الجمهورية الجزائرية الشعبية الديمقراطية

Algeria of Republic Democratic People's

وزارة التعليم العالي والبحث العلمي

Ministry of Higher Education and Scientific Research

جامعة الشهيد حمة لخضر الوادي

University of Echahid Hamma Lakhdar El-Oued

جامعة الشهيد حمة لخضر الوادي

FACULTY OF TECHNOLOGIE

DEPARTMENT OF MECHANICAL

Thesis

Submitted in partial fulfilment of the requirements for the Degree of

ACADEMIC MASTER

Field: Sciences and Technology

Option: Mechanical engineering

Specialty: Energy

Theme

Design and Performance Analysis of Tubular Heat Exchangers

by:

- **DJOUADI MOHAMMED ABD ELILAH**
- **DIAB AZEDDINE**

Supervised by:

- **Dr. KHECHEKHOUCHE ABDERRAHMANE**

President:

- **Dr. DAGHOUM KHALIL**

Discussed:

- **Dr. BOUKHARE ALI**

AcademicYear:2024/2025

Abstract (English)

This Master's project focused on the design, construction, and experimental validation of a tubular heat exchanger, using local materials, to serve as a versatile test bed within the University of El Oued laboratory. The primary objective was to provide a practical platform for studying fundamental heat transfer phenomena. The experimental methodology involved circulating hot and cold water through the heat exchanger in both co-flow and counter-flow arrangements, initially at equal flow rates and then doubling the cold fluid flow rate. Temperature profiles were accurately recorded using thermocouples at 5-minute intervals. The results clearly demonstrate the superior performance of the counter-flow configuration, achieving a heat exchanger efficiency of up to 0.5610 (56.10%). In contrast, the co-flow arrangement exhibited lower efficiencies, ranging from 0.1944 (19.44%) to 0.4172 (41.72%). Doubling the cold fluid flow rate significantly improved the co-flow efficiency by 114.6%, with only a modest increase of 0.25% in the already highly efficient counter-flow mode. All experiments demonstrated steady fluid flow in the laminar regime, with Reynolds numbers ranging from approximately 280 to 547. This project has successfully established a valuable laboratory tool that will greatly enhance teaching and practical research capabilities in the fields of heat transfer and fluid mechanics.

Keywords:

- Tubular heat exchanger - Heat transfer - Counter-flow and co-flow - Experimental validation

- Efficiency - Thermocouples - Reynolds number - Laminar flow - Cold fluid flow rate

- Fluid mechanics .

الملخص

ركز مشروع الماستر هذا على تصميم، بناء، والتحقق التجريبي لمبادل حراري أنبوبي، باستخدام مواد محلية ليكون بمثابة منصة اختبار متعددة الاستخدامات داخل مختبر جامعة الوادي . كان الهدف الأساسي هو توفير منصة عملية لدراسة ظواهر انتقال الحرارة الأساسية. تضمنت المنهجية التجريبية تدوير الماء الساخن والبارد عبر المبادل الحراري في ترتيبات تدفق متوازية ومتعاكسة ، في البداية بمعدلات تدفق متساوية، ثم بمعدل تدفق السائل البارد مضاعف. تم تسجيل بيانات درجات الحرارة بدقة باستخدام المزدوجات الحرارية على فترات 5 دقائق. أظهرت النتائج بشكل لا لبس فيه الأداء المتفوق لتكوين التدفق المتعاكس، حيث حققت فعالية مبادل حراري تصل إلى **0.5610 (56.10%).** في المقابل، أظهر ترتيب التدفق المتوازي فعالية أقل، تتراوح من **0.1944 (19.44%)** إلى **0.4172 (41.72%).** أدى مضاعفة معدل تدفق السائل البارد إلى تحسين ملحوظ في فعالية التدفق المتوازي بنسبة **114.6%**، بينما أسفر عن زيادة هامشية بلغت **0.25%** فقط في وضع التدفق المتعاكس الذي كان فعالاً للغاية بالفعل. أظهرت جميع التجارب باستمرار تدفق السائل في **نظام التدفق الطبقي** ، مع أرقام رينولدز تتراوح تقريبًا بين **280** و **547** .لقد نجح هذا المشروع في إنشاء أداة مختبرية قيمة ستعزز بشكل كبير التعليم العملي وقدرات البحث في انتقال الحرارة وميكانيكا الموائع.

الكلمات المفتاحية :

- مبادل حراري أنبوبي - انتقال الحرارة - التدفق المتعاكس والتدفق المتوازي - التحقق التجريبي - الكفاءة - المزدوجات الحرارية - عدد رينولدز - الجريان الصفحي - معدل تدفق السائل البارد - ميكانيكا الموائع .

DEDICATION

to my dear parents

whose unwavering support, sacrifices, and prayers have been the foundation of everything i've achieved—this accomplishment is as much yours as it is mine.

to my family

for their constant encouragement and belief in me, even during the times i doubted myself.

to my dear friends

who stood by me with their kind words, patience, and smiles during the hardest times—thank you for making this journey lighter.

and to my classmates

who shared with me moments of hard work and dedication, the stress of exams, and both the highs and lows of academic life. your companionship has been an invaluable source of strength. through you, i've learned that success is not only about results, but also about those who walk the path with us.

this project reflects your love, your faith in me, and your presence in my life.

ACKNOWLEDGEMENTS

First, we praise Allah, the Almighty, for granting us the strength and patience to complete this work to its end.

We extend our sincere thanks and highest appreciation to Dr. Abderrahmane Khechekhouche, doctor, at the Faculty of Technology, for his valuable guidance, warm reception, continuous assistance, kindness, and constant availability throughout the preparation of this thesis, in addition to his constructive advice.

We also express our deep gratitude to the members of the examination committee who kindly agreed to evaluate this work, and to all our esteemed professors for their support and teaching throughout our academic journey.

TABLE OF CONTENTS

Chapter 3. Construction and experimental studies

LIST OF FIGURES

LIST OF TABLES

List of abbreviations

- **A:** Heat Transfer Surface Area
- **°C:** Degrees Celsius
- **cp:** Specific Heat Capacity
- **Co-current:** Flow in the same direction
- **Counter-current:** Flow in opposite directions
- **D, d:** Diameter (outer and inner, respectively)
- **Gr:**Grashof Number
- **Gz:**Graetz Number
- **h:** Heat Transfer Coefficient
- **HDPE:** High-Density Polyethylene
- **HVAC:** Heating, Ventilation, and Air Conditioning
- **HVAC&R:** Heating, Ventilation, Air Conditioning, and Refrigeration
- **HX:** Heat Exchanger
- **ID:** Inner Diameter
- **J:** Joule
- **K:** Kelvin
- **k:** Thermal Conductivity
- **kg:** Kilogram
- **kg/s:** Kilograms per second
- **L:** Length
- **LMTD:** Logarithmic Mean Temperature Difference
- **Lt:** Theoretical Length
- **m:** Meter
- **m^3/s:** Cubic meters per second
- **μ:** Dynamic Viscosity
- **n:** Number of Exchangers in Series
- **Nu:**Nusselt Number
- **OD:** Outer Diameter
- **PPR:** Polypropylene Random Copolymer
- **Pr:**Prandtl Number
- **PVC:** Polyvinyl Chloride
- **$\dot{Q}$:** Heat Transfer Rate (Thermal Power)
- **Re:** Reynolds Number
- **ρ:** Density
- **s:** Second
- **Tcold:** Cold Fluid Temperature
- **Thot:** Hot Fluid Temperature
- **Tin:** Inlet Temperature
- **Tout:** Outlet Temperature
- **U:** Overall Heat Transfer Coefficient
- **W:** Watt
- **ϵ:** Effectiveness

General Introduction

This master's thesis examines the practical design, fabrication, and evaluation of a tubular heat exchanger, a critical component in many applications in energy mechanics. Recognizing the fundamental importance of heat exchangers and the value of practical experience in engineering education, this thesis undertakes a comprehensive study encompassing both theoretical foundations and experimental validation.

The main objectives of this Master's thesis are:

- First, to demonstrate the feasibility and acceptable performance of a locally manufactured tubular heat exchanger.
- Second, and most importantly, to establish a reproducible methodology enabling individuals or institutions without existing prototypes to independently create, install, and test their own units, with results consistent with the original designs.
- Finally, this work aims to validate the potential of local materials and accessible techniques for the construction of functional heat exchangers, thus providing a valuable and reliable resource for practical learning and experimentation within the framework of university mechanical engineering education and potentially beyond.

This thesis is structured into three distinct chapters.

- Chapter 1 provides an extensive literature review of tubular heat exchangers, exploring their design principles, operational characteristics, and existing research. This literature review establishes the theoretical framework for the subsequent stages of the work.
- Chapter 2 details the methodology used for the calculation and design of the tubular heat exchanger prototype. This chapter describes the theoretical models and engineering principles applied to determine the key parameters and specifications of the manufactured unit.
- The core of this research lies in Chapter 3, which presents the experimental work and its results. This chapter describes the manufacturing process of a tubular heat exchanger from locally sourced materials in our laboratory. It also details the testing procedures conducted to evaluate the functional performance of the developed prototype. The results obtained

from our experimental setup are then analyzed and compared to the performance of an original, commercially available tubular heat exchanger.

- The thesis concludes with a general conclusion of the results and their implications for future work and educational applications.

Chapter 1.

Bibliographic Study

1.1. Introduction

Heat exchangers are essential components in a wide range of engineering systems, playing a crucial role in processes ranging from basic heating and cooling to complex industrial operations and advanced energy technologies. Their efficiency and reliability are paramount for optimal system performance and energy efficiency. This chapter explores the multifaceted world of heat exchangers and presents a collection of recent advances and research covering new repair methodologies, innovative heat transfer enhancement techniques, the growing application of nanofluids, the sustainable potential of geothermal and ground-source systems, challenges and solutions specific to high-temperature industrial environments, as well as the complex areas of numerical modeling, simulation, optimization, and intelligent design. By synthesizing these diverse and interconnected fields, this chapter aims to provide a comprehensive overview of the current state of heat exchanger technology and highlight promising avenues for future research and development.

