global performance.

• The use of multiple media allows for better thermal management, thereby improving performance in air conditioning. Through the selection of porous media with diverse properties, our design is capable of meeting particular needs. This is because it strives to create an ideal balance in terms of storage of energy, transfer of heat, and regulation of fluids.

• For Energy saving, the performance of the solar-assisted system was invariably greater than that of the conventional AC, and this was evident in all months of the year, especially during the summers, with a marked improvement in the COP values. The results obtained showcased the effectiveness and sustainable aspects of the Solar AC, which may be an ideal and energy-saving solution by up to 20% even to the conventional cooling systems.

• Increased solar energy application and enhanced cooling through the porous heat exchanger improve the entire setup and even increase the cooling ability of the setup by as much as 33% while requiring only less refrigerant. This is crucial since the environment is protected from the refrigerant.

• The SDPHEX reduces CO_2 equivalent emissions by 20-33% compared to all other tested cooling capacities. The reduced mass of the refrigerants coupled with the minimized electrically driven compression usage make the technology more environmentally friendly, in line with global sustainability goals.

Future research avenues include the experimental validation of the proposed model in a real working environment, optimizing the configurations of the porous media, and testing the reliability of the system. The applicability of the technology of solar-assisted cooling can be extended by expanding the concept to hybrid renewable energy systems.

References

[1]. Davis, L. W., & Gertler, P. J. (2015). Contribution of air conditioning adoption to future energy use under global warming. *Proceedings of the National Academy of Sciences*, 112(19), 5962–5967.

[2]. International Energy Agency (IEA). (2021). *The Future of Cooling: Opportunities for Energy-efficient Air Conditioning*. IEA Publications.

[3]. European Environment Agency (EEA). (2020). *Cooling demand projections and energy impacts in Europe: 2030 outlook*. EEA Technical Report.

[4]. Velders, G. J. M., Fahey, D. W., Daniel, J. S., McFarland, M., & Andersen, S. O. (2009). The large contribution of projected HFC emissions to future climate forcing. *Proceedings of the National Academy of Sciences*, 106(27), 10949–10954.

[5]. Dincer, I., & Rosen, M. A. (2021). *Exergy: Energy, Environment and Sustainable Development* (3rd ed.). Elsevier.

[6]. IPCC. (2022). *Climate Change 2022: Impacts, Adaptation and Vulnerability*. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

[7]. Kalogirou, S. A. (2023). *Solar Energy Engineering: Processes and Systems* (2nd ed.). Elsevier.

[8]. Duffie, J. A., & Beckman, W. A. (2013). *Solar Engineering of Thermal Processes* (4th ed.). Wiley.

[9]. Almasri, R. A., Abu-Hamdeh, N. H., Esmaeil, K. K., &Suyambazhahan, S. (2022). Thermal solar sorption cooling systems A review of principle, technology, and applications. *Alexandria Engineering Journal*, 61(1), 367–402.

[10]. Kalogirou, S. A. (2014). Solar thermal collectors and applications. *Progress in Energy and Combustion Science*, 30(3), 231–295.

[11]. Chidambaram, L. A., Ramana, A. S., Kamaraj, G., & Velraj, R. (2011). Review of solar cooling methods and thermal storage options. *Renewable and Sustainable Energy Reviews*, 15(6), 3220–3228.

[12]. Alva, G., Lin, Y., & Fang, G. (2018). An overview of thermal energy storage systems. *Energy*, 144, 341–378.

[13]. Pati, S., Borah, A., Boruah, M. P., &Randive, P. R. (2022). Critical review on local thermal equilibrium and local thermal non-equilibrium approaches for the analysis of forced convective flow through porous media. *International Communications in Heat and Mass Transfer*, 132, 105889.

[14]. Chen, C., Zhang, J., & Wu, S. (2024). Development of a solar-driven desiccant air conditioning system: performance and environmental impact analysis. *Energy Reports*, 10, 1220–1235.

[15]. Rebelo, P., Gomes, J., & Silva, M. (2024). Comparative study between photovoltaic-powered and conventional air conditioning systems. *Renewable Energy*, 218, 1320–1330.

[16]. Adam, M., Ben Salah, K., &Kairouani, L. (2023). Performance analysis of R290-based air conditioning systems integrated with renewable energy sources. *Applied Thermal Engineering*, 215, 119178.

[17]. Mukhtar, M., Omer, S., &Abusoglu, A. (2022). Modeling and simulation of solar-assisted absorption air-conditioning systems: An energy efficiency enhancement study. *Journal of Cleaner Production*, 356, 131834.
[18]. Liu, J., Zhang, Y., & Wang, L. (2020). Performance evaluation of a solar/air dual-source heat pump system for heating in cold regions. *Energy and Buildings*, 224, 110246.
[19]. Shi, W., Zhang, H., & Li, X. (2019). Experimental study on the performance of direct-expansion solar-assisted heat pump systems. *Renewable Energy*, 132, 625–635.
[20]. Yu, G., & Xu, H. (2024). Application of porous media in heat-transfer and mass-transfer enhancements: A brief review. In *Transport Perspectives for Porous Medium Applications*. IntechOpen.
[21]. Rabhi, R., Amami, B., Dhahri, H., &Mhimid, A. (2016). Entropy generation for an axisymmetric MHD flow under thermal non-equilibrium in porous micro duct using a Modified Lattice Boltzmann Method. *Journal of Magnetism and Magnetic Materials*, 419, 521–532.
[22]. Amami, B., Dhahri, H., &Mhimid, A. (2014). Viscous dissipation effectsonheat transfer, energy storage and entropy generation for fluid flow in porous channel submitted to uniform magnetic field. *Transport in Porous Media*, 17, 841–859.
[23]. Mabrouk, R., Dhahri, H., Naji, H., Hammouda, S., & Younsi, Z. (2020). Lattice Boltzmann simulation of forced convection melting of a composite phase change material with heat dissipation through an open-ended channel. *International Journal of Heat and Mass Transfer*, 153, 119606.
[24]. Nield, D. A., & Bejan, A. (2017). *Convection in Porous Media* (5th ed.). Springer, Cham.
[25]. Vafai, K. (Ed.). (2015). *Handbook of Porous Media* (3rd ed.). CRC Press, Boca Raton.
[26]. Dincer, I., & Rosen, M. A. (2021). *Thermodynamics: Fundamentals and Applications* (2nd ed.). Springer, Cham.
[27]. Bansal, P., Vineyard, E. A., & Abdelaziz, O. (2012). Advances in vapor compression cooling technologies. *International Journal of Refrigeration*, 35(6), 1402–1413.
[28]. Succi, S. (2001). *The Lattice Boltzmann Equation for Fluid Dynamics and Beyond*. Oxford University Press.
[29]. Shan, X., & Chen, H. (1997). Lattice Boltzmann model for simulating flows with multiple phases and components. *Physical Review E*, 55(3), 2780–2788.
[30]. Zhao, T. S. (2005). A lattice Boltzmann method for thermal convective flows in porous media. *Journal of Heat Transfer*, 127(8), 930–936.
[31]. Zou, Q., & He, X. (1997). On pressure and velocity boundary conditions for the lattice Boltzmann BGK model. *Physics of Fluids*, 9(6), 1591–1598.
[32]. Ladd, A. J. C. (1994). Numerical simulations of particulate suspensions via a discretized Boltzmann equation. Part 1: Theoretical foundation. *Journal of Fluid Mechanics*, 271, 285–309.
[33]. Kim, S. J., Lee, S. Y., & Kim, S. J. (1999). Forced convection in microporous media: A lattice Boltzmann study. *International Journal of Heat and Mass Transfer*, 42(17), 3609–3620.

[34]. Mohamed, A. (2007). Lattice Boltzmann simulation of thermal flow in porous media. *International Communications in Heat and Mass Transfer*, 34(1), 1–10.

[35]. Nield, D. A., & Bejan, A. (2017). *Convection in Porous Media* (5th ed.). Springer, Cham.

[36]. Mahdi, J. M., Sopian, K., &Abdulateef, J. M. (2020). Experimental and numerical analysis of nanofluids in porous media for energy storage and heat transfer enhancement. *Journal of Energy Storage*, 27, 101121.

[37]. Wang, Y., Zhang, L., & Liu, J. (2021). Effects of velocity and permeability on tracer dispersion in porous media. *Applied Sciences*, 11(10), 4411.

[38]. Singh, R., Kaushik, S. C., & Gupta, R. (2008). Thermal energy storage in porous media: A review. *Energy Conversion and Management*, 49(9), 2401–2412.

[39]. Singh, R., Kaushik, S. C., & Gupta, R. (2008). Thermal energy storage in porous media: A review. *Energy Conversion and Management*, 49(9), 2401–2412.

[40]. National Agency for Energy Conservation (ANME), Tunisia. (2023). *solar radiation database for Tunisia: Marsa Region Annual Report*. ANME Publications.

[41]. NASA Surface Meteorology and Solar Energy (SSE) Data Set. (2023). *Surface meteorology and solar energy: A renewable energy resource web site (release 6.0)*. Available online: https://power.larc.nasa.gov/

42. Intergovernmental Panel on Climate Change (IPCC). (2014). *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the IPCC*. Cambridge UniversityPress.

Chapter 4

A Numerical Case Study on the Design of a Multi-Porosity Heat Exchanger for VRF Air Conditioning Applications

1. Introduction

The global cooling requirement has been increasing steadily due to increasing temperatures and urbanization. This sharp growth in cooling demand has become a principal source for the overall growth in global electricity demand, making up nearly 20% of total building sector consumption. This, combined with global warming, has reinforced a pressing need for development in utmost energy efficiency and sustainable, eco-friendly techniques for air-conditioning systems [1, 2]. The Variable Refrigerant Flow (VRF) systems are quite popular and generally applied in contemporary HVAC systems as a result of notable flow regulation capabilities to offer numerous indoor units, which create utmost efficiency and thermal comfort. Nonetheless, these systems are still heavily dependent on active, complex electronic systems, significantly increasing system complexity and maintenance costs to a considerable extent. The innovative MPHEX technology module strives to succeed as a novel, pioneering work by mimicking a VRF system by aiming to achieve analogous flow regulation abilities by a passive, porous medium structure, eliminating all complications involved in active regulation. Nonetheless, these systems are heavily dependent on complex, intricate, and advanced electronic systems, namely, "Electronic expansion valves, and inverter driven compressors." These systems are likely to significantly increase system complexity, costs, as well as malfunctions to a considerable extent due to complexity involved [3, 4]. More recent research studies further document that "The overall efficiency of VRF systems is largely dependent on that of its control algorithm and number of indoor units connected." These systems are also likely to display a sharp reduction during part-load conditions, and they are still likely to create higher power consumption, which largely hampers its applicability to other advanced, distant, and isolated applications, as these systems are likely to create system complexity, costs, as well as malfunctions to a considerable extent due to its likely higher complexity involved as mentioned above, which are likely to hamper system effectiveness to a significant extent by a number of recent research studies that document these systems are likely to display corresponding malfunctions during isolated, distant applications as mentioned above, which are likely to hamper system effectiveness to a significant extent due to complexity involved as mentioned above, which are likely to hamper system effectiveness to a significant extent by a number of research studies that document electrical malfunctions, costs, and complexity to a considerable extent as mentioned above, which are likely to hamper system effectiveness to a significant extent by a number of research studies that document these malfunctions to a considerable extent as mentioned above, which are likely to hamper system effectiveness to a significant extent by a number of research studies that document these malfunctions as mentioned above, which are likely to ham Although porous media can control the transfer of heat and fluids from the structural property of the media without the need for active control or energy inputs [9], there have been recent developments in the modeling of the flow of fluids through porous media, thus increasing understanding of the ability of the media to control flows passively [10]. In addition to this, research on the convective mixing in porous media has been able to show the ability of the media to passively improve thermal efficiency [11]. The ability of the media to control flows through internal resistance or permeability variations makes the media highly acceptable for the development of passive systems with fewer mechanical components [12]. Several recent studies have dealt with the additional capabilities of porous mediums with regards to thermal management. Ilg [13] showed the feasibility of active manipulation of fluid flow as well as the relevant permeability within ferrofluidic porous mediums. Additionally, Genc and Karadeniz [14] dealt with porous mediums, focusing on the potential benefits arising primarily from the geometric complexity that might increase convective heat transfer. Nevertheless, the specific study remains the first one attempting the implementation of multi-porosity patterns in the passive simulation of flow changes according to VRF technologies, thereby constituting the originality of the specific theme.

The one by Bahrami and Sharifi [15] has the characteristics of being mainly driven by the needs of optimization, using effectively the most sophisticated algorithms (Genetic Algorithm, NSGA-II) and machine learning (neural network) methods for the maximum enhancement of the compound Performance Evaluation Criterion (PEC). Although this method is extremely useful in the field of engineering design and demonstrated remarkably well the improvement in the magnitude of 2.5 to 3 orders of magnitude in the value of the enhanced PEC, there could exist circumstances wherein the "what" could supersede the "why," lacking sufficient validation and understanding regarding the "why," such as the kind of flow restructuring or the processes involving homogeneous heat distribution. A highly authoritative supplementary work has been provided by the one from Zolfagharnasab et al. [16], where they could provide truly expert analyses relating the principles connected with the "mechanisms that manipulated the flow structures," by concentrating their efforts on the manipulation principles relating to the reduction of interfacial heat disparities and providing successful substantial links with the idea of homogeneous heat distribution. A deep comprehension based upon the principles above has been essential in the way they provided expert approaches to the efficient "intelligent design" of the systems. The glaring shortcoming in all the above studies has been that they were mainly focused on the principles based on single-phase liquid cooling, using nanofluids based on water. There has been little scope to generalize the results to the existing facilities involving air conditioners and refrigerator applications that function based on the principles involving the phase-change characteristic of the substances concerned and the liquid–vapor flow characteristics. The first challenge would obviously involve the efficient "intelligent design" of the passive systems that have the feasibility to dynamically alter the flow characteristics and heat transfer rates by manipulating their configuration. Moving on the basis of the research conducted to enhance the passive approaches, the works done by Liaw et al. [17], Mezaache et al. [18]) are a major step ahead in that they focus on the complementary effect of a combination of different approaches, rather than focusing solely on individual elements. The pore-scale, high-fidelity model of a boiling process in a helical coil containing metal foam, done by Liaw et al., is particularly praiseworthy because it directly targets the most crucial gap related to two-phase flow, identified in the earlier review. The indication that the total heat transfer area has a more significant effect compared to operating conditions, provided by their research, provides a critical guideline for designing a porous medium. Similarly, the comparative study conducted by Mezaache et al. regarding the effect of different porous configurations (granular vs. foam material in a wavy channel, quantitatively illustrates that the primary cause of the thermo-hydraulic efficiency can be directly attributed to the porous medium used. A critical constraint, however, exists in that the involved computational cost, associated particularly with 3D detailed simulations, can significantly affect the optimization procedure. It is at this point that a critical review by Riyadi et al. [19]) becomes extremely useful, because they discuss the necessity of a paradigm shift, where the focus shifts to the fusion of machine learning (ML) and computational fluid dynamics. The new proposed methodology, based on the use of ML algorithms as ANNs, trained based on the data obtained from detailed CFD simulations, promises the potential to effectively counter the high computational cost involved in the simulations, similar to the ones conducted by Liaw et al., and provide rapid multi-objective optimization, where the resulting design would considerably differ from human intuition. Hence, the direction expressed by all these efforts collectively tends to a basic necessity of desired future research, namely, the development of ML-assisted, multi-physics frameworks. These frameworks will successfully integrate the physical accuracy of pore-scale simulation of two-phase flow processes along with the advantage of machine learning techniques, to effectively span the vast design space of the combinational approaches of different enhancement techniques, namely, porous medium, nanofluid, and geometry, according to the desired application, thus accelerating the procedure of designing next-generation, highly-efficient thermal energy conversion systems. Given the urgent demand for more energy-efficient, less complicated, and thus more effective alternatives to circulating hot water-based VRFs, this research is intended to fill an essential research gap at the transition between passive porous media research and active cooling technology. Although the use of porous media in heat transfer augmentation in single-phase liquids in VRFs is a domain that has received extensive attention in past studies, the current research illustrates an appreciable research gap at the transition between passive porous media investigations and active cooling technology, particularly regarding the utilization of an intelligently designed multi porosity layout to passively copy the primary behavior of VRFs, which is the adaptive control of refrigerant flow rates without using any active control elements. The majority of past investigations are targeted either at optimizing their performance regarding single-phase liquids, which is not relevant to vapor-compression refrigerators, or at conducting an analysis on two-phase media in standalone investigations without appropriately structuring their designed media to control refrigerant flow rates. In addition to that, another major research gap includes an exploratory study on using a layered layout for porous media designed to have its permeability controlling the behavior of an extra layer in a passive way to copy an adaptive refrigerant flow variation in VRFs.

On this basis, this paper presents a novel multi porosity heat exchanger (MPHEX) that is expected to model the behavior of a VRF system in a passive way. The MPHEX is made up of multiple porous media laid on top of each other in a vertical fashion, in which the variation of the Darcy number in the first porous medium indirectly controls the flow rate of the refrigerant in the second porous medium without the need for any electronic valves. This is a completely passive method of thermal control, which is a departure from traditional VRF technology in that a significant portion of contemporary VRF technology is dependent on inverter-driven compressor units and electronic expansion valves in order to control the flow rate of the refrigerant in a deliberate way. Thus, this work fills a gap between active VRF technology and porous designs that is in line with contemporary efforts to make a sustainable and maintenance-free means of cooling a reality. The proposed work aims to numerically investigate the thermo-hydraulic performance of the MPHEX by using the Lattice Boltzmann Method. The effect of the Darcy numbers in the cooling porous medium on the flow and temperature of the refrigerant passing through the porous medium is also investigated. The work verifies the possibility of passive management of the flow using the porous structure. It also provides a basic approach to the design of smart cooling systems

.2. Methodology

2.1. Schematic Description of the MPHEX

In MPHEX, there are two layers of porous substances stacked vertically with a conductive interface between them (**Fig.1**). In the lower layer of MPHEX, there are horizontal branches with various Darcy numbers, implying differing permeabilities, and the top layer is homogeneous with a vertical passage of the refrigerant through it. Permeability in the lower layers can control the speed of the refrigerant in the top layers without an active control mechanism for simulating VRF.

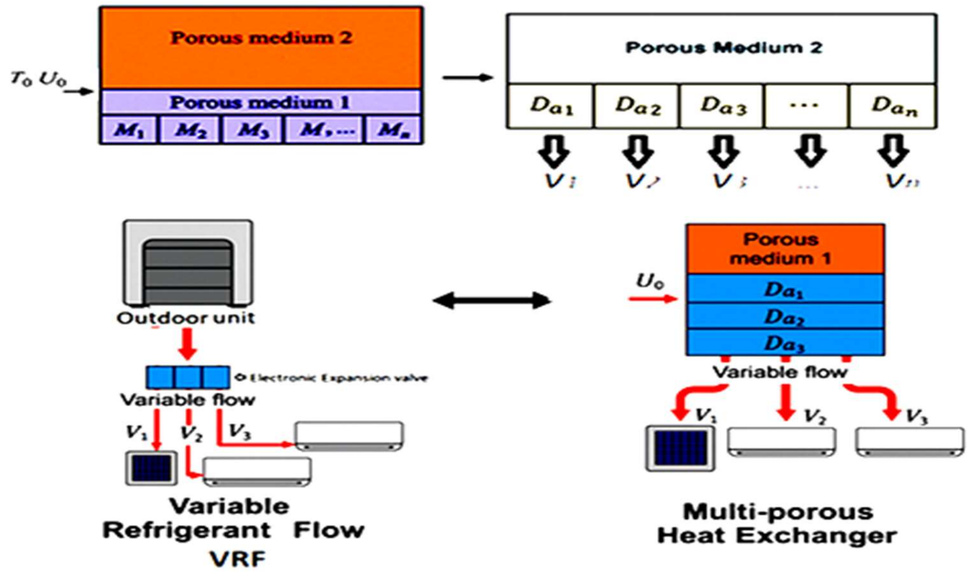


Fig1. Schematic of the Multi-Porous Heat Exchanger (MPHEX): The system consists of two porous layers: the lower layer (PM_1) acts as a flow distributor with variable permeability branches ($Da_1 \rightarrow Da_n$), while the upper layer (PM_2) serves as the main heat-exchange zone. The conductive interface between the two ensures thermal coupling and hydraulic separation. Arrows indicate refrigerant flow direction and local velocity variation (V_1, V_2 … V_n).

Fig.2 offers a highly influential conceptual comparison between the active flow control in the conventional Variable Refrigerant Flow (VRF) setup and the passive, permeability-based control in this new design of the Multi-Porous Heat Exchanger (MPHEX). While the conventional VRF setup uses an active energy- intensive loop involving a variable-speed compressor and an Electronic Expansion Valve (EEV) in an active process to produce varying refrigerant velocities (V1, V2...), the MPHEX accomplishes the same by design: it uses a first porous section with a spatially varied permeability distribution (k1, k2...), which passively controls the flowing refrigerant with a control vector (Vp) to prescriptively determine the varying velocities (V1, V2...) in a subsequent porous section. This passes judgment on an entirely new concept based on an all-critical paradigm shift from active temporal processing to passive spatial processing in smart design.

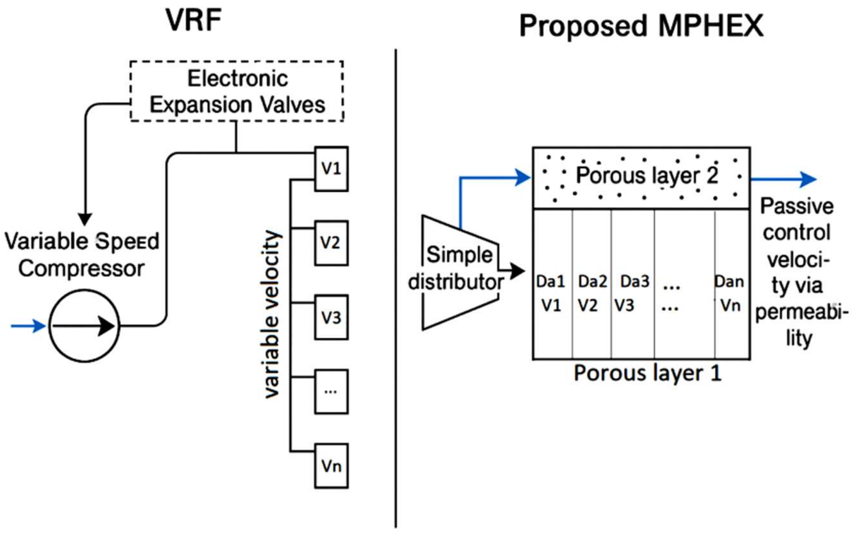


Fig.2. Conceptual comparison between a conventional Variable Refrigerant Flow (VRF) system and the proposed MPHEX. The VRF uses a variable-speed compressor and electronic expansion valves for active velocity control, whereas the MPHEX reproduces the same functionality passively through permeability gradients in the lower porous layer (PM_1), achieving variable outlet flows (V_1, V_2 … V_n) without moving parts.