1.2. Novel repair method for tube heat exchanger

Heat exchangers are very essential components of most engineering systems. Of interest is the common application of shell-and-tube heat exchangers (STHEs) due to their efficiency, flexibility, and applicability to treat different flow regimes and types. STHEs slowly experience various limitations such as corrosion, mechanical wear, and leakage, which undermine its performance and need to be repaired in order to ensure its usability. This study suggests a new repair method to extend the service life of failed STHE tubes by using new tube fittings. A comprehensive thermo-mechanical model is developed with the analysis of STHE performance, thermal contact resistance of fitted tubes, and mechanical stability of assembled structures. The governing equations are solved together with the assistance of Engineering Equation Solver (EES). All the submodels are validated against analytical or experimental findings and have good agreement. Design parameters of prime interest and their influence on thermal and mechanical behavior of STHEs are investigated systematically. Findings indicate that retention of heat load increases with the increment of the slope of the contact surface above 10° and reducing the effective surface roughness to below 3 µm. Among various interference fits, locational interference fitting is most advantageous both in thermal and mechanical performance. Higher operating pressure and tube diameter are equally significant in the choice of maintaining a safety factor of more than 1.5. The repair method is versatile in application to any STHE tube diameter, provided the material of the fitting tube possesses a yield strength of more than 300 MPa. Even when all the tubes are press-fitted, reduction of peak heat load is limited to 4.23%, even that falling within the acceptable range of less than 10% of originally designed heat load [1].

Based on the developing needs of industry and market, industrial and market demands for energy saving and heat recovery have increased enormously. In order to address these needs, various types of heat exchangers were conceived and investigated. This paper is a brief overview of already published literature describing the research status, structural classification, and engineering uses of heat exchangers with a focus on developing and using plate, shell, and tube heat exchangers. With an unstable numerical calculation approach, the efficiency of heat transfer in tube heat exchangers is thoroughly investigated. Based on the analysis of wall temperature variation with time, this study offers a theoretical foundation for further improved future research and technological application in heat exchangers [2].

The following is an experimental investigation of a novel Triple Fluid Heat Exchanger (TFHEX) suggested for efficient heat management in hybrid-cooled servers. The TFHEX is a double-tube finned heat exchanger with two liquid phases (hot water and warm water) and one gas phase (hot air). Hot air flows through the fins while hot water flows through the inner tube during its operation. Hot air and hot water heat extraction is accomplished by cooling water flowing through the annular tube. The model of TFHEX is tested in a wind tunnel at various heat loads by changing the flow rate at a fixed inlet fluid temperature. Total heat exchanger efficiency is determined by the heat transfer efficiency at different flow rates. Experimental results are contrasted with analytical expectations as well. Despite certain discrepancies between experiment and analysis outcomes, the outcomes reveal that TFHEX dissipates heat effectively over a wide range of fluid ratios, thus facilitating effective tailoring. This makes it a suitable solution for high-ambient deployment of data centers[3].

Surface heat exchangers find broad application in energy conversion and utilization systems, predominantly in heating, cooling, and heat recovery systems. Plate heat exchangers are one such example, finding extensive applications in single-phase and phase-change operations. The current work considers single-phase operations of plate heat exchangers, i.e., gas heat exchange. Types of plate heat exchangers are described, for instance gasketed, brazed, and welded plate heat exchangers. Based on a structural point of view, applications of these exchangers for gas heat transfer are presented. Gasketed and brazed plate heat exchangers, integrated into piping systems in the form of a heat exchanger, are generally used for liquid-liquid heat transfer. The pillowplate heat exchanger, a specially designed welded plate heat exchanger, is best for liquid-gas use due to its hydraulic diameter being small in inner channels and hydraulic diameter being large in outer channels. The primary-surface recuperator, a welded plate heat exchanger with high-temperature gas-gas use, is utilized under high pressure. In addition, the plain constructed glued plate heat exchanger is applied to air-air heat exchange, where the inclusion of an air-air plate heat exchanger with two fans is considered a system. New uses of plate heat exchangers in gas heat transfer are also addressed in this paper [4].

This paper introduces a new approach to minimizing thermal intermittency in heat exchangers, a significant challenge in enhancing the energy efficiency and maximizing thermal management for a broad spectrum of applications. A double-fluid slab-finned minichannel heat exchanger integrated with a number of phase change materials (PCMs) is introduced and optimized using computational fluid dynamics (CFD) simulations based on the finite element method. The human body heat transfer coupling, hot working fluid and airflows, and PCMs' phase transition are taken into account by the model. In charging, PCMs take up thermal energy, which is transferred to the airside during discharging. Four different configurations of PCM distributions are taken into account, namely, series, series-parallel, series-combined, and parallel-combined configurations. It is demonstrated that encasing all five slabs in multiple PCMs significantly enhances thermal performance compared to single-PCM systems. Under discharging, the multi-PCM model sustained an air outlet temperature above 30 °C for 80 seconds, rapidly transferring 80% of the stored energy (215 kJ) to the airside with a maximum PCM effectiveness of 62%. It also transferred up to 85% more thermal energy to the airside during the initial five minutes of discharging compared to previous single-PCM studies. The contribution of this research lies in the integration of greater than one PCMs with double fluid flows, increasing heat exchanger-based thermal management. The model suggested has significant engineering potential, including improved energy efficiency and operational performance in thermal management systems. In automobiles, it offers improved thermal performance by maintaining cabin comfort during brief stop times in automobiles with the start-stop technology[5].

This study presents a new Functionally Graded Hybrid Triply Periodic Minimal Surfaces (FGH-TPMS) heat exchanger structure by combining Gyroid and Diamond TPMS structures to enhance heat transfer performance and fluid dynamics. Conventional heat exchangers have drawbacks in compactness, weight reduction, and thermal performance. The proposed FGH-TPMS layout overcomes these challenges, achieving 5.26%–7.43% enhancement of heat transfer coefficients and 14.4% reduction of flow resistance at moderate Reynolds numbers, which increases energy efficiency and lowers operating costs. Through its gradual transition from a Gyroid structure at the inlet to a Diamond structure at the outlet, the FGH-TPMS layout enhances the Performance Evaluation Criterion (PEC) by 15.7% compared to the Gyroid baseline. These findings exhibit the potential of the FGH-TPMS design for next-generation heat exchanger technology development[6].

Figure 1.1.Heat exchange in the workshop

1.3. Heat Transfer Enhancement Techniques

This paper addresses the advancement in heat transfer augmentation using active and passive techniques. Review of literature indicates that these techniques have been successful in enhancing heat transfer performance. Various techniques like electrohydrodynamics, magnetic field, corona wind, vortex generator, tape and coil insert, surface roughness, and duct modification have been addressed. Their performance has been compared. Observations have revealed that passive methods have been more extensively investigated due to their reliability, safety, and lack of additional power demands. Among these, duct modification is a very effective method for HTE. Literature reveals that the combination of active and passive HTE methods may increase their advantages and deliver improved performance. While active techniques exhibit impressive improvements, passive techniques remain in favor due to their simplicity of application and cost-effectiveness. Passive enhancement hardware such as vortex generators and artificial roughness can significantly alter flow patterns, hence enhancing heat transfer. Surface modifications with ribs, dimples, or roughness have also been discovered to increase thermal performance by over 200% compared to smooth channels. Coupling modified ducts with other passive strategies provides a viable means to further performance enhancement[7].

The increasing significance of combating climate change using renewable energy solutions cannot be denied, and shallow geothermal energy is a cost-effective and sustainable source. Ground-source heat pump systems make use of this renewable energy, and the ground heat exchanger is an important part that has a significant impact on the coefficient of performance of the system. The article provides a general overview of existing developments in ground heat exchangers considering the impact of system geometric configuration, pipe material, working fluid, and depth on various performance factors like heat flux, heat transfer coefficient, outlet temperature, thermal resistance, and pressure drop. Although the impact of geometric design on system performance is well established, no such comprehensive review exists in this regard. This paper aims to bridge this gap by reviewing recent studies on ground heat exchangers[8].

This study experimentally investigates the heat transfer, friction factor, and thermal performance of a tube equipped with twisted rings (TRs). Tests were conducted with TRs having three width ratios (W/D = 0.05, 0.1, and 0.15) and three pitch ratios (p/D = 1, 1.5, and 2) for Reynolds numbers ranging from 6000 to 20,000, with air as the test fluid. For comparison, experiments were also conducted on standard circular rings (CRs). The experimental results indicate that, in most cases, TRs possess smaller Nusselt numbers and friction factors than CRs, except at the largest width ratio (W/D = 0.15) and the smallest pitch ratio (p/D = 1.0). In addition, the Nusselt number and friction factor both increase with increasing width ratio and decreasing pitch ratio. But the best thermal performance factor is with TRs of the lowest width and pitch ratios. Empirical correlations for heat transfer (Nu) and friction factor (f) are also presented in this paper[10].

This research incorporates experimental investigation of the mixed convection heat transfer in a coil-in-shell heat exchanger in relation to varying Reynolds and Rayleigh numbers, ratio of tube to coil diameter, and dimensionless coil pitch. The purpose is to determine how parameters like coil pitch, tube diameter, mass flow rates in shell-side and tube-side will affect the modified effectiveness and the performance coefficient in vertical helical coiled tube heat exchangers.

Steady-state analysis was performed and for laminar as well as turbulent flow conditions within the coil experiments were conducted. It can be seen from the results that mass flow rate of tube-side and shell-side influences significantly on axial temperature profile of the heat exchanger. The $\varepsilon - NTU$ correlation in a mixed convection heat exchanger was seen to be approximatively identical with that for simple counter-flow heat exchanger[12].

Fin-and-tube heat exchangers are among the most prevalent heat exchangers for thermal energy conversion in air conditioning, refrigeration, automotive applications, and electronic cooling. Due to the need for more efficient and compact heat exchangers, extensive research has been conducted in this field. This paper provides a comprehensive review of experimental and numerical studies of various heat transfer enhancement mechanisms in fin-and-tube heat exchangers. The effects of different geometrical parameters on heat transfer and pressure drop for each mechanism are presented. Further, comparisons between different enhancement techniques and novel compound designs of fin-and-tube heat exchangers are considered. Special topics such as surface treatment, particle deposition, thermal contact resistance, and construction materials are also surveyed. Finally, existing correlations for predicting heat transfer and pressure drop characteristics of fin-and-tube heat exchangers are classified and compared based on their validation ranges[17].

Cross-flow heat exchangers are a specific type of heat exchanger where two fluids exchange heat as they flow perpendicular to one another. These systems are typically made up of multiple tubes or cylinders with hot fluid and a cold fluid flowing over them. Additional fins and delta winglets are typically added to enhance heat transfer, causing turbulence and increasing thermal efficiency. The use of vortex generators also aids system miniaturization. Nevertheless, the use of passive enhancement techniques in cross-flow heat exchangers may significantly increase pumping power requirements. The paper presents a comprehensive overview of recent advancement in cross-flow heat exchangers, specifying important developments, performance evaluation criteria, and prospective improvements. Recent state-of-the-art approaches are extensively explained, along with suggestions for future direction in this subject[18].