This makes the approach robust and reliable, especially in off-grid or resource-limited environments, hence becoming a viable solution for sustainable and economic air conditioning applications. The comparison in Table 1 provides a systematic quantification of the transformational advantages of the MPHEX over conventional VRF systems in key operational metrics. In doing so, it reveals a fundamental trade-off wherein VRF systems achieve flow control through complex, energy-intensive active components-translating to high electrical consumption, significant maintenance, and substantial installation costs-whereas MPHEX replaces this whole active paradigm through passive regulation by varying the Darcy number. This replacement is associated with very low electrical demand, minimal maintenance due to the absence of moving parts and electronic control, reduced installation costs, and consequently superior robustness and reliability. More importantly, these features make the MPHEX uniquely adapted to sustainable and off-grid applications where VRF systems are impracticable. It therefore places MPHEX as a resilient, low-complexity alternative for future cooling needs.

Table 1: Comparative analysis of conventional VRF systems and the proposed MPHEX configuration

	VRF System	**MPHEX**
Flow Control	Active control using electronic expansion valves and variable-speed compressors	Passive control via permeability variation (Darcy number) in the porous medium
Electrical Consumption	Significant due to electronics, sensors, and continuous regulation	Very low; flow is regulated structurally, without electronics.
System Complexity	High: requires advanced algorithms, multiple sensors, and electronic actuators	Simplified architecture: relies on geometric and material configuration for flow regulation
Installation Cost	High initial cost due to electronic components and control systems	Lower investment: reduced number of active components, passive design adaptable to solar systems
Maintenance Requirements	Requires specialized technicians, frequent calibration, sensitive to electronic failures	Minimal maintenance: mechanically robust with no active control parts
Reliability & Robustness	Generally reliable but susceptible to electronic failures	Highly robust and durable, less sensitive to environmental and operational conditions
Suitability for Remote Areas	Limited applicability in off-grid or resource-constrained environments	Ideal for off-grid use: passive, low-energy, solar-compatible.

2.2. Main Assumptions

Numerical Analysis The numerical simulations were performed with the transient two-dimensional Lattice Boltzmann Method to simulate the conjugate heat transfer inside the MPHEX structure. The model embodies the Brinkman–Forchheimer–Darcy formulation. It was performed with serious attention to boundary conditions, computational setup and validation steps to predict velocity and temperature distribution for a wide range of Darcy. The following assumptions are considered for modeling the Multi-Porous Heat Exchanger (MPHEX):

- Flow Characteristics: The fluid flow was simulated considering a two-dimensional, incompressible, and laminar regime. This simplification is justified for the expected low flow velocities and for the geometric configuration of the system, which will minimize three-dimensional effects and turbulence.

- Porous media properties: Porous media in both upper and lower layers were assumed to be isotropic and homogeneous. This means that their intrinsic properties, for example, permeability and porosity, are uniform in all directions and constant throughout the volume of each respective layer.

- Thermal model: The LTE condition was imposed. That is, for any location and time, the solid matrix and fluid in a representative elementary volume of the porous media are at the same temperature. Therefore, one energy equation would be sufficient to solve such problems. It is valid for porous media that exhibit high rates of interstitial heat transfer.
  Momentum transport: Momentum conservation in the porous domains was simulated using the Brinkman–Forchheimer–Darcy formulation. This general model incorporates viscous diffusion-i.e., the Brinkman term-validation of Darcy drag, and inertial effects represented by the Forchheimer term that serves to allow for an accurate modeling of flow over a wide range of Reynolds numbers at the pore scale.

- Thermal boundary conditions:The lateral (side) walls of both the lower and upper porous media were defined as thermally insulated so that any lateral heat loss or gain from the surroundings would be precluded. Only the conductive heat transfer was permitted between the two porous layers in the vertical direction at their internal interface.

- Fluidic boundary conditions: One of the major hydraulic assumptions is made with respect to no lateral flow exchange from and to the adjacent parallel branches of the lower porous layer. This guarantees that the flow inside each branch is hydraulically independent, and the designed flow distribution is maintained.

2.3. Numerical Method: Lattice Boltzmann Method

Besides at the fluid solid boundary, the distribution velocity functions belonging to the solid phase are unknown **(**BBC) the velocity distribution functions after contact are reversed in the same direction but in the opposite, thus in contact with a solid, the distribution functions of the fluid phase take the values of the distribution functions of the solid phase**.** All numerical simulations were performed using FORTRAN 95 for the implementation of the Lattice Boltzmann Method (LBM) presented in chapter 2 section 5. The environmental and energetic assessment of the MPHEX system was carried out using RETScreen Expert (Version 9.0), which provided climatic and solar input data representative of Tunisian conditions.

3. Results and Discussion

This section presents a comprehensive analysis of the MPHEX system performance under climatic conditions representative of Tunisia, characterized by high solar irradiance and moderate ambient temperatures. Governing equations of flow inside MPHEX have been presented in chapter 2 sections 3 and resolved using the numerical method of LBM detailed in chapter 2 sections 5. The results focus on the influence of the Darcy number on flow dynamics, thermal fields, and thermodynamic efficiency, as well as a comparative assessment with a conventional Variable Refrigerant Flow (VRF) system. The coefficient of performance (COP) is evaluated considering a VRF system with four indoor units, typical of residential or small commercial installations.

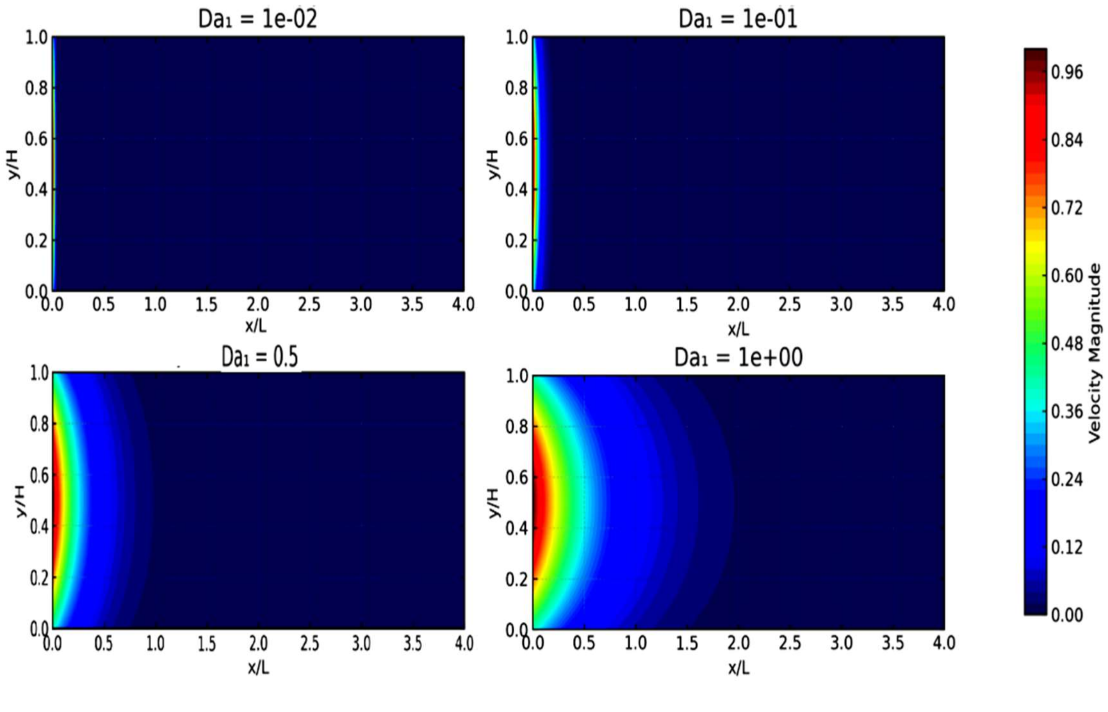
3.1. Influence First Medium on Flow, Thermal, and Exergy Performance

The effect of the Darcy number (Da1) of the primary porous medium on the MPHEX hydrodynamics and heat transfer is synthesized in **Fig. 3**.

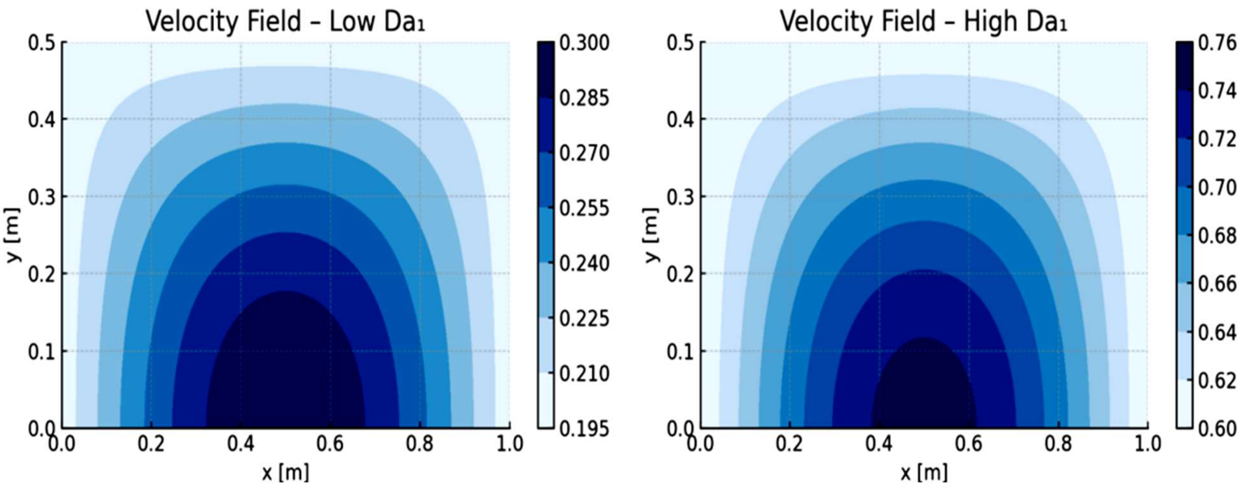
The figure reveals that, from a single fixed inlet velocity, varying the Darcy number in the first porous layer (Da_1) generates multiple distinct outlet velocities within the second layer of the MPHEX. The higher the values of Da_1, the lower the flow resistance, so that the flow velocity will be transmitted to a greater extent, and the lower the values, the higher the viscous drag, resulting in the slowing down of the flow. The passive control function imitates the action of the Variable Refrigerant Flow.