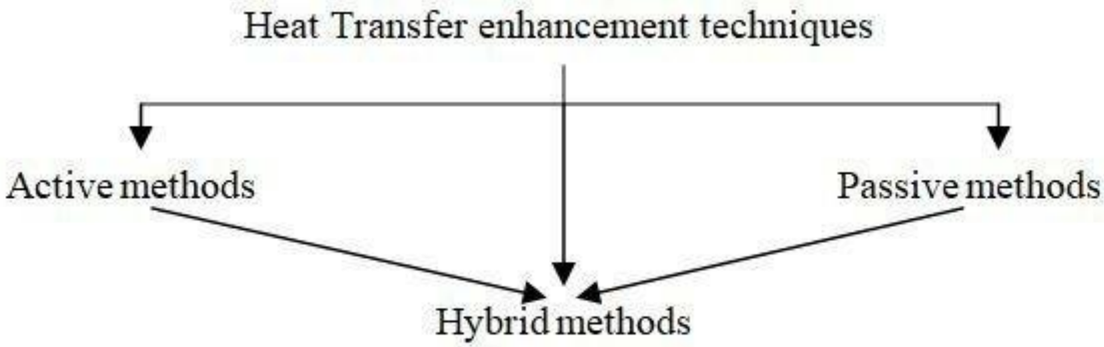


Figure 1.2.Heat Transfer enhancement techniques

1.4. Role of Nanofluids in Heat Exchangers

This study mathematically investigates the impact of twisted tubes and Al2O3 nanofluid on the thermal performance of shell and tube heat exchangers. Computational fluid dynamics (CFD) simulations using different models of turbulence are conducted, including the realizable k-ε and second-order realizable k-ε models. To validate, comparisons are made with published studies that utilized the first-order realizable k-ε model as the best method. 0.5 kg/s, 1 kg/s, and 2 kg/s mass flow rates are employed to determine thermal performance. Twisted tubes test pure water along with 5%, 10%, 15%, and 20% Al2O3 nanofluids, whereas smooth tubes heat exchangers (with and without 6 baffles) take only pure water. The experiments reveal that the use of twisted tubes instead of smooth tubes increases the heat transfer coefficient by approximately 20% but introduces a pressure drop of 14%. The combined use of 20% nanofluid and twisted tubes (compared to pure water and smooth tubes with 6 baffles) also increases heat transfer by 8% and reduces pressure drop by 40%. These results confirm that the use of nanofluids and twisted tubes enhances heat performance at the expense of reducing pump energy costs, an economical alternative to traditional baffled heat exchangers[9].

Nanofluids are increasingly used in cooling systems such as heat exchangers and renewable energy use such as solar cells, where they are used as a heat transfer fluid. In this review, techniques of stabilizing nanofluids and measuring it are discussed, including zeta potential measurement, electron microscopy, and photographic sedimentation analysis. Recent advancements in the stabilization of nanofluids and investigations on the parameters influencing thermal properties are discussed as well. The article presents the most important uses of nanofluids in cooling systems with the prominent benefits of enhanced heat transfer, reduced heat transfer time, reduced sizes of the heat exchangers, and improved energy and heat efficiency. The most prevalent parameters affecting the thermal conductivity of nanofluids are concentration, temperature, particle type, base fluid, and nanoparticle properties [13].

Heat exchangers constitute an important component in chemical processing plants, dairy and food sectors, and power facilities. Advances in heat exchangers are mainly to minimize energy usage. An efficient heat exchanger optimizes heat transfer rates with minimal pumping energy at low energy savings costs. Plate heat exchangers (PHEs) have been extensively used in all areas of engineering owing to the simplicity, ease of maintenance, and flexibility they offer over other types. Passive surface augmentation methods for single- and two-phase flow, as well as applications of nanofluids in different types of PHE, are discussed in this paper. Geometrical parameters' impact on hydraulic-thermal performance, as well as fouling deposits' formation on PHE, are also studied. Chevron angle is found to be the most prominent geometrical parameter in the calculation of flow properties. Heat transfer coefficient (HTC), Nusselt number (Nu), and pressure drop (ΔP) all increase as β, γ, and ϕ increase. ΔP increases with vapor quality and mass flow rate but decreases with increased saturation pressure in two-phase flow. Optimum geometric parameters for maximum heat transfer are β: 30°-60°, γ: 0.075–0.6, and φ: 1.18–1.3. Nanofluid application is recommended in case of laminar flow by a majority of the literature[14].

1.5. Ground and Geothermal Heat Exchangers

A field test system was established to test the thermal performance of different types of U-vertical ground coupled heat exchangers (UGCHE). It includes single and double U-pipes with sandstone backfills and a single U-pipe with cement backfills. The tests were conducted in various conditions including different inlet temperatures, flow rates, soil type, backfill material, numbers of U-pipes, and operating modes. An inner heat source model was used to simulate the subsurface temperature field, and simulation was done using specialized porous medium software. The results from the simulation and experiments were intended to advance knowledge on the factors responsible for the thermal performance of UGCHE systems[11].

Ground (or geothermal) heat exchangers increasingly stand as a valuable means of tapping shallow geothermal energy. This paper presents a critical review and a thorough introduction to the heat transfer analysis of borehole and foundation pile ground heat exchangers with focus on various analytical models. In view of the multi-disciplinarity involved in ground heat exchanger thermal operations, literature is reviewed here on a time-scale basis for considering multiple scales for space and time. The present work collates, discusses, and summarizes most recent developments reported for heat-source models, short-time models, energy pile models, in situ thermal response testing, indoor sandbox model tests, and parameter estimation as an inverse problem. Most importantly, the one U-pipe ground heat exchanger unit-step temperature response (i.e., the G-function) is calculated and compared for six analytical models: an infinite cylinder-source model, two infinite line-source models, two finite line-source models, and a composite-medium line-source model. The paper concludes by emphasizing some of the outstanding issues that must be addressed [16].

Supercritical and trans-critical carbon dioxide (SCO_2) cycles are widely used in refrigeration, heat pumps, and power generation, where heat exchangers play a key role. In this paper, a critical evaluation of heat exchangers under cooled SCO_2 flows is made with emphasis on the influence of thermo-physical property variations in the region near the critical point on heat transfer efficiency. The study first emphasizes fundamental SCO_2 heat transfer characteristics before elaborating on experimental findings, computational fluid dynamics (CFD) simulation, dynamic response, and SCO_2 heat exchanger design. A number of heat transfer improvement techniques are discussed, and a mathematical approach based on a polynomial Gaussian probability density function is proposed to model SCO_2 thermo-physical properties with temperature. The study shows that for Reynolds numbers of 1.9×10^4 to 2.55×10^5, methods such as surface protrusions, rough elements, twisted tape inserts, and nano-coatings may be able to offer effective heat transfer improvement. Further numerical and experimental data are recommended. The present review provides preliminary guidelines for the design, optimization, and experimental study of SCO_2 cooling heat exchangers[21].

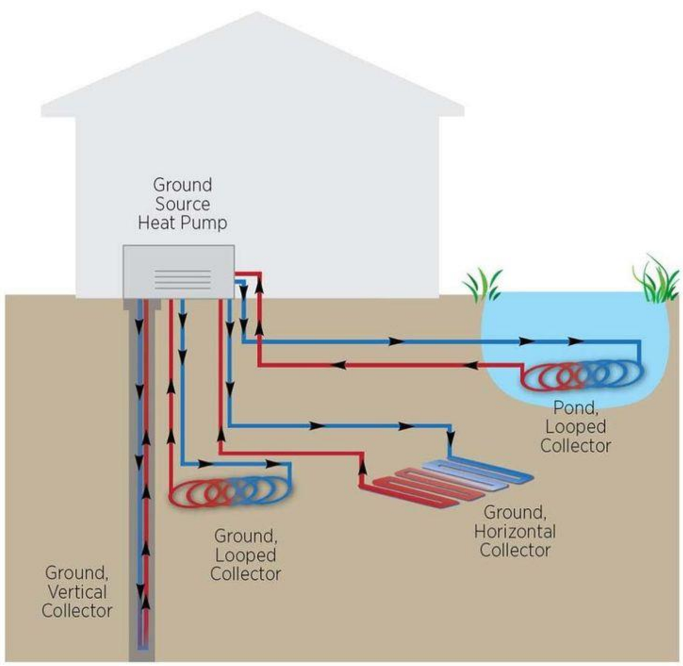


Figure 1.3. Ground and Geothermal Heat Exchangers

1.6. High-Temperature and Industrial Heat Exchangers

This study discusses the role of heat exchangers to increase efficiency in heat transfer, with emphasis on benefits of Process Integration. A heat exchanger facilitates thermal energy transfer from a fluid to another fluid with no contact and mixing. Heat exchangers are used across a wide scope of applications ranging from building heating and cooling systems to achieving optimal performance in industrial machinery and engines. This paper presents a concise summary of different heat exchanger designs with a focus on their applications and significance in thermal management[19].

Heat exchangers, as the fundamental components of most energy systems, are crucial to technological and industrial processes. Heat exchangers are classified based on their applications and operating conditions. The principal types of heat exchange equipment and the selection criteria for some types based on temperature, flow behavior, and pressure drop are covered in this paper. Additionally, the study presents an overview of computer software utilized to analyze heat exchangers and for computational fluid dynamics (CFD) modeling software, design software, and performance analysis software. The advantages of different analytical and numerical methods of heat transfer efficiency analysis are emphasized[22].

High-temperature heat exchangers have been the subject of increasing interest in recent years due to the advantages they provide in industrial processes. There is typically a maximum operating temperature limit for heat exchangers. Above that temperature, the heat exchanger needs special material and design considerations. Currently, this temperature is 600°C, which is above the previous level due to advancements in heat transfer and materials in recent years. This article provides a general review of various high-temperature heat exchanger designs, materials, heat transfer fluids, and the main technical problems and scientific gaps in the area. The aim is to determine how the efficiency, economic viability, and safety of high-temperature heat exchangers can be improved. The survey reveals that: (i) molten salts, liquid metals, helium, and supercritical carbon dioxide are the most suitable heat transfer fluids for service at high temperature; (ii) the most common configurations are shell-and-tube, plate, plate-fin, helical coil, finned tube, printed circuit, double-pipe, and bayonet tube heat exchangers; and (iii) iron- and nickel-based alloys, as well as ceramics, are the most commonly used materials. Some of the key challenges for high-temperature heat exchangers include corrosion, material degradation over time, loss in performance, and limited service life. The paper also discusses key design criteria, including fluid types, operating conditions, required heat transfer rates, and cost considerations, and provides a brief but informative state-of-the-art review while identifying gaps for future research [23].

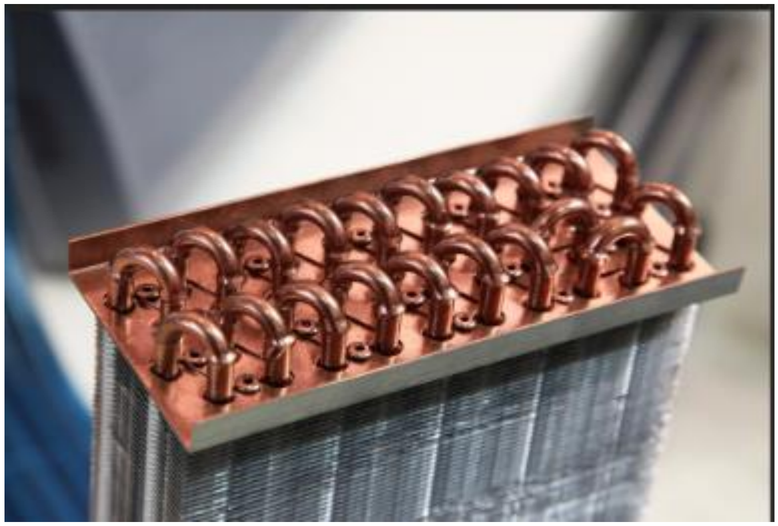


Figure 1.4. High-Temperature and Industrial Heat Exchangers

1.7. Numerical Modeling and Simulation of Heat Exchangers

Printed circuit heat exchangers (PCHEs) are high-performance, compact heat exchangers with advantages such as low-temperature operation, high-pressure tolerance, and high heat transfer capability. They have shown great potential for use in advanced nuclear power, solar thermal power generation, and hydrogen energy technology. This review summarizes and classifies recent findings in PCHE studies, with focus placed on flow and heat transfer behavior obtained from experimental and numerical approaches. Current research is mostly focused on single-phase flow with supercritical carbon dioxide or helium as the working fluid. Some basic problems remain to be solved, such as understanding detailed development of the flow and temperature fields, multi-phase flow regimes, and the high Reynolds-number regime. Future research directions are also indicated by this paper for enhancing PCHE performance and its application [20].

This study will try to emphasize some of the overlooked aspects of the concept of effectiveness (the ratio of the actual heat transfer to the maximum possible heat transfer) in heat exchangers, offering a critical perspective and a thorough explanation. The paper demonstrates that the effectiveness parameter must be accorded greater importance when used in fluid-flow parametric or sensitivity analyses of heat exchangers. Omitting the consideration of its latent properties would result in the derivation of fallacious or misleading conclusions regarding the performance of effectiveness curves. Exactly, it is illustrated that the trend of the effectiveness curve versus the Reynolds number on one side of the heat exchanger can increase, decrease, or follow an ascending-descending trend, depending on the mass flow rate of the fluid (Reynolds number) on the other side. While this criticism may not necessarily indicate a flaw in the effectiveness definition of heat exchangers, ignoring such attributes may lead to inappropriate inference in sensitivity analysis. Furthermore, it is unrealistic to provide empirical correlations to effectiveness vs. flow parameters without knowledge of attributes discussed in this study. To validate this view, experiments were conducted on a double-helical tube heat exchanger to analyze the concerned thermal parameters and statistically determine the identified characteristics of effectiveness. The analysis, however, can be extended to any heat exchanger [24].

This book contains advanced methods of numerical modeling of tube heat exchangers that are aimed to make design and operating calculations of exchangers with complex flow systems easier. The book covers new heat transfer correlations for laminar, transition, and turbulent flows. The majority of the book addresses experimental testing of heat exchangers, including approaches to evaluating uncertainty in indirect measurement. In addition, the book introduces a new approach to determining Nusselt number correlations on tube wall sides simultaneously through the nonlinear least squares method and computational fluid dynamics (CFD) modeling-based derivation of air-side Nusselt number correlations. Moreover, it examines the design of a control system based on a mathematical model of an automobile radiator and compares its performance with a digital proportional-integral-derivative (PID) controller. The book can be used by students, academics, and researchers as well as heat exchanger designers and manufacturers [25].

This paper reports on enhanced approaches to numerical modeling of tube heat exchangers, providing beneficial aid in both design and operating calculations for complicated flow patterned exchangers. New relationships for heat transfer in laminar, transition, and turbulent flows are introduced. Experimental testing of heat exchangers is highlighted a lot, as well as methods employed for assessing uncertainty of indirect measurement. Moreover, the book creates a new approach to generate correlations of Nusselt number for both sides of tube walls simultaneously using the nonlinear least squares approach and computational fluid dynamics (CFD) modeling for the purpose of establishing air-side Nusselt number correlations. In addition, the book investigates the design of a car radiator mathematical model-based control system compared to a digital proportional-integral-derivative (PID) controller. The book is ideal for students, researchers, teachers, and engineers involved in the designing and manufacturing of heat exchangers [26].

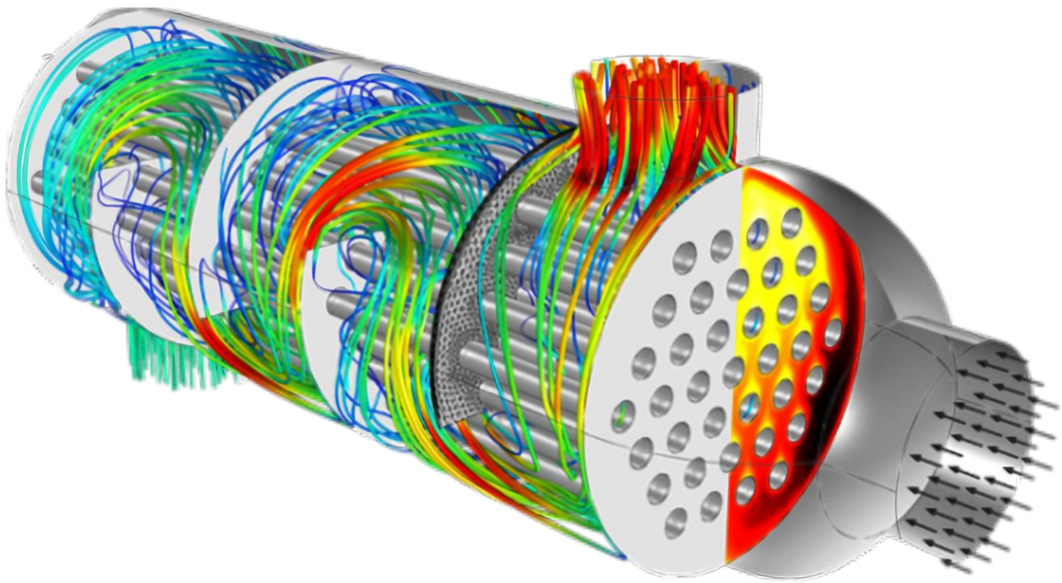


Figure 1.5. Numerical Modeling and Simulation of Heat Exchangers

1.8. Optimization and Smart Design in Heat Exchangers

The significant part played by heat exchangers (HXs) in power systems has long been understood, where HXs can potentially influence overall performance. With topology optimization (TO) and additive manufacturing, the latter can potentially be a pioneering technique for generating optimal HX structures to improve heat transfer. Although a few TO algorithms for HXs are already reviewed in the literature, there still exists no in-depth and comparative overview of their features, strengths, weaknesses, and limitations. This paper tries to overcome this limitation by giving a comprehensive, state-of-the-art overview of TO for HXs of recent decades, with the outline of the most promising technological avenues. All the phases of TO-design parametrization, modeling of thermal behavior, optimization, and final implementation—are reviewed thoroughly in respective sections with special focus on principal benefits, limitations, and challenges. Our study determines that though current TO techniques are much advanced, they also suffer from various problems in managing industrial HXs with complex structures and flow patterns. Moreover, three new approaches—machine learning, model order reduction, and moving morphable components—are explored as potential ways to enhance the efficiency of TO [27].

This article introduces a novel metaheuristic optimization technique based on the foraging behavior of the falcon species called the Falcon Optimization Algorithm (FOA). FOA is effective, efficient, probabilistic, population-based algorithm with minimal parameter tuning need for its three-phase movement decision-making process. Simulation experiments with twelve common benchmark single-objective test functions demonstrate the efficacy, efficiency, and robustness of the technique compared to other algorithms. Besides, the use of FOA for single-objective optimization of shell-and-tube and plate-fin heat exchangers resulted in better performance than previously. Yes, the total cost of shell-and-tube heat exchangers was decreased by 28% and 57.8% in case 1 and case 2, respectively, while the units of entropy generation decreased by 15.42% in case 1. For the plate-fin heat exchanger, effectiveness improved by 10% in case 2. All these optimizations are also combined with thermal-hydraulic analysis. Furthermore, FOA produced results superior to those cited in the literature [28].

1.9. Conclusion

The studies compiled in this chapter highlight the continued innovation and critical importance of heat exchanger technology in addressing contemporary technical challenges. From the development of a new repair method to extend the lifespan of shell-and-tube heat exchangers to the exploration of functionally graded hybrid structures for enhanced performance, this research highlights the ongoing quest for greater efficiency and reliability. This chapter also highlights the significant impact of heat transfer enhancement techniques, the potential of nanofluids to revolutionize thermal performance, and the sustainable solutions offered by geothermal and groundwater heat exchangers. It also addresses the specific requirements of high-temperature industrial applications and the crucial role of numerical modeling and optimization for intelligent, high-performance designs. Ultimately, the perspectives presented here not only reflect current advances in heat exchanger technology, but also pave the way for future innovations aimed at improving energy efficiency, reducing operating costs, and enhancing sustainability in various industrial and technical fields.