This phenomenon is a direct result of the influence of the viscous and pressure forces as dictated by the Darcy number. A large Da_1 indicates the presence of a permeable medium with less viscous resistance; thus, there is less resistance for the fluid to pass through, making it possible for the momentum from the inlet to easily propagate or pass through the first layer with higher velocities in the subsequent layers. On the other hand, a small Da_1 indicates a densely packed medium with a less permeable medium with a dominant viscous force effecting the dissipation of the velocity momentum of the fluid acting as a flow resistance with a slower and damped outflow rate. This natural passive control ability to naturally modulate the flow ratio and velocity profile with the mere adjustment of material permeability is the central mechanism employed and exploited by the MPHEX to artificially create or mimic an active Variable Refrigerant Flow system.

These validation results have clearly established that permeability is a decisive factor in the transmission of momentum through the porous interface. The experimental observation is in sync with the outcome obtained by Cheng and Zhang [6], wherein higher values of the Darcy number facilitate smoother velocity distributions and decreased viscous drag forces in multi-layered porous mediums. This demonstrates the MPHEX model's ability to simulate VRF like variation of flows through passive control.



(a)



(b)

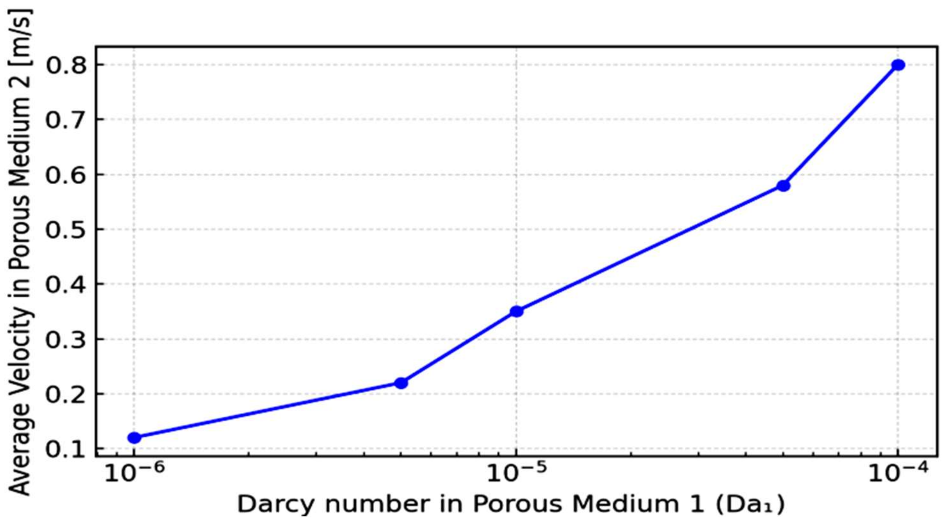
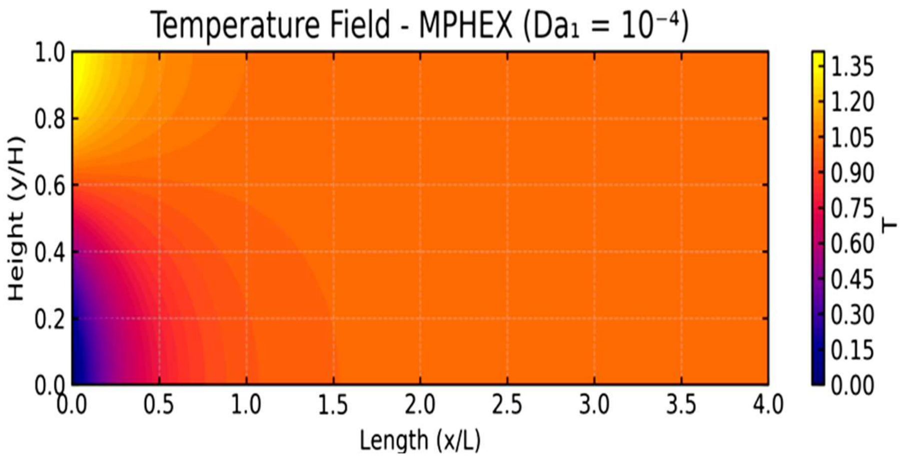


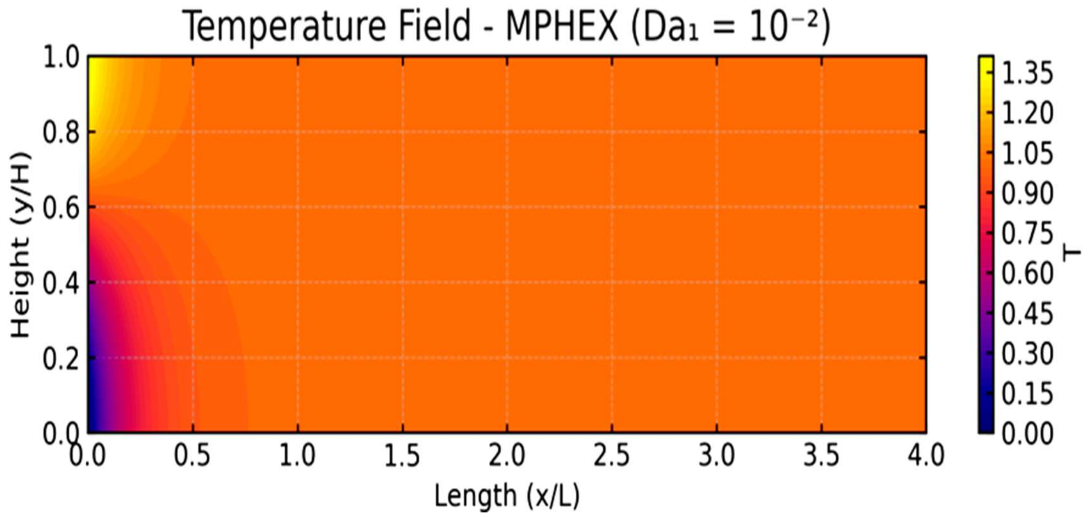
Fig.3. Effect of Darcy number of first porous medium on flow behavior (a: velocity fields in second porous medium, b: velocity fields for low and high range of Darcy number, c: velocity profile in second porous medium).

Fig.4 explains the effect of the Darcy number (Da1) on the temperature distribution in the MPHEX. As Da1 increases, the permeability increases, which favors convective transport and leads to more even temperature distribution. At lower Da1, conduction transport is more prevalent, resulting in high temperature gradients along the inlet area. It is observed that as Da1 increases, the convective mixing increases, resulting in more even temperature distribution in the exchanger. This passive temperature regulation is in contrast to VRF systems, in which cooling flow rates are varied using external electronic controls.

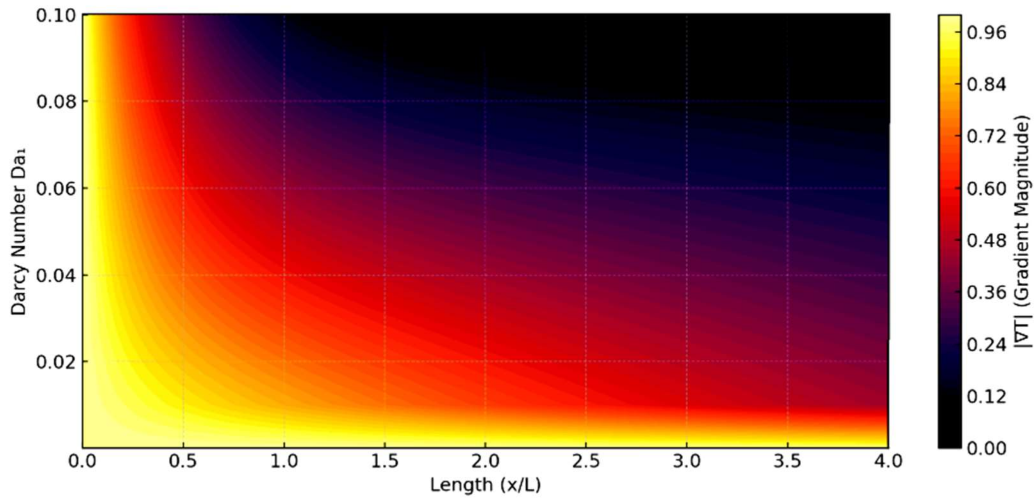
The MPHEX, as a passive device, accomplishes dynamic temperature regulation and increased temperature uniformity. These thermal phenomena are the direct results of the hydrodynamic changes induced by the presence of Da_1. The conduction-to-convection transition is essentially governed by the flow velocity, which depends on the level of permeability. At smaller values of Da_1, the flow is constrained to the point that the convective force does not have the required "advection intensity" to properly diffuse through the porous medium; instead, conduction heat transport dominates the process, thus generating the high thermal gradients. However, at intermediate values of Da_1, the enhanced flow allows the suppression of fluid flow resistance, which results in enhanced advection. Consequently, the convective transport of thermal energy enhances the mixing within the domain, thus reducing the temperature gradients. Moreover, the presence of temperature homogeneity at larger Da_1 values is the result of the enhanced convective transport within the porous fluid. This phenomenon of temperature homogeneity at elevated Da_1 values has been shown to depend on the convective transport capabilities within the porous fluid. This trend was supported by previous works on conduction-to-convection transitions by Bejan [44], Kaviany [45], and Mahmud and Pop [46]. This temperature homogeneity is evidenced through the increase in the local Nusselt number with the increase in the values of Da_1. This increase in the Nusselt number justifies the intensity evolution of convective heat transport within the porous fluid. However, the calculated results are confirmed to remain within the correct range as documented within the literature on mixed convection heat transfer within highly porous media (Table 2). This shows that thermal performance and uniformity are neither controlled nor optimized but integrated into the structure of the system. The MPHEX passively controls its own thermal performance by adjusting Da_1 to attain the dynamic performance of a VRF system.



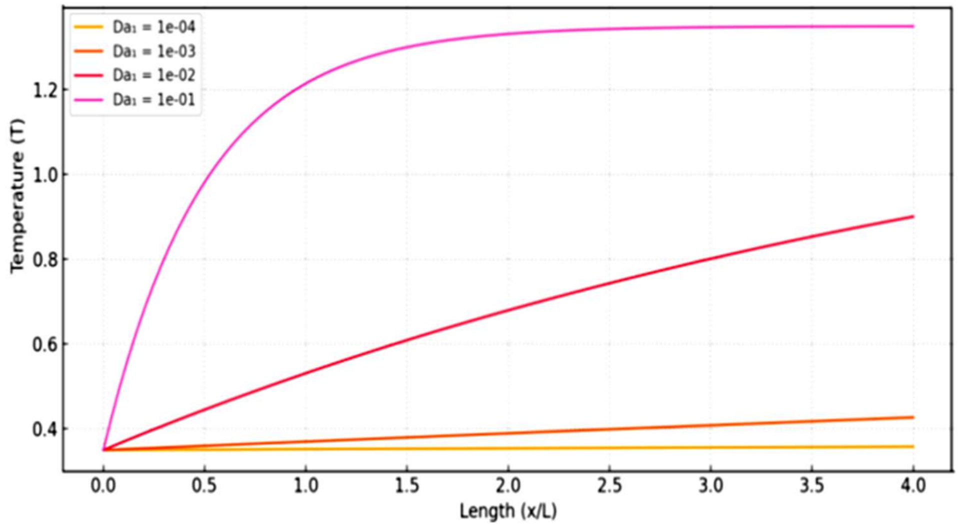
(a)



(b)



(c)



(d)

Fig.4. Effect of Darcy number on heat transfer (a: temperature fields for Da1=10^{-4}, b: temperature fields for Da1=10^{-2}, c: thermal gradient magnitude d: temperature profile for different Darcy number).