Reference

[1] Delibaş, H., &Yılmaz, İ. H. (2025). A novel repair method for the lifespan and performance improvement of a shell-and-tube heat exchanger: A thermo-mechanical approach. *Engineering Failure Analysis, 170,* 109333. https://doi.org/10.1016/j.engfailanal.2025.109333

[2] Liu, J., Liu, D., Shang, F., Yang, K., Cao, X., &Zheng, C. (2024). Progress on heat transfer characteristics of heat exchangers with different structures. *2024 6th Asia Energy and Electrical Engineering Symposium (AEEES),* 26–31. https://doi.org/10.1109/AEEES61147.2024.10544945

[3] Kuppusamy, N. R., Seng, L. P., & Wei, D. K. C. (2019). Experimental analysis of novel triple fluid heat exchanger for hybrid cooling application. *2019 IEEE 21st Electronics Packaging Technology Conference (EPTC),* 781–785. https://doi.org/10.1109/EPTC47984.2019.9026567

[4] Saranmanduh, B., Zhao, W., Fu, W., Liang, W., Bai, S., Ma, J., Meng, K., &Baoyin, H. (2025). Review of plate heat exchanger utilized for gases heat exchange. *Renewable and Sustainable Energy Reviews, 210*, 115224.
https://doi.org/10.1016/j.rser.2024.115224

[5] Jalilian, S., &Fartaj, A. (2025). Advanced thermal intermittency management using a multi-PCM double-fluid slab-finned heat exchanger: Design, CFD modeling, and performance evaluation. *Thermal Science and Engineering Progress, 59,* 103299. https://doi.org/10.1016/j.tsep.2025.103299

[6]Wang, J., Qian, C., Zhang, F., Qiu, X., Yu, B., Shi, J., Chen, J. (2025). Experimental and numerical analysis of functionally graded hybrid TPMS heat exchangers for enhanced flow and thermal performance. *Applied Thermal Engineering*, *264*, 125528. https://doi.org/10.1016/j.applthermaleng.2025.125528

[7] Bhattacharyya, S., Vishwakarma, D. K., Srinivasan, A., & others. (2022). Thermal performance enhancement in heat exchangers using active and passive techniques: A detailed review. *Journal of Thermal Analysis and Calorimetry, 147*, 9229–9281. https://doi.org/10.1007/s10973-021-11168-5

[8] Javadi, H., MousaviAjarostaghi, S. S., Rosen, M. A., &Pourfallah, M. (2019). Performance of ground heat exchangers: A comprehensive review of recent advances. *Energy*, *178*, 207–233.

https://doi.org/10.1016/j.energy.2019.04.094

[9] Thianpong, C., Yongsiri, K., Nanan, K., &Eiamsa-ard, S. (2012). Thermal performance evaluation of heat exchangers fitted with twisted-ring turbulators. *International Communications in Heat and Mass Transfer, 39*(6), 861–868. https://doi.org/10.1016/j.icheatmasstransfer.2012.04.004

[10] Ghorbani, N., Taherian, H., Gorji, M., &Mirgolbabaei, H. (2010). An experimental study of thermal performance of shell-and-coil heat exchangers. *International Communications in Heat and Mass Transfer, 37*(7), 775–781. https://doi.org/10.1016/j.icheatmasstransfer.2010.02.001

[11] Sadeghianjahromi, A., & Wang, C. C. (2021). Heat transfer enhancement in fin-and-tube heat exchangers – A review on different mechanisms. *Renewable and Sustainable Energy Reviews, 137*, 110470.

https://doi.org/10.1016/j.rser.2020.110470

[12] Mangrulkar, C. K., Dhoble, A. S., Chamoli, S., Gupta, A., &Gawande, V. B. (2019). Recent advancement in heat transfer and fluid flow characteristics in cross flow heat exchangers. *Renewable and Sustainable Energy Reviews*, *113*, 109220. https://doi.org/10.1016/j.rser.2019.06.027

[13] Ghazanfari, V., Imani, M., Shadman, M. M., Amini, Y., &Zahakifar, F. (2023). Numerical study on the thermal performance of the shell and tube heat exchanger using twisted tubes and Al_2O_3 nanoparticles. *Progress in Nuclear Energy, 155*, 104526. https://doi.org/10.1016/j.pnucene.2022.104526

[14] Porgar, S., Vafajoo, L. and Ali, H.M. (2023), Effects of Key Parameters on Nanofluid Thermal Performance in Heat Exchangers. Chem. Eng. Technol., 46: 818-836. https://doi.org/10.1002/ceat.202200527

[15] Kumar, S., Singh, S. K., & Sharma, D. (2022). A Comprehensive Review on Thermal Performance Enhancement of Plate Heat Exchanger. *International Journal of Thermophysics*, *43*(109).

https://doi.org/10.1007/s10765-022-03036-7

[16] Li, X., Chen, Y., Chen, Z., & Zhao, J. (2006). Thermal performances of different types of underground heat exchangers. *Energy and Buildings, 38*(5), 543–547. https://doi.org/10.1016/j.enbuild.2005.09.002

[17] Li, M., & Lai, A. C. K. (2015). Review of analytical models for heat transfer by vertical ground heat exchangers (GHEs): A perspective of time and space scales. *Applied Energy*, *151*, 178–191.
https://doi.org/10.1016/j.apenergy.2015.04.070

[18] Li, W., & Yu, Z. (2021). Heat exchangers for cooling supercritical carbon dioxide and heat transfer enhancement: A review and assessment. *Energy Reports*, *7*, 4085-4105. https://doi.org/10.1016/j.egyr.2021.06.089

[19] Manish Jangir. (2022). Review of Literature on Heat Transfer Enhancement in Heat Exchangers. *International Journal of Innovations in Science, Engineering And Management*, 20-24.
https://ijisem.com/journal/index.php/ijisem/article/view/12

[20] Al-Obaidi, A. R. (2020). Types of heat exchangers in industry, their advantages and disadvantages and the study of their parameters. ResearchGate.https://www.researchgate.net/publication/346859312_Types_of_heat_exchangers_in_industry_their_advantages_and_disadvantages_and_the_study_of_their_parameters

[21] Mahmoudinezhad, S., Sadi, M., Ghiasirad, H., &Arabkoohsar, A. (2023). A comprehensive review on the current technologies and recent developments in high-temperature heat exchangers. *Renewable and Sustainable Energy Reviews*, *183*, 113467. https://doi.org/10.1016/j.rser.2023.113467

[22] Huang, C., Cai, W., Wang, Y., Liu, Y., Li, Q., & Li, B. (2019). Review on the characteristics of flow and heat transfer in printed circuit heat exchangers. *Applied Thermal Engineering*, *153*, 190-205. https://doi.org/10.1016/j.applthermaleng.2019.02.131

[23] Yan, S. R., Moria, H., Pourhedayat, S., Hashemian, M., Asaadi, S., SadighiDizaji, H., &Jermsittiparsert, K. (2020). A critique of effectiveness concept for heat exchangers; theoretical-experimental study. *International Journal of Heat and Mass Transfer*, *159*, 120160.
https://doi.org/10.1016/j.ijheatmasstransfer.2020.120160

[24]Cengel, Y. A., &Ghajar, A. J. (2019). Heat and mass transfer: Fundamentals and applications (6th ed.). Springer.
https://doi.org/10.1007/978-3-319-91128-1

[25] Hussein, H. A. M., Zulkifli, R., Wan Mahmood, W. M. F. B., &Ajeel, R. K. (2022). Structure parameters and designs and their impact on performance of different heat

exchangers: A review. *Renewable and Sustainable Energy Reviews*, *154*, 111842. https://doi.org/10.1016/j.rser.2021.111842

[26] Fawaz, A., Hua, Y., Le Corre, S., Fan, Y., &Luo, L. (2022). Topology optimization of heat exchangers: A review. Energy, 252, 124053. https://doi.org/10.1016/j.energy.2022.124053

[27] Segundo, E. H. de V., Mariani, V. C., & Coelho, L. dos S. (2019). Design of heat exchangers using Falcon Optimization Algorithm. *Applied Thermal Engineering*, *156*, 119-144.

https://doi.org/10.1016/j.applthermaleng.2019.04.038

[28] University of Oran 2. (2021). Study and modeling of a heat exchanger [Master's thesis or Doctoral dissertation, University of Oran 2]. University of Oran Digital Repository.https://ds.univ_oran2.dz:8443/bitstream/123456789/8852/1/Etude%20et%20Mod%C3%A9lisation%20d%E2%80%99un%20%C3%A9changeur%20de%20chaleur.

Figure 1.1

https://cpms.tn/our-services/heat-exchanger-fabrication-and-repair/

Figure 1.2

https://www.researchgate.net/figure/General-classification-of-heat-transfer-enhancement-techniques_fig1_348012623

Figure 1.3

https://www.pinterest.com/pin/geothermal-heating-guide-costs-and-benefits--720294534138266038/

Figure 1.4

https://th.bing.com/th/id/OIP.y_DPyyqtdazkplC3xnjTZwHaE7?r=0&rs=1&pid=ImgDetMain&cb=idpwebp2&o=7&rm=3

Figure 1.5

https://th.bing.com/th/id/R.6c3161bf2bec29780433a46f5c83e705?rik=V%2bcBcuu7AEDGzw&pid=ImgRaw&r=0&sres=1&sresct=1

Chapter 2.

Theoretical study on heat exchangers

2.1. Introduction

Heat exchangers are ubiquitous and indispensable components in a wide range of industrial, commercial, and domestic applications. Their primary function is to efficiently transfer thermal energy between two or more fluids at different temperatures, without necessarily mixing them. From the precise temperature control required in the food and pharmaceutical industries to large-scale energy recovery in power plants and chemical plants, the design and operation of these devices are essential for optimizing energy efficiency, process control, and economic viability. This chapter explores the fundamental principles governing the operation of heat exchangers, provides a comprehensive classification of common types, addresses their specific application areas, and details the crucial aspects of their design and thermal sizing. Understanding these elements is essential for engineers and technicians involved in the design, optimization, and maintenance of systems in various sectors.

2.2. Classification of Heat Exchangers

Figure 2.1. presents a hierarchical classification of heat exchangers. At the top, two main categories are distinguished: regenerative and recuperative heat exchangers.

Regenerative heat exchangers involve intermittent heat transfer where heat from a hot fluid is temporarily stored in a medium (such as a matrix or drum) before being transferred to a cold fluid. These include fixed matrix and rotary types (with subtypes such as drum and disc).

Recuperative heat exchangers, on the other hand, perform continuous heat transfer through a wall separating the fluids. They are divided into direct contact (where fluids mix, as in spray coolers) and indirect contact (where fluids remain separated). Indirect contact exchangers include those with primary surface (such as plates, with subtypes like smooth, spiral, and gasketed plates) and those with extended surface (such as finned tubes and double tubes).

Finally, an important branch of indirect contact exchangers is tubular heat exchangers, which can be single tube (spiral) or shell and tube, with fixed, removable, or U-tube bundle configurations. The diagram also notes that the flow in a heat exchanger can be counter-current, parallel, or cross-flow, and that exchangers can handle single-phase or two-phase flows on each side.