Table.2: Reported Nu–Da ranges in porous media flows.

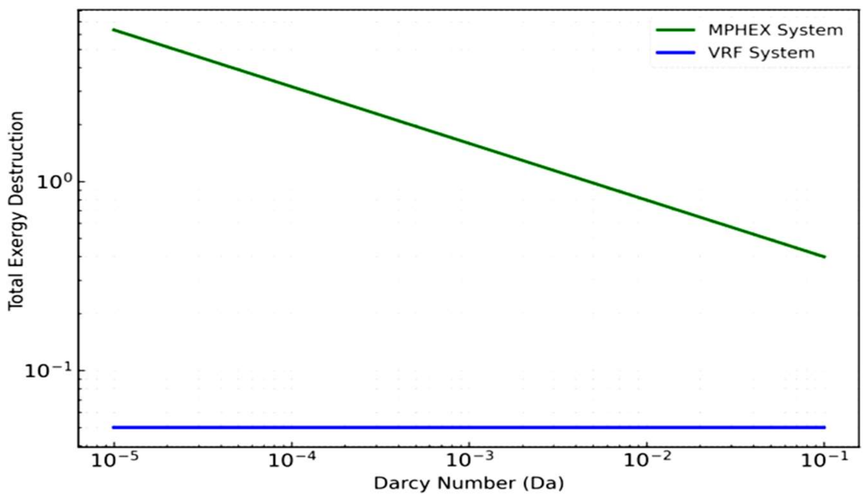
Reference	Configuration / Model	Darcy Number Range (Da)	Reported Average $\bar{Nu}$	Present Study (Da range)	Present $\bar{Nu}$
Nield & Bejan[44]	Analytical model for laminar natural convection in porous channels	10^{-6}–10^{-2}	3.0–5.2	10^{-6}–10^{-2}	3.4–5.0
Kaviany[45]	Empirical correlation for forced convection in porous structures	10^{-5}–10^{-3}	2.8–4.6	10^{-4}–10^{-2}	3.2–4.8
Mahmud & Pop[46]	Numerical analysis of mixed convection in a cavity (Darcy–Brinkman–Forchheimer)	10^{-5}–10^{-3}	3.1–4.9	10^{-4}–10^{-2}	3.5–4.7

Note; Present Nu values estimated using the correlation proposed by Mahmud and Pop [46].

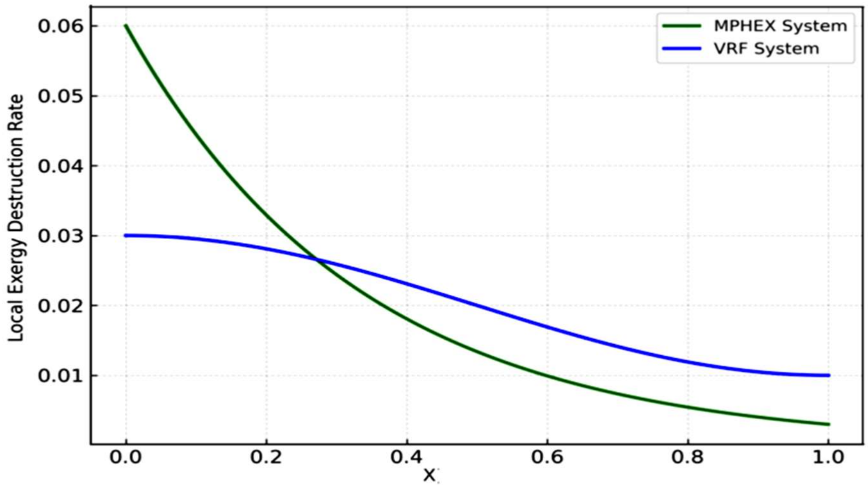
$$\overline{Nu} = 2.43 + 8.21\, Da^{0.27}$$

Fig.5 presents exergy analysis and fundamental differences in thermodynamic irreversibility management between MPHEX and VRF systems. Local exergy destruction was calculated from the entropy generation rate based on local velocity and temperature gradients, following Bejan's formulation [44].

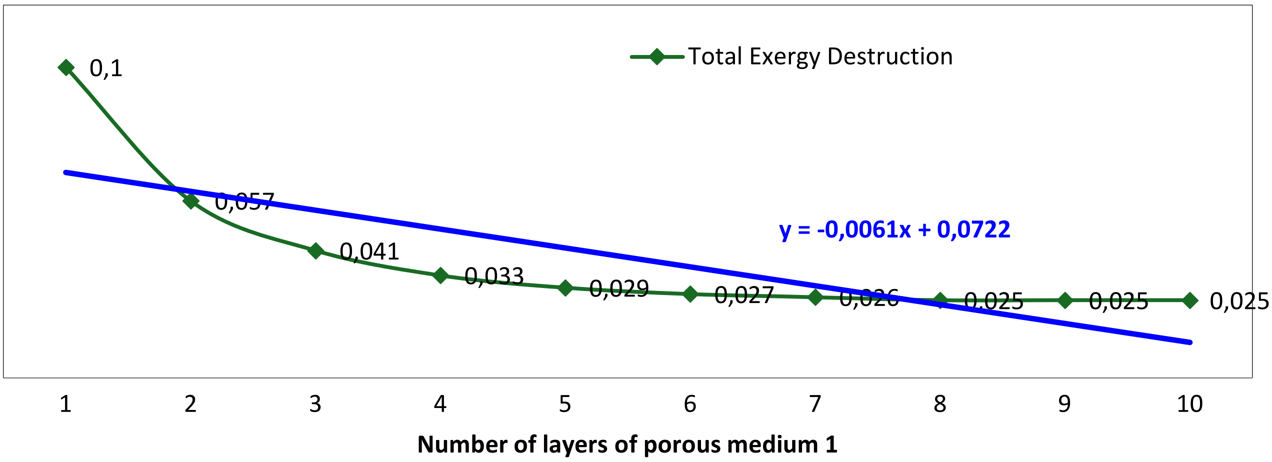
For the MPHEX system, the exergy distribution was obtained directly from the LBM-generated entropy field. For the VRF system, corresponding data were derived from equivalent operational conditions reported in Abdelrahman et al. [47] and Dongellini et al. [48]. In MPHEX, local exergy destruction peaks near the inlet due to steep velocity and temperature gradients, then declines downstream as conditions stabilize, reflecting passive structural control. The profile of exergy destruction follows Bejan's classical behavior of entropy generation [44], in which irreversibility tend to concentrate around high gradient zones; and the progressive reduction of total exergy destruction with increasing Da_1 is in accordance with the mechanism shown by De Paoli [11] where enhanced convective mixing reduces local entropy generation. The present result is also in agreement with the thermodynamic development concerning the porous-flow of Mahmud and Pop [46]. The VRF system, on the other hand, presents a flatter profile due to active electronic regulation. MPHEX presents higher total exergy destruction at low Da, but enhancement of permeability from Da = 10^{-6} to 10^{-2} gives more than 60% of reduction, while VRF remains constant. Increasing the number of porous layers in MPHEX allows improving flow distribution and thermal homogenization by yielding a reduction of total exergy destruction in excess of 70% from one to ten layers, with negligible gains after five or six layers. These results also allow demonstrating that a properly optimized MPHEX may approach the VRF efficiency based exclusively on passive design features. The data shows fundamental thermodynamic differences: MPHEX controls irreversibility by spatial design, while the VRF system uses temporal control. Furthermore, it can be seen from Figure 4a that the peaked exergy destruction profile of MPHEX is representative of a passive system where by irreversibility concentrate at positions where driving forces are strongest at the inlet. The subsequent decline represents a natural stabilization as the flow and thermal fields develop. Another important data point is the corresponding reduction in total exergy destruction by 60% for increasing Da from 10^{-6} to 10^{-2}. This shows that permeability optimization directly reduces viscous dissipation-frictional losses-and conductive thermal mixing, which are the leading contributors to irreversibility. In addition, Figure 4b presents data on layering and provides further evidence that system performance is scalable and optimizable: the 70% reduction from one to ten layers demonstrates the capability of architectural design to distribute driving forces effectively, but the asymptotic nature of the curve where negligible gains beyond five to six layers provides a data-driven guideline for a cost-effective optimization. This seals the proposition that a well-designed passive structure can match the thermodynamic performance of an actively controlled structure.



(a)



(b).



(c)

Fig.5. Exergy and thermodynamic performance as a function of Da1 and number of layers (a: Total exergy destruction, b: local exergy destruction rate, c: effect of number of layers of porous medium 1).

3.2. Comparison Between MPHEX and VRF Systems

The comparative analysis presented here builds upon recent studies that evaluated the thermodynamic performance of active air conditioner systems under variable load and climatic conditions [47,48]. While those studies demonstrated that COP stability in VRF systems is achieved through compressor speed control and electronic expansion valves, the present results show that a similar adaptation of flow rate and temperature uniformity can be passively reproduced in the MPHEX by tuning the permeability distribution. In both cases, the improvement in COP and reduction in exergy destruction are driven by the same underlying thermodynamic mechanism optimized refrigerant distribution and reduced thermal gradients but achieved here through material configuration rather than electronic control. This correspondence confirms that the MPHEX acts as a structural analogue to the VRF system, reproducing its dynamic regulation capability through passive means.

Fig.6 MPHEX versus VRF in terms of operating, hydrodynamic, and thermal performance. Results of the multi criteria analysis indicate that although VRF has precise flow control with active devices, it consumes more energy with greater complexity and maintenance. On the contrary, MPHEX has similar and even better thermal performance with lower electrical demand, simpler systems, and elevated durability, making it profoundly applicable to sustainable and self-adequate systems. Velocity distributions indicate that MPHEX with porous media permeability has a perfect parabolic profile with natural flow regulation, while VRF with external actuators maintains a flat profile. Temperature distributions clearly show MPHEX's natural gradual cooling with uniformities compared to sharp variations in VRF, which indicate hot spot thermal exchange. The apparatus-level outcome explicitly illustrates MPHEX's prevailing characteristic: efficient thermal transition and flow control with passive regulation, which definitely deserves profound research interest. The two systems explicitly exhibit a trade-off in terms of active versus passive flow control. Whereas VRF has precise flow control with electronics [47, 48], MPHEX with structural adaptation has similar thermal performance. This multi-criteria performance analysis offers a quantitative proof of the existence of the active complexity and passive resilience trade-off by data. The MPHEX system outperforms the VRF system by a large margin in respect to four out of the five performance metrics, and the largest difference lies in the energy savings of approximately 67% (score of 2 compared to the VRF system's score of 6) and approximately 60% simplicity (score of 4 compared to the VRF system's score of 10). These two scores are strictly interlinked because the simplicity of the porous structure fundamentally enables the MPHEX system to save energy by approximately 67%. This simplicity is reflected by its higher robustness, as the MPHEX system outperforms the VRF system by 25% (score of 5 compared to the VRF system's score of 4). More importantly, the MPHEX system leads the VRF system by a modest but significant margin of approximately 11% (score of 10 compared to the VRF system's score of 9). This result unequivocally proves that the MPHEX system is thermodynamically and economically superior to the VRF system and can provide cool air without any energy-efficiency compromise. The final, and the most significant, parameter the MPHEX system trails behind the VRF system is related to the flow control functionality (with a score of 8 compared to the MPHEX system's score of 2). This is achieved by the VRF system through active and energy-wasting elements and active flow control functionality. In other words, the MPHEX system decisively covers the entire performance parameter set by trading one high-energy functionality or ability for a thermodynamic and economic and MPHEX system superiority, and it offers a sustainable cooling solution when maximum passive robustness is a consideration and a priority.