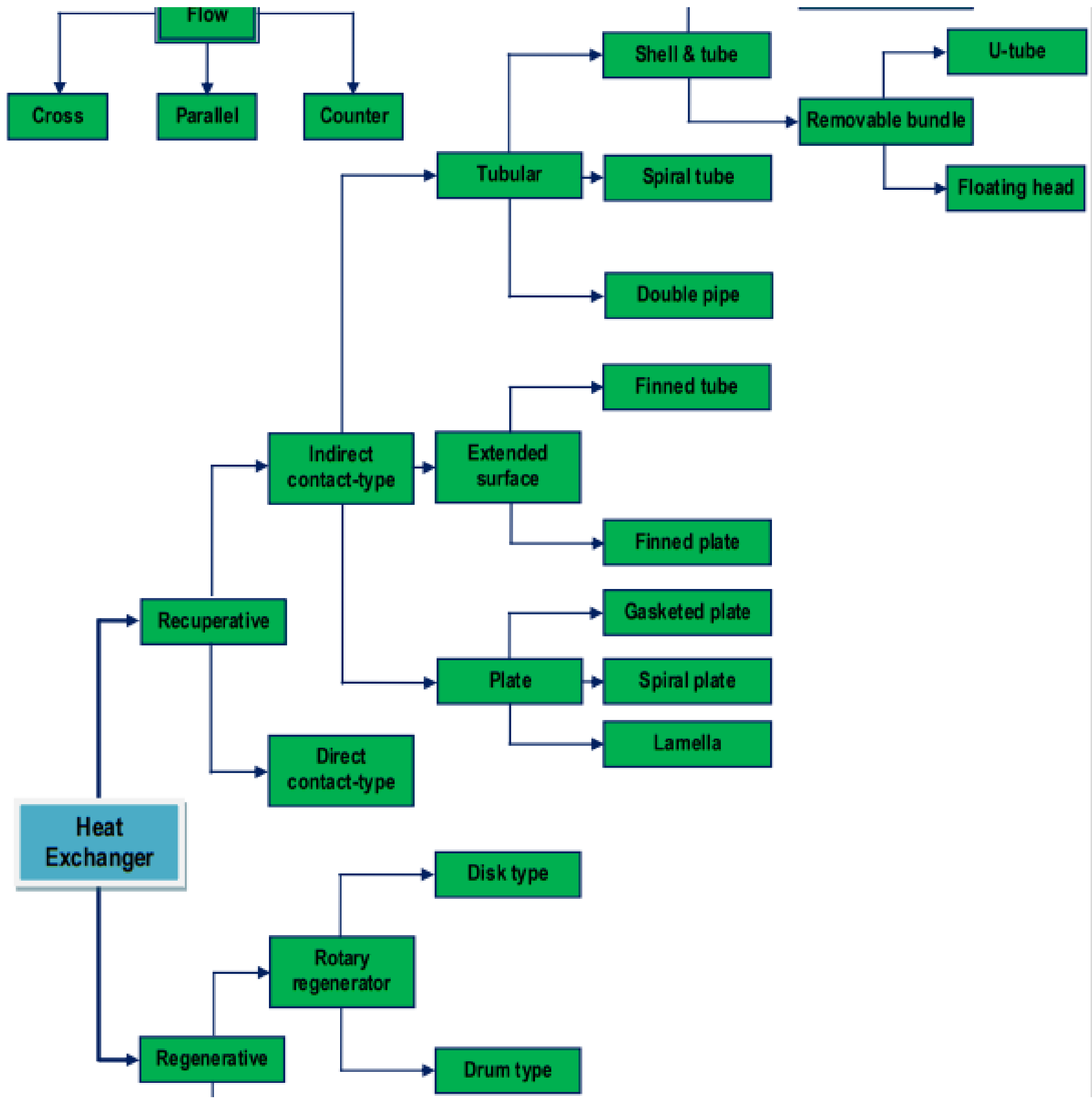


Figure 2.1. Classification of heat exchangers

2.3. Types of Heat Exchangers

2.3.1. Plate Heat Exchangers

- **Operating Principle**

Plate heat exchangers operate by using a series of metal plates to transfer heat between two fluids. These plates are generally corrugated to increase the surface area and create turbulent flow, which improves heat transfer efficiency. Fluids flow in alternating channels between the plates, and heat is transferred through the plates from one to the other as shown in Figure 2.2.

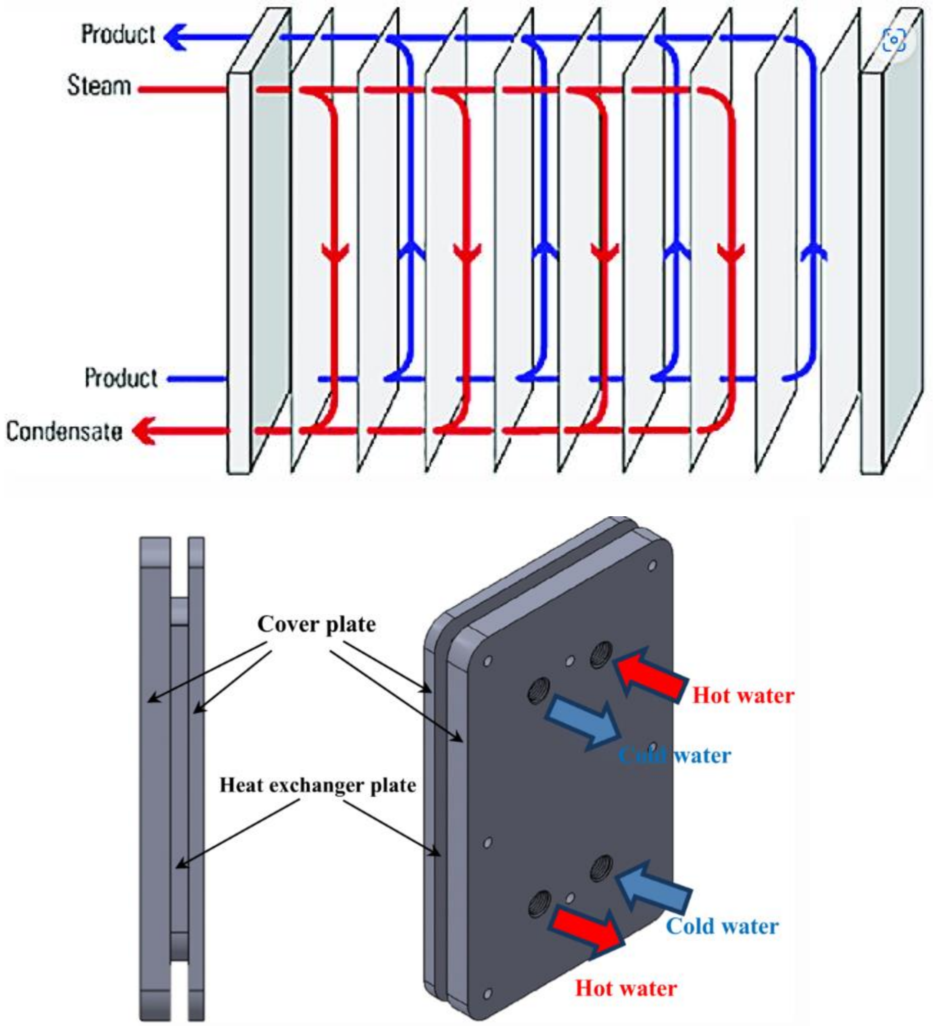


Figure 2.2. Plate HeatExchanger

- **Areas of Use**

They are widely used in various industries, including food and beverage, chemical, pharmaceutical, heating, ventilation, and air conditioning (HVAC), as well as in industrial processes. They are particularly suitable for applications where efficient heat transfer is crucial.

- **Advantages and Disadvantages**

Table 2.1 highlights their high thermal transfer efficiency and compact design, valuable assets for applications where space is limited and energy efficiency is paramount. Their ease of cleaning and maintenance, as well as the ability to expand their capacity by adding plates, offer great flexibility. They perform particularly well with low-viscosity fluids and ensure uniform flow distribution, promoting homogeneous heat transfer.

Nevertheless, their use is generally not recommended for very high pressures, and their initial cost can be higher for large capacities. They are also susceptible to fouling by large particles or viscous fluids, and the gaskets, while ensuring sealing, can be potential points of failure requiring regular maintenance.

Table 2.1. Characteristics of a plate heat exchanger

Characteristic	Advantages	Disadvantages
Efficiency	High heat transfer efficiency	
Footprint	Compact design	
Maintenance	Easy to clean and maintain	May require more gasket maintenance
Flexibility	Flexibility and easy expandability by adding plates	
Viscosity	Suitable for low-viscosity fluids	Sensitive to fouling by large particles or viscous fluids
Flow	Good flow distribution and uniform heat transfer	
Pressure		Generally less suitable for high pressures
Cost		Can be more expensive for very large capacities
Gaskets		Gaskets can be a point of failure

2.3.2. Finned Tube Heat Exchangers

- **Operating Principle**

Finned tube heat exchangers use tubes with attached fins to increase the surface area available for heat transfer. One fluid circulates inside the tubes, while the other fluid (usually a gas, such as air) circulates through the fins. The fins improve heat transfer between the tube and the external fluid as shown in Figure 2.3.

Figure 2.3. Double pipe heat exchanger

- **Areas of Use**

They are commonly used in heating, ventilation, air conditioning, and refrigeration (HVAC&R) systems, as well as in car radiators, oil coolers, and industrial processes where heat transfer between a liquid and a gas is necessary.

- **Advantages and Disadvantages**

Table 2.2 highlights their efficiency in heat transfer between a liquid and a gas, an essential characteristic for heating, ventilation, and air conditioning systems. Their relatively compact design allows for high thermal transfer capacity in a confined space, and their cost is often more advantageous for gas-liquid applications. The variety of fin configurations offers the possibility to optimize performance according to specific needs.

However, their use is generally limited to low-pressure applications on the gas side, and cleaning between the fins can be difficult. The accumulation of frost or dust can significantly reduce their efficiency, and material selection is crucial to prevent corrosion.

Table 2.2.Double Pipe Heat Exchanger

Characteristic	**Advantages**	**Disadvantages**

Gas-Liquid Transfer	Very efficient for heat transfer between a liquid and a gas	
Footprint	Relatively compact design for high transfer capacity	
Cost (Gas-Liquid)	Generally lower cost than other types for gas-liquid applications	
Optimization	Possibility of different fin configurations to optimize performance	
Pressure (Gas)		Generally limited to low-pressure applications on the gas side
Maintenance		Can be difficult to clean between fins
Fouling		Performance can be significantly reduced by frost or dust accumulation
Corrosion		More susceptible to corrosion if materials are not properly chosen

2.3.3. Double Pipe Heat Exchangers

- **Operating Principle**

Double pipe heat exchangers consist of two concentric tubes, one tube inside another. One fluid flows in the inner tube, while the other fluid flows in the annular space between the two tubes. Heat is transferred through the wall of the inner tube as shown in Figure 2.4.

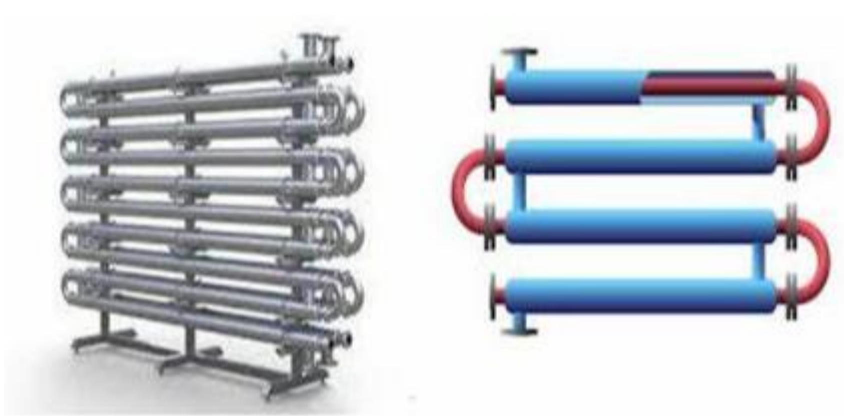


Figure 2.4. Double pipe heat exchanger

- **Areas of Use**

They are used in various industrial applications, including fluid heating and cooling, heat recovery, and chemical processes. They are particularly suitable for applications where flow rates are low and efficient heat transfer is required.

- **Advantages and Disadvantages**

Table 2.3 emphasizes their simple and robust design, as well as their ease of construction and maintenance, significant advantages for certain industrial applications. Their ability to operate under high pressure makes them useful in demanding conditions, and the diversity of available materials allows them to be adapted to different fluids and temperatures.

Nevertheless, their thermal transfer efficiency per unit area is generally lower than that of other types of exchangers, and they can become bulky for large capacities. Their flexibility in terms of capacity modification is also more limited.

Table 2.3.Double Pipe Heat Exchanger

Characteristic	Advantages	Disadvantages
Design	Simple and robust design	Generally lower heat transfer efficiency per unit area
Maintenance	Easy to build and maintain	
Pressure	Suitable for high-pressure applications	
Materials	Can be manufactured with various materials	
Footprint		Potentially large footprint for large capacities
Flexibility		Less flexible in terms of capacity modification

2.3.4. Condensers and Evaporators (as specific heat exchangers)

- **Operating Principle**

Condensers and evaporators are specific types of heat exchangers used in refrigeration and air conditioning systems. A condenser is a heat exchanger that condenses a gas into a liquid by releasing heat. An evaporator is a heat exchanger that evaporates a liquid into a gas by absorbing heat as shown in Figure 2.5, [1].

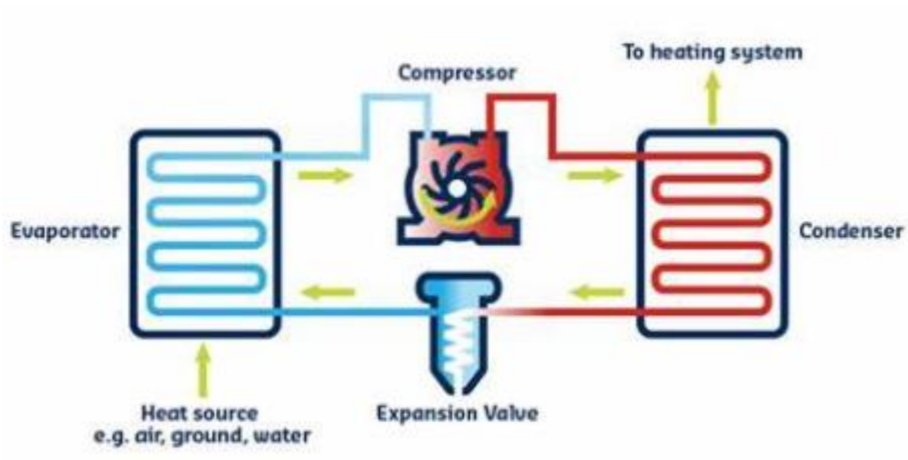


Figure 2.5.Condenser and Evaporator

- **Areas of Use**

Condensers and evaporators are essential components of refrigeration systems, air conditioning, heat pumps, and many industrial processes involving phase changes.

- **Advantages and Disadvantages**

Table 2.4 highlights their specific design and optimization for phase changes, a fundamental aspect of refrigeration and air conditioning systems. Their adaptability to different refrigerants and the variety of available configurations allow them to meet the specific requirements of each application.

However, their performance is intrinsically linked to the operating conditions of the entire system. Furthermore, frost accumulation on evaporators can negatively impact their efficiency, and the choice of materials must be compatible with the refrigerant used to ensure the longevity and performance of the exchanger.

Table 2.4.Condensers and Evaporators

Characteristic	Advantages	Disadvantages

Function	Specifically designed for phase changes	Performance is highly dependent on system operating conditions
Refrigerant	Can be optimized for different refrigerants	Design and materials must be compatible with the refrigerant
Configurations	Available in various configurations to suit applications	
Frost (Evaporators)		Frost accumulation can reduce efficiency

2.3.5. Shell and Tube Heat Exchangers

- **Operating Principle**

The operating principle of a shell and tube heat exchanger is based on the flow and thermal contact of two liquids. A heated or hot fluid circulates around a cold fluid and transfers heat in the direction of the cold fluid's flow. Heat is transferred from one fluid to the other through the tube walls. Baffles can be used to direct the shell-side fluid perpendicular to the tubes, thus creating more turbulent flow and increasing the heat transfer coefficient.

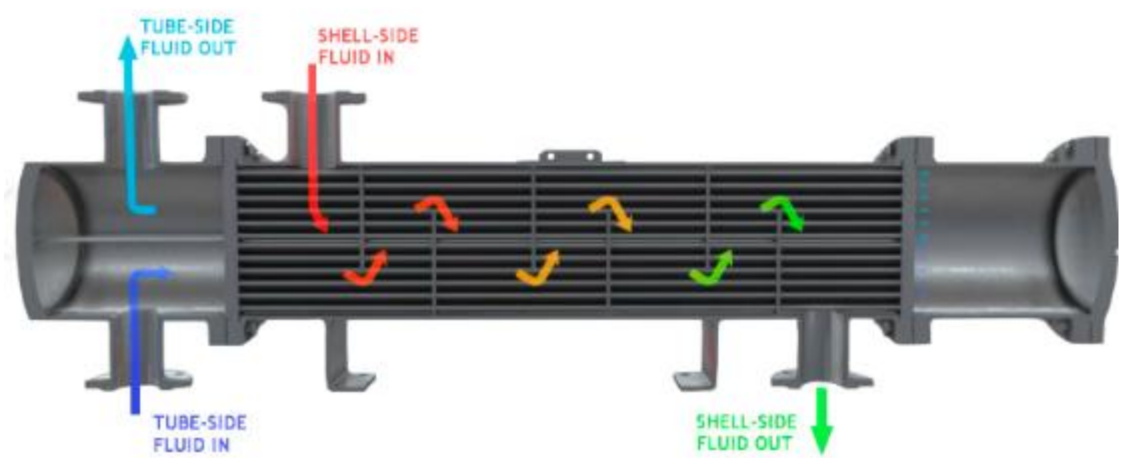


Figure 2.6. Shell and Tube Heat Exchanger

- **Areas of Use**

Shell and tube heat exchangers are versatile and serve in various applications across many sectors. They are commonly used to cool hydraulic oil and oil in engines, transmissions, and hydraulic power units. With the right material selection, they can also be used to cool or heat other fluids, such as swimming pool water or supercharged air. They are also typically used in steam locomotive boilers and in large power plants with steam turbines. They are essential in the food, beverage, dairy, and pharmaceutical industries for the production of consumer products while ensuring safety, efficiency, and consistency.

- **Advantages and Disadvantages**

Table 2.5 highlights their robustness and ability to operate under high pressure, making them suitable for demanding industrial environments. Their design allows for a certain ease of maintenance, although this may vary depending on the configuration. The flexibility in material selection and tube arrangement gives them adaptability to various applications and temperature ranges.

However, they may exhibit lower thermal transfer efficiency than plate heat exchangers in some cases and tend to be bulkier. Furthermore, they are susceptible to fouling if the fluids used are not sufficiently clean, and flow distribution in the shell can lead to less uniform heat transfer. While their initial cost may be more advantageous for large installations, they can be more difficult to modify once installed.

Table 2.5.Shell and tube heat exchangers

Characteristic	Advantages	Disadvantages
Pressure	Suitable for high-pressure applications	
Robustness	Robust and reliable design	
Maintenance	Easy to clean and maintain (depending on design)	
Flexibility	Design flexibility (materials, tube arrangement)	May be more difficult to modify or extend once installed
Temperature	Suitable for a wide range of temperatures	
Cost	Generally lower cost for large sizes	Potentially higher initial cost for certain configurations
Efficiency		Less efficient than plate heat exchangers in some applications
Footprint		Potentially larger footprint

Fouling	Sensitive to fouling if fluids are not clean
Flow	Less uniform heat transfer due to shell-side flow distribution

2.4. Heat Exchanger Sizing

To reliably and accurately size heat exchangers, we must take into account several key aspects of the process.

A heat exchanger is a system for exchanging energy in the form of heat between a hot fluid and a cold fluid. In practice, all the power given by the hot fluid (hf) is absorbed by the cold fluid (cf), resulting in the following energy balance:

$$\dot{Q}hf = \dot{Q}cf \quad (1)$$

2.4.1. Equation placeholder (related to energy balance)

The thermal power in a fluid in the liquid state depends on the mass flow rate and the difference between the inlet and outlet temperatures. In a fluid with a phase change under saturation conditions (condensation or evaporation), the thermal power depends on the mass flow rate and the enthalpy of phase change, which is determined by the saturation pressure.

The process is defined when all parameters have been set by the client, except one, which will be calculated by applying the preceding energy balance.

For example:

Liquid product (p), liquid service (s). The usual practice is to define the flow rate and the inlet and outlet temperatures of the product, and to leave one of these three values free for the service fluid:

$$\dot{m}p \,.\, Cpp \,.\, (T_2p - T_1p) = \dot{m}s \,.\, Cp \,.\, (T_2s - T_1s) \quad (2)$$

Liquid product (p), service with phase change(s). The usual practice is to define the flow rate and the inlet and outlet temperatures of the product, as well as the service pressure, leaving the service flow rate free.

$$\dot{m}p \,.\, Cpp \,.\, (T_2p - T_1p) = \dot{m}s \,.\, hs[Ps] \quad (3)$$

2.4.2. Thermal Properties in Heat Exchanger Design

For heat exchanger design, the following thermal properties must be known for both the product and the service: density, specific heat, conductivity, and viscosity. In general, it is useful for the designer to know the value of these properties at different temperatures within the operating range.

However, in the food industry, this information is of paramount importance: the viscosity of food products varies very strongly with temperature (more pronounced at low temperatures), and it is common to observe non-Newtonian behavior of the product, where viscosity also depends on the flow rate through the heat exchanger.

Therefore, a correct characterization of thermal properties is the basis for optimal tubular heat exchanger design.Once the process is established and the thermal properties of the fluids are characterized, the work of defining the heat exchanger begins.

2.4.3. Material Selection in Heat Exchanger Design

As an example, SACOME manufactures its heat exchangers from stainless steel and offers its clients other special materials for applications with a high risk of corrosion.