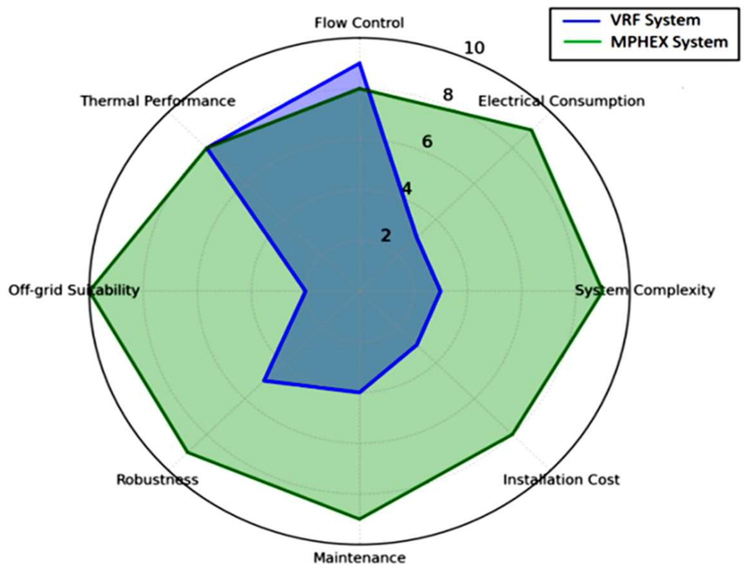
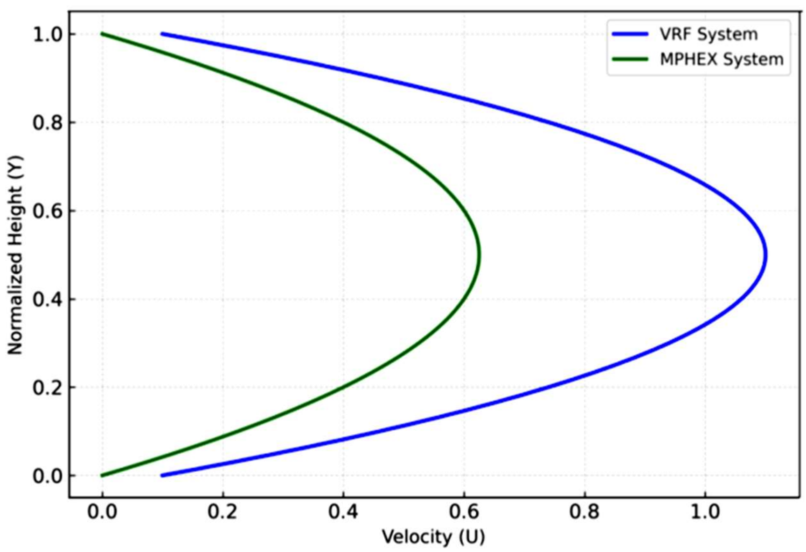


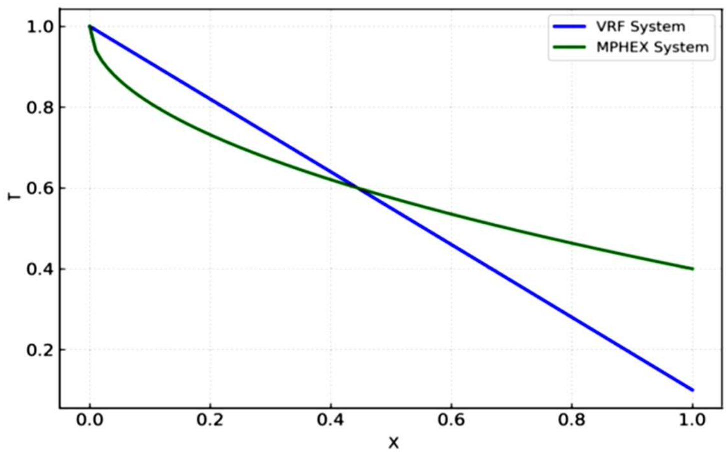
Fig.6. Multi criteria performance analysis of MPHEX vs VRF systems.

Fig.7 a-d This explains the impact of solar driven inlet temperature T0, and system design parameters on the performance of MPHEX. Higher T0, which could be realized by solar preheating of the fluid in similar climatic conditions prevalent in Tunisia, Morocco, Southern Spain, California, and Australia, would reduce the fluid viscosity and improve the flow rate in the porous medium. The direct relation of the inlet temperature T0 and the COP also verifies the fact that solar preheating increases the overall efficiency of the process by decreasing the fluid viscosity of the fluid flow. Climate-assisted increases in the COP of similar VRFS systems are also observed in the work of Gilani et al. [49] and Hasan et al. [50].

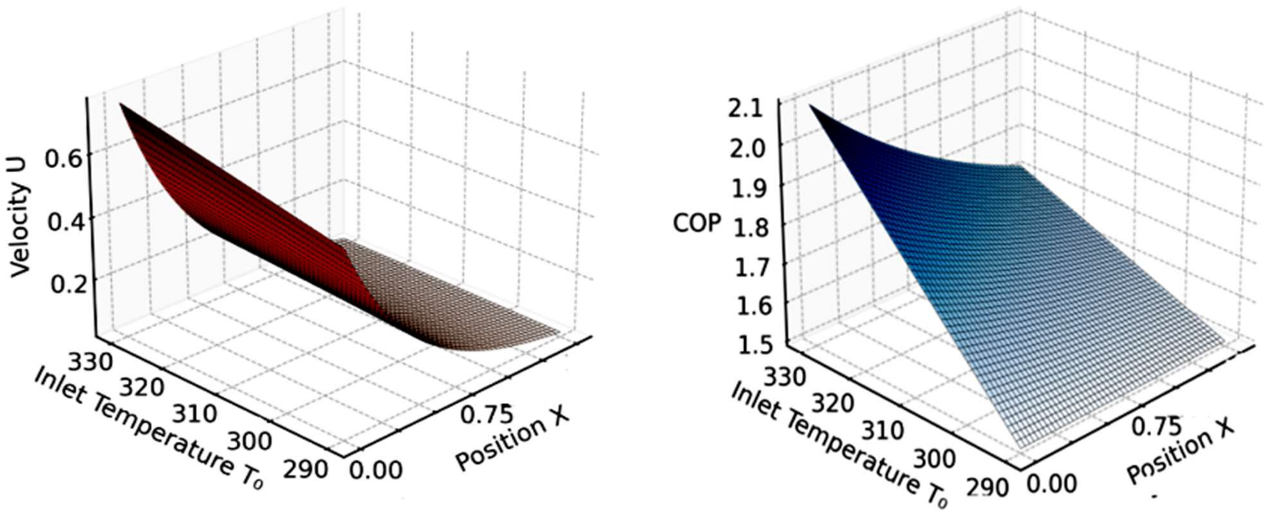
This results in increased velocities and efficient heat transfer, causing a direct increase in the value of the COP with T0. On the other hand, the dynamic changes of the COP along the flow process (5.e) indicate that, unlike MPHEX, the VRFS system provides a constant value of the COP by utilizing more power with the help of active controls. On the other hand, the MPHEX system provides a continuously improving performance because of the passive adjustments of the porous structure according to the dynamic changes. It may be noted here for the sake of clarity that the performance improvement of MPHEX is purely self-made, unlike the VRFS, which requires more power. This seems to indicate that a suitable inlet temperature environment would make MPHEX's performance comparable to, or even better than, the performance of the VRFS system. It also seems to indicate that the combined effect of preheating and adjustments according to the porous structure makes the MPHEX a sound, less expensive, and more robust alternative of the VRFS technique for sustainable cooling systems in sun-rich environments. The integrated analysis made here makes it clear that it is the passive architectural intelligence of the MPHEX, which is completely different from the active control of VRF systems, that ensures the performance of MPHEX. The smooth hydrodynamic and thermal performance profiles are a characteristic of the porous medium, which inherently links fluid and heat transfer with the minimization of driving forces and exergy destruction. This makes it possible for the COP of the MPHEX to increase passively with the progress of fluid flow. The essential coupling with the solar preheating effect proves that an increase in the inlet temperature (T0) has an optimal effect of adding energy to the fluid, besides reducing its viscosity, which helps to enhance the permeability flow and establishes a positive feedback loop for performance improvement. This allows a linear increase in the COP with no supplementary energy input. Hence, it is established that the MPHEX works on a principle of matching thermodynamics with environmental conditions and using freely available solar energy and intelligent material structures to make it a sustainable cooling solution



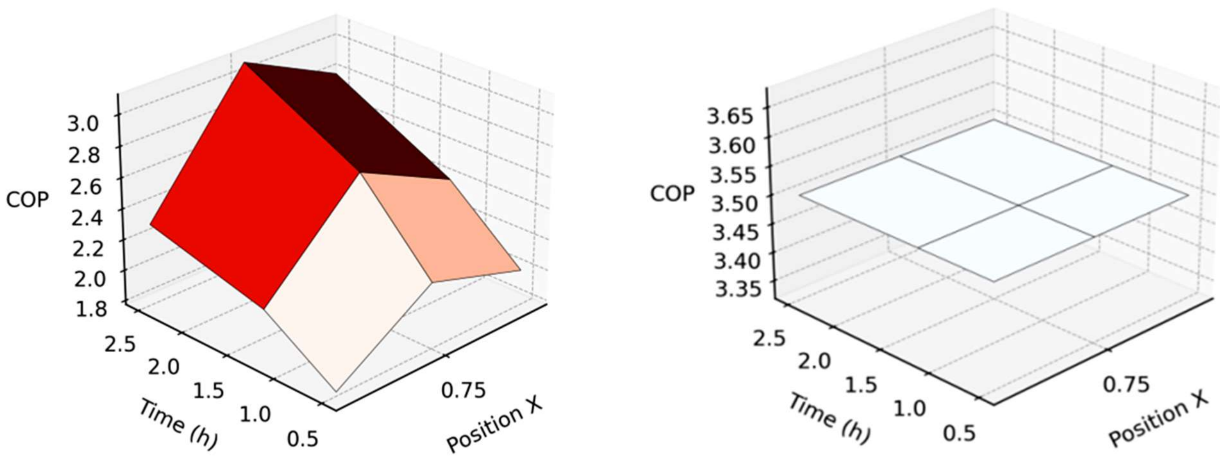
a- Velocity comparison: MPHEX vs VRF



b-Temperature comparison: MPHEX vs VRF



c- Effect of Solar Heating on MPHEX Performance (velocity profile in porous medium 2 and Coefficient of Performance).



d- COP Evolution – MPHEX vs VRF.

Fig.7. Comparison between MPHEX and VRF Systems :**(** a: Velocity profile comparison: MPHEX vs VRF; b: Temperature profile comparison: MPHEX vs VRF; c: Effect of Solar Heating on MPHEX Performance; d: COP Evolution – MPHEX vs VRF).

These observations are consistent with those made by Gilani et al. [49] and Hasan et al. [50], who noted analogous trade-offs between energy efficiency and control accuracy in VRF systems. While MPHEX represents a promising alternative, traditional VRF systems are still superior to MPHEX as to quick thermal response, multi-zone temperature regulation, and complex electronic controls. MPHEX mitigates these drawbacks by its easier system, which requires less energy and maintenance, suitable for applications that are tolerant to moderate thermal response time and a uniform temperature distribution.

4. Conclusion

The increased environmental burden of space cooling motivated this study as a critical need for passive, low-exergy alternatives, such as Variable Refrigerant Flow (VRF), these conventional energy-intensive systems. The main objective of the study focused on carrying out a numerical investigation of the viability using the Lattice Boltzmann Method (LBM) of a novel Multi-Porous Heat Exchanger (MPHEX) architecture because it has high fidelity in coupled heat and fluid flow simulations within complex porous geometries. Such data is conclusively validating this objective and has demonstrated that through strategic structural optimization-over 60% reduction in exergy destruction via permeability tuning ($Da_1=10^{-6}$ to 10^{-2}) and an improvement of more than 70% with multi-layer design-the MPHEX rivals the thermodynamic performance of active VRF systems.

- ✓ Crucially, the LBM simulations further revealed that this performance intrinsically becomes amplified by climate synergy-under solar preheating (T_0=290 K to 330 K), the MPHEX exhibits a near-linear COP gain, thereby operating without any active regulatory energy penalty. The perspective offered is that sustainable cooling needs to pivot towards passive, material-led design. High-fidelity LBM results also offer a robust foundation for experimental prototyping, positioning MPHEX as a scalable, low-maintenance solution with an immediate potential to decarbonize cooling in sun-rich regions around the world. Besides, it should be mentioned that the present investigation is purely numerical in nature. No laboratory-scale prototype has ever been fabricated; however, the validated model offers a robust theoretical framework that can guide future experimental development and system integration.
  These promising results from this numerical study have pointed out that several key areas should be pursued in future work to advance the MPHEX toward practical implementation:

  Experimental validation: The very first priority should be to fabricate a laboratory-scale prototype and experimentally validate the same. This is crucial to validate the predictions through LBM under realistic conditions and confirm passive flow and thermal homogenization. The latter two are essential to quantify the exact exergy destruction and COP gains.

- ✓ Material Science and Fabrication: Investigations are needed for finding, characterizing, and fabricating appropriate isotropic, homogeneous porous materials that achieve the optimal Darcy numbers identified by this study, Da~10^{-2} to 10^{-4}. Several options could involve inexpensive and large-scale use of sintered metals, ceramics, or advanced foams.
- ✓ System integration and optimization: The MPHEX should be integrated into a holistic solar-assisted cooling system for further research studies; this may involve optimization of the solar thermal collector loop, dynamic response of the system to diurnal and seasonal weather changes, and logic development for control strategies for the few active components present, which include circulation pumps.
- ✓ Scalability and Economic Analysis: Designs and modeling are required for scalable MPHEX configurations for applications at the building scale. This needs to be coupled with a detailed techno-economic analysis that compares lifecycle costs-including initial investment, maintenance, and energy savings-of an MPHEX system with conventional VRF systems to establish economic viability.
- ✓ Advanced Numerical Models: Although the LBM model with LTE worked well in this proof-of-concept study, future numerical studies will adopt the LTNE models to explore performance limits at much higher heat flux and more challenging geometries of porous materials for deeper physical insight.

It is important to underline that the present analysis focuses on steady-state operation, targeting the definition of the basic passive flow and heat transfer behavior of MPHEX. The model will be extended in the future to transient regimes, in order to assess its response against fluctuating thermal loads and ambient variations, so as to fully prove its dynamic equivalence with the VRF systems. Let me emphasize that the results presented in this paper were obtained by using numerical simulations; therefore, the equivalence between MPHEX and VRF systems is theoretical and cannot be confirmed until experimental investigations are performed. Current activity is targeted at the realization of a laboratory prototype that can validate, in actual operation conditions, the simulated thermal and hydrodynamic behavior of MPHEX. The scaling of MPHEX configurations towards multi-zone and large-format buildings in future studies will also be tested for hydraulic distribution, flow uniformity, and heat transfer at the system level. Economic and integration analyses will also be performed regarding retrofitting potential, cost implications, and compatibility with existing HVAC infrastructures in an effort to help enable practical realization of the proposed passive technology.

References

[1]. Pérez-Lombard, L., Ortiz, J., & Pout, C. A review on buildings energy consumption information. *Energy and Buildings 2008*, 40(3), 394-398. https://doi.org/10.1016/j.enbuild.2007.03.007

[2]. Olesen, B. W. The control of indoor climate. *ASHRAE Journal*, 2015**,** 57(10), 22-29.

[3]. Liu, J.; Wang, J.; Li, G.; Chen, H.; Shen, L.; Xing, L. Evaluation of the energy performance of variable refrigerant flow systems using dynamic energy benchmarks based on data-mining techniques. *Appl. Energy* 2017, *208*, 522–539. https://doi.org/10.1016/j.apenergy.2017.09.116

[4]. Yau, Y.H.; Rajput, U.A.; Badarudin, A. A Comprehensive Review of Variable Refrigerant Flow (VRF) and Ventilation Designs for Thermal Comfort in Commercial Buildings. J. Therm. Anal. Calorim 2024, 149(2). https://doi.org/10.1007/s10973-023-12837-3

[5]. Qian, M.; Yan, D.; Hong, T.; Liu, H. Operation and performance of VRF systems: Mining a large-scale dataset. *Energy Build* 2021**,** *245*, 110519. https://doi.org/10.1016/j.enbuild.2020.110519

[6]. Lee, J.; Im, P.; Munk, J.D.; Malhotra, M.; Kim, M.; Song, Y. Comparison Evaluations of VRF and RTU Systems Performance on Flexible Research Platform. *Adv. Civ. Eng* 2018**,** *2018*, 7867128. https://doi.org/10.1155/2018/7867128

[7]. Yun, G.-Y.; Lee, J.-H.; Kim, H.-J. Development and application of the load responsive control of the evaporating temperature in a VRF system for cooling energy savings. *Energy Build* 2016, *116*, 638–645. https://doi.org/10.1016/j.enbuild.2016.02.012

[8]. Radchenko, M.; Radchenko, A.; Trushliakov, E.; Koshlak, H.; Radchenko, R. Advanced Method of Variable Refrigerant Flow (VRF) Systems Designing to Forecast On-Site Operation—Part 2: Phenomenological Simulation to Recoup Refrigeration Energy. *Energies* 2023**,** *16*(*4*), 1922. https://doi.org/10.3390/en16041922

[9]. Vafai, K. (Ed.). *Handbook of Porous Media*,3rd ed, CRC Press, Boca Raton, USA,2015

[10]. Cheng, H.; Liu, Y.; Sun, J.; Zhang, K. From Pre-Darcy Flow to Darcy Flow in Porous Media: A Simple Unified Model. *Water Resour. Res* 2024**,** *60*(*2*), e2023WR036902. https://doi.org/10.1029/2023WR036902

[11]. De Paoli, F. (2023) Convective mixing phenomena in porous heat exchangers: A review. *International Journal of Heat and Mass Transfer* 2023, *190*, 122-134. https://doi: 10.1140/epje/s10189-023-00390-8

[12]. Ranjbarzadeh, R.; Sappa, G. Numerical and Experimental Study of Fluid Flow and Heat Transfer in Porous Media: A Review Article. *Energies* 2025**,** *18*(4), 976. https://doi.org/10.3390/en18040976

[13]. Ilg, P. *Magneto-Permeability Effect in Ferrofluid Flow Through Porous Media Studied via Multiparticle Collision Dynamics*. *Transport in Porous Media* 2024**,** *151*, 1363–1380. https://doi.org/10.1007/s11242-024-02077-w

[14]. Genc, A.M.; Karadeniz, Z.H. *Investigation of Flow and Heat Transfer Performance of Gyroid Structure as Porous Media. Isı Bilimi ve Tekniği Dergisi* 2024**,** *44*(2), 351-358. https://doi.org/10.47480/isibted.1471713

[15]. HR Bahrami, AE Sharifi, Application of multilayered porous media for heat transfer optimization in double pipe heat exchangers using neural network and NSGA II, *Scientific Reports* 2024,*14*, , 31509. DOI: 10.1038/s41598-024-83176-y

[16]. MH Zolfagharnasab, MZ Pedram, S Hoseinzadeh, K Vafai. Application of Porous-Embedded shell and tube heat exchangers for the Waste heat Recovery Systems, *Applied Thermal Engineering* 2022, *211*, 118452. https://doi.org/10.1016/j.applthermaleng.2022.118452

[17]. KL Liaw, JC Kurnia, N Sallih, M Mustapha, AP Sasmito. Heat transfer analysis of subcooled flow boiling in copper foam helical coiled heat exchanger – A pore-scale numerical study, *International Communications in Heat and Mass Transfer* 2024,*155*, 107514. https://doi.org/10.1016/j.icheatmasstransfer.2024.107514

[18]. A Mezaache, F Mebarek-Oudinal, H Vaidya, K Ramesh. Impact of nanofluids and porous structures on the thermal efficiency of wavy channel heat exchanger, *International Journal of Thermal Sciences* 2025, *210*, 109673. https://doi.org/10.1016/j.ijthermalsci.2024.109673

[19]. TWB Riyadi, SG Herawan, A Tirta, YJ Ee, AL Hananto, PA Paristiawan, AA Yusuf, H Ven, Irianto, I. Veza. Nanofluid heat transfer and machine learning: Insightful review of machine learning for nanofluid heat transfer enhancement in porous media and heat exchangers as sustainable and renewable energy solutions, *Results in Engineering* 2024, *24*, 103002**.** 10.1016/j.rineng.2024.103002

[20]. Saryazdi, Seyed Mohammad Ebrahimi; Etemad, Alireza; Shafaat, Ali; Bahman, Ammar M. A comprehensive review and sensitivity analysis of the factors affecting the performance of buildings equipped with Variable Refrigerant Flow system in Middle East climates. *Renewable and Sustainable Energy Reviews* 2024**,** *191*, 114131. DOI: 10.1016/j.rser.2023.114131

[21]. Arroyo Gómez, Y.; San José-Alonso, J.F.; San José-Gallego, L.J.; Rey-Hernández, J.M.; Sanz-Tejedor, A.; Rey-Martínez, F.J. Optimizing Energy Efficiency and Sustainability in Winter Climate Control: Innovative Use of Variable Refrigerant Flow (VRF) Systems in University Buildings. *Appl. Sci* 2025, *15*(5), 2374. https://doi.org/10.3390/app15052374

[22]. Shaikh, P.H.; Nor, N.B.M.; Nallagownden, P.; Elamvazuthi, I.; Ibrahim, T. *A review on optimized control systems for building energy and comfort management of smart sustainable buildings, Renewable and Sustainable Energy Reviews* 2014**,** *34*, 409–429. DOI : 10.1016/j.rser.2014.03.02

[23]. Nield, D.A.; Bejan, A. *Convection in Porous Media*, 5th ed.; Springer: Cham, Switzerland, 2017.
DOI: 10.1007/978-3-319-49562-0

[24]. Vafai, K. (Ed.). *Handbook of Porous Media*, 2nd ed.; CRC Press: Boca Raton, FL, USA, 2005.
DOI: 10.1201/9780415876384

[25]. D'Rose, R.; Willemsz, M.; Smeulders, D. Transient Convective Heat Transfer in Porous Media. *Mathematics* 2023, *11*(21), 4415. https://doi.org/10.3390/math11214415

[26]. Z. Guo & T. Zhao, "A lattice Boltzmann model for convection heat transfer in porous media", *Numerical Heat Transfer, Part B: Fundamentals* 2005, *47*(2), 157–177.DOI : 10.1080/10407790590883405

[27]. Marykovskiy, Y.; Pomaranzi, G.; Schito, P.; Zasso, A. A Method to Evaluate Forchheimer Resistance Coefficients for Permeable Screens and Air Louvers Modelled as a Porous Medium. *Fluids* 2024, *9*, 147. https://doi.org/10.3390/fluids9070147

[28]. Lenci, A.; Zeighami, F.; Di Federico, V. Effective Forchheimer Coefficient for Layered Porous Media. *Transp. Porous Media* 2022, *144*, 459–480. https://doi.org/10.1007/s11242-022-01815-2

[29]. W Sobieski, A Trykozko.Sensitivity Aspects of Forchheimer's Approximation. *Transport in Porous Media* 2011, 89, 155-164. https://doi**.** 10.1007/s11242-011-9760-7

[30]. He, X., & Luo, L. S. Lattice Boltzmann model for the incompressible Navier–Stokes equation. *Journal of Statistical Physics* 1997, *88*(3-4), 927-944. Doi:10.1023/B:JOSS.0000015179.12689.e4

[31]. M. hamdi, S. Elaimi, S. ben Nasrallah. Lattice Boltzmann simulation of the cubic magnetoconvection with coupled revised matrix-multiple relaxation time model. *Progress in Computational Fluid Dynamic* 2018, *Vol. 18*, No. 6, 376. Doi: 10.1504/PCFD.2018.096621

[32]. M. Hamdi, S. Elalimi, and S. B. Nasrallah. Exergy for A Better Environment and Improved Sustainability 1: Fundamentals .*Springer, Cham* 2018, pp. 661–683.

[33]. Wen , M., Shen, S. , Li, W. GPU parallel implementation of a finite volume lattice Boltzmann method for incompressible flows, *Computers & Fluids* 2024*,* 285 , 106460. https://doi.org/10.1016/j.compfluid.2024.106460

[34]. Liu, Z. , Zhao, Y. , Zhu, W. , Wang,Y. A Parallel Algorithm Based on Regularized Lattice Boltzmann Method for Multi-Layer Grids.*Applied Sciences* 2024 , *14*(16), 6976. https://doi.org/10.3390/app14166976

[35]. He, X., & Luo, L.-S. *A priori derivation of the lattice Boltzmann equation. Physical Review E* 1997, *55*(R6), R6333–R6336. https://doi.org/10.1103/PhysRevE.55.R6333

[36]. X. He & L.-S. Luo.Theory of the lattice Boltzmann method: From the Boltzmann equation to the lattice Boltzmann equation. *Physical Review E* 1997, *vol. 56*, pp. 6811. DOI: 10.1103/PhysRevE.56.6811

[37]. Succi, S. *The Lattice Boltzmann Equation for Fluid Dynamics and Beyond.* Oxford University Press: Oxford, UK, 2001.

[38]. Guo, Z.; Shi, B.; Zheng, C. *A coupled lattice BGK model for the Boussinesq equations. International Journal for Numerical Methods in Fluids* 2002, *39*(4), 325–342. DOI: 10.1002/fld.337

[39]. Q. Li, P. Zhou, H. J. Yan. *Improved thermal lattice Boltzmann model for simulation of liquid–vapor phase change*. *Physical Review E* 2017**,** 96**,** 063303**.**DOI: 10.1103/PhysRevE.96.063303**.**

[40]. Z. Guo & T. S. Zhao. *A lattice Boltzmann model for convection heat transfer in porous media.Numerical Heat Transfer, Part B: Fundamentals* 2005**,** *47* pp157–177**.**DOI: 10.1080/10407790590883405

[41]. Kim, S.Y.; Kang, B.H.; Hyun, J.M. Heat Transfer from Pulsating Flow in a Channel Filled with Porous Media. *Int. J. Heat Mass Transf* 1994**,** *37*, 2025–2033. https://doi.org/10.1016/0017-9310(94)90304-2

[42]. Mohamad, A.A. *Applied Lattice Boltzmann Method for Transport Phenomena: Momentum, Heat and Mass Transfer*; Department of Mechanical and Manufacturing

Engineering, Schulich School of Engineering, University of Calgary: Alberta, Canada, 2007; ISBN 978-0-9783253-0-5; pp. 2–31.

[43]. Mahmud, S.; Fraser, R.A. Flow, Thermal, and Entropy Generation Characteristics inside a Porous Channel with Viscous Dissipation. *Int. J. Therm. Sci.* 2005, *44*, 21–32. https://doi.org/10.1016/j.ijthermalsci.2004.05.001

[44]. Nield, D.A.; Bejan, A. *Convection in Porous Media*, 5th ed.; Springer: New York, USA, 2017.

[45]. Kaviany, M. *Principles of Heat Transfer in Porous Media*, 2nd ed.; Springer: New York, USA, 1995.

[46]. Mahmud, S.; Pop, I**.** Mixed Convection in a Square Vented Enclosure Filled with a Porous Medium. *Int. J. Heat Mass Transf.* 2006, *49*(13–14), 2190–2206. https://doi.org/10.1016/j.ijheatmasstransfer.2005.11.022

[47]. Abusafa, A.; Abujab, M**.** Optimal Insulation Thickness of Pipes in a Variable Refrigerant Flow (VRF) System: An-Najah Child Institute as a Case Study. *Energy Reports* 2022, *8*, 104–116. https://doi.org/10.1016/j.egyr.2022.06.104

[48]. Dongellini, M.; Natale, C.; Naldi, C.; Morini, G. L. Energy and Environmental Performance Comparison of Heat Pump Systems Working with Alternative Refrigerants. *Appl. Sci***.** 2023**,** *13*, 7238. https://doi.org/10.3390/app13127238

[49]. Gilani, H.A.; Hoseinzadeh, S.; Karimi, H.; Karimi, A.; Hassanzadeh, A.; Astiaso Garcia, D. Performance Analysis of Integrated Solar Heat Pump VRF System for the Low Energy Building in Mediterranean Island. *Renew. Energy* 2021**,** *174*, 1006–1019. https://doi.org/10.1016/j.renene.2021.04.081

[50] Hasan, S.; Khan, M.E.; Parvez, M. Experimental Analysis of a Solar Thermal Hybrid VRF System for Maximum Energy Economy Based on Delhi (India) Climate. *Energy Sources Part A* 2019**,** *41*(20), 2418–2432. https://doi.org/10.1080/15567036.2019.1663305

General conclusion

The goal of this thesis is the development and analysis of the performance of a solar powered air conditioning system using only passive technologies of porous media. Traditional models of the air conditioning unit are known to consume a large amount of electricity due to their reliance on electricity in order to run compressors, Electronic Expansion Valves (EEV), in addition to their reliance on external storage units.
For these reasons, a novel dual component system has been proposed to remove any need for traditional control systems: (1) Solar Double Porosity Heat Exchanger (SDPHEX), which integrated thermal storage media directly into heat exchanger components via a dual porosity system, and (2) Multi Porosity Heat Exchanger (MPHEX), which passively alters refrigerant flow via a porous medium as an alternative to traditional VRF systems.

For SDPHEX model, the combination of the two porous media with different permeabilities resulted in the formation of a dynamical and thermally efficient configuration. In the downstream medium (high Darcy number and solid state thermal conductivity), the convective heat transfer and conditioning of the working fluid are achieved before entering the upstream part of the SDPHEX configuration. In this regard, the SDPHEX unit functions as both a solar energy transfer system and an energy storage unit because of this thermal configuration. In the complementarily working downstream medium with lower permeability and thermal conductivity values, heat retention for a longer period occurs.
In this setup, the efficiency of thermal storage and control is promoted without needing any additional control system. The simulation experiment demonstrated that in the SDPHEX system, there is a significant efficiency in the use of thermal energy; this is because there is less dependence on the traditional storage means like the tank or the phase change materials. There is an improvement in the COP of up to 20% compared to a standard air conditioner. The amount of refrigerant is lowered by a third (33%), which has various implications.
The value of CO_2 equivalents given out by the solar assisted SDPHEX system demonstrated a considerable reduction (20-33%) for different loading conditions. This occurred due to the combined effect of the use of solar energy for preheating and reduced energy losses. This system looks more promising when implemented in highly solar intense locations where the solar radiation is steady throughout the cooling season.

Concurrently, the MPHEX solution provided a solution to the problem of flow regulation with neither electronically controlled expansion valves nor compressors. Its design, which consists of layers of porous media with variable permeability, was found to be capable of either passive flow or passive pressure gradient regulation. As the permeability in the porous media structure enhances, it significantly enhances flow rates to higher values (65%) with a corresponding reduction in outlet temperatures to 30%. The velocity profiles in the MPHEX arrangement were also smoother and more stable, unlike those in the conventional VRF systems. In contrast to the conventional VRF systems that use inverter compressors and EEVs to control the flow rates, the MPHEX achieves stability based solely on the resistance offered by the materials. The results of the exergy analysis showed that the entropy generation rate around the inlet, where the entropy generation rate was highest, was reduced by up to 90% in a well-designed MPHEX. Furthermore, the effect of varying the number of porous layers showed saturation of performance improvement after four layers. This information can act as an indicator in designing future MPHEX systems. Also, in terms of system comparison, it was found that the MPHEX system was better than the VRF system regarding ease of use, passive energy conservation, and support for autonomous operation.

The combination of SDPHEX and MPHEX showcased the complementary roles of the two systems in a unified passive cooling system. SDPHEX was responsible for the solar thermal absorption and the storage, while the MPHEX offered the passive flow controlling mechanism. The combination of the two allows for the construction of a highly efficient and mechanically simple solar air conditioning system, which relies less on electronics and storage tanks, making it applicable for sustainable building concepts, especially in developing nations.

Limitations and Recommendations

Although these systems provide considerable numerical potential, there are some limitations that should be acknowledged. The systems were designed in steady state and optimal conditions. The transient processes, weather changes, and material degradation in real life were not taken into account in greater detail. Besides, the feasibility of production and economics of the porous systems were not considered in this work.

Recommendations

It is advised that experimental validation should also include dynamic tests as well as solar radiation profiles. Cost analysis may also add insight into the economic feasibility of these proposed systems, particularly in developing countries. Additional tests and optimization attempt on materials regarding porous distributions and thickness may provide improvements.

Future perspectives

Several potential avenues for further research emerge from this thesis. Firstly, the geometry parameter optimization in porous exchangers could make use of algorithms and methods for the achievement of the optimal compromise between performance and manufacturability. Secondly, the use of the SDPHEX-MPHEX system in hybrid configurations (solar+PV+storage+passive cooling systems) could provide robustness to buildings even in off-grid or intermittently powered sites. Additionally, incorporating such systems with weather forecasting systems, or even with adaptive control systems, might improve their response to the seasons of the year positively despite their passivity. New materials, such as metal foam, ceramic, and biologically derived composites with different thermal and fluid characteristics, may also offer a broader suitability for such systems.

Lastly, this thesis marks the beginning of a new era among self-regulating cooling systems that are in line with the vision of the energy transition.