2.4.4. Geometry Selection in Heat Exchanger Design

This choice depends on the type of process and the nature of the product. SACOME's technical service will guide you in selecting the appropriate tubular heat exchanger, evaluating the client's different requirements: flow rates, pressure drops, available space, etc. The most commonly used tubular geometries are tube-in-tube, annular space, and shell and tube as shown in Figure 2.7a to 2.7c.

Figure 2.7a. Échangeur de chaleur tube dans tube

Figure 2.7b. Échangeur de chaleur à espace annulaire

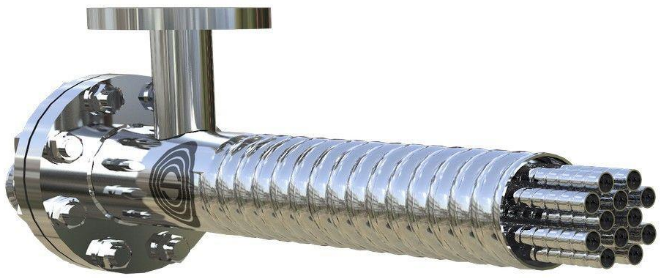


Figure 2.7c. Échangeur de chaleur à calandre et tubes

2.4.5. Thermal Sizing of Tubular Heat Exchangers

From the definition of the tubular heat exchanger, the key point of the designer's work is the sizing of the equipment. The designer must calculate the optimal heat transfer surface that allows the specified process to be carried out while satisfying all the requirements imposed by the client as shown in Figure 2.6.

Figure 2.8. Thermal sizing of the tubular heat exchanger

To do this, the following transfer equation is applied, where Q is the power exchanged by the fluids, U is the overall heat transfer coefficient, A is the heat transfer surface, and LMTD is the logarithmic mean temperature difference[2].

$$\dot{Q} = U.A.LMTD \tag{4}$$

This equation must be discretized along the heat exchanger into a sufficient number of sections: the efficiency of heat transfer between the fluids varies along the heat exchanger because, among other things, thermal properties vary with temperature and complex thermal phenomena occur along the tubular heat exchanger.

To understand the calculation procedure, the heat transfer heat transfer surface. In what follows, this procedure is illustrated on a concentric double pipe heat exchanger treating counter-current liquid fluids.

2.4.6. Determination of Exchanged Power

This is obtained directly from the process data already established for the product, which will generally be handled by the inner tube.

$$\dot{Q} = \dot{m}p\ .Cpp\ .\Delta Tp \tag{5}$$

2.4.7. Determination of the Logarithmic Mean Temperature Difference

It is defined between two sections of the heat exchanger and depends on the inlet and outlet temperatures of the product and service. When applied to the entire tubular heat exchanger, these four temperatures are known; when applied to a discretization, the a priori values are unknown and an iterative convergence process must be executed.

$$\boldsymbol{LMTD} = \frac{(\boldsymbol{Tss}-\boldsymbol{Tep})-(\boldsymbol{Tes}-\boldsymbol{Tsp})}{\boldsymbol{ln}\left(\frac{(\boldsymbol{Tss}-\boldsymbol{Tep})}{(\boldsymbol{Tes}-\boldsymbol{Tsp})}\right)} \tag{6}$$

2.4.8. Determination of the Overall Heat Transfer Coefficient

This is obtained by the sum of each of the thermal resistances present:

$$U = \frac{1}{Rhp+Rsp+Rhs+Rfs+Rp} \tag{7}$$

2.4.9. Convective Thermal Resistance

This resistance evaluates the heat transfer that occurs by convection. It is inversely proportional to the fluid's heat transfer coefficient, h. In the product channel, where Dp and dp are the outer and inner diameters of the inner tube, it is:

$$Rhp = \frac{1}{hp} \cdot \frac{Dp}{dp} \tag{8}$$

$$Rhs = \frac{1}{hs} \tag{9}$$

The critical step in heat exchanger design is precisely the reliable and accurate determination of the heat transfer coefficients h; an erroneous calculation of these coefficients will lead to insufficient operation of the tubular heat exchanger, even if it does not reach the desired temperatures.

Depending on the flow channel (tube, annular space, etc.) and the flow regime (laminar, turbulent, etc.), an appropriate empirical correlation for the Nusselt number (Nu) will need to be established, which is the dimensionless parameter from which the heat transfer coefficient h is obtained. In general, the Nusselt number will depend on other dimensionless parameters such as the Reynolds number, Prandtl number, Graetz number, Grashof number, etc.

2.4.10. Conductive Thermal Resistance

Evaluates the heat transfer that occurs by conduction in the inner tube that separates the two fluids. For a tube, with k being the thermal conductivity of the metal, it is defined as:

$$Rk = \frac{Dp}{2k} \cdot ln\left(\frac{Dp}{dp}\right) \tag{10}$$

2.4.11. Fouling Thermal Resistance

During heat exchanger operation, it is common for films formed by impurities from the fluids themselves to deposit on the surfaces in contact with the fluids. These fouling resistances worsen heat transfer.

In applications, generally industrial, where it is necessary to delay the shutdown of the tubular exchanger for cleaning, it is common to consider that these additional resistances will be present from the start, thus oversizing the equipment. In food applications, they are not taken into account because cleaning work is more continuous.

On the product side, it is:

$$\boldsymbol{Rfp = fp.\frac{Dp}{dp}} \quad \textbf{(11)}$$

On the service side, it is:

$$\boldsymbol{Rfs = fs} \quad \textbf{(12)}$$

2.4.12. Calculation of Required Heat Transfer Surface

By direct application of the transfer equation, the required heat transfer surface can be obtained. The inner tube diameter having already been fixed, the solution to the problem is to obtain the total length of the exchanger Lt:

$$\boldsymbol{A = \pi.Dp.L}\text{c} = \boldsymbol{\frac{\dot{Q}}{U.LMTD}} \quad \textbf{(13)}$$

The result obtained is the theoretical required surface. However, an existing tube length on the market, L, must be chosen: if this length is less than the theoretical length, then a certain number of exchangers, n, must be arranged in series.

$$\boldsymbol{n.L \geq Lc} \quad \textbf{(14)}$$

In all cases, it will always be advisable to choose a heat transfer surface larger than the theoretical surface, depending on the greater or lesser uncertainty that exists when determining the thermal properties of the fluids, fouling resistances, or heat transfer factors. To quantify this oversizing, a required or "dirty" overall heat transfer coefficient is defined:

$$\boldsymbol{\pi.Dp.n.L} = \frac{\dot{Q}}{Us.LMTD}$$

$$\% = \boldsymbol{100\left(\frac{U}{Us} - 1\right)} \quad \textbf{(15)}$$

2.5. Conclusion

This chapter has provided a comprehensive overview of heat exchangers, from their general classification to the complex details of their thermal sizing. We explored the distinctions between regenerative and recuperative types and examined the operating principles, advantages, and disadvantages of common recuperative designs, including plate, finned-tube, double-tube, and shell-and-tube heat exchangers, as well as specialized condensers and evaporators. The critical importance of understanding fluid thermal properties, selecting appropriate materials and geometries, and rigorously defining configurations was emphasized. In addition, a detailed methodology for thermal sizing of shell-and-tube heat exchangers was presented, highlighting the importance of energy balance, logarithmic mean temperature difference, and accurate determination of the overall heat transfer coefficient, which takes into account convective, conductive, and fouling resistances. Ultimately, effective heat exchanger design and selection are essential for achieving optimal thermal performance, operational efficiency, and long-term reliability in various industrial processes.

References

[1] https://www.linquip.com/blog/difference-between-condenser-and-evaporator/ accessed 4/15/2025.

[2] Bilirgen, H., Dunbar, S., & Levy, E. K. (2013). Numerical modeling of finned heat exchangers. *Applied Thermal Engineering*, *61*, 278-288.

Figure 2.1
https://www.google.com/url?sa=i&url=http%3A%2F%2Fheatexchan.blogspot.com%2F2019%2F06%2Fclassification-of-heat-exchangers.html&psig=AOvVaw25bbRtgu3E4gQ_7gXWGKKc&ust=1750530890197000&source=images&cd=vfe&opi=89978449&ved=0CBAQjRxqFwoTCPD0lb_EgI4DFQAAAAAdAAAAABAE

Figure 2.2
https://www.google.com/url?sa=i&url=https%3A%2F%2Fwww.researchgate.net%2Ffigure%2FSchematic-of-a-plate-heat-exchanger-47_fig8_324811679&psig=AOvVaw1y1VuH8bCJbYksrG9GCNpW&ust=1750530971016000&source=images&cd=vfe&opi=89978449&ved=0CBAQjRxqFwoTCKjk6d_EgI4DFQAAAAAdAAAAABAE
https://www.researchgate.net/publication/343409696/figure/fig4/AS:960045160361990@1605904011241/Schematic-diagram-of-a-plate-heat-exchanger_Q320.jpg

Figure 2.3

https://encrypted-tbn2.gstatic.com/images?q=tbn:ANd9GcRvMtI5--rmNfpf_wq_-I180JZ7fnbmPUmtuI08YFTk5iqMpo-1
Figure 2.5
https://www.researchgate.net/publication/359388262/figure/fig1/AS:1159623927185421@1653487297943/Basic-heat-pump-cycle-Heating-mode-14.png
Figure 2.6
https://savree.com/en/encyclopedia/shell-and-tube-type-heat-exchanger
Figure 2.8
https://encrypted-tbn0.gstatic.com/images?q=tbn:ANd9GcRTS5cAtb2-qC8LsbsvSWJfob6MEgFQiYN5xJSUnaxjLkeAp-7A
https://encrypted-tbn0.gstatic.com/images?q=tbn:ANd9GcR5wmAYINVYHJ2Uot_2Y7SC_3Q9LYki0KREfuqccBo6J4ZwDl31

Chapter 3. Construction and experimental studies

3.1. Introduction

Heat exchangers are essential to almost all industrial and energy conversion processes, playing a vital role in the efficient management of thermal energy. This chapter transcends theoretical discourse by presenting a comprehensive account of the practical aspects of studying a shell-and-tube heat exchanger. We will first detail the step-by-step construction of our experimental shell-and-tube heat exchanger, providing an overview of the technical considerations and assembly procedures underlying its functionality. Next, the meticulous preparation of the experimental setup will be described in detail, ensuring reproducibility and accuracy of data acquisition. The core of this chapter will then present the experimental results obtained under controlled conditions. Through rigorous analysis and graphical representation, these results will convincingly demonstrate the high efficiency of our heat exchanger, validating its performance against established theoretical models and contemporary literature. This practical study aims to bridge the gap between theoretical understanding and real-world application, unequivocally illustrating the efficiency and reliability of the designed shell-and-tube heat exchanger.

3.2. Construction step of a tubular heat exchanger

Building the tubular heat exchanger required a series of meticulous steps, detailed in Table 3-1, to ensure its structural integrity and functional accuracy.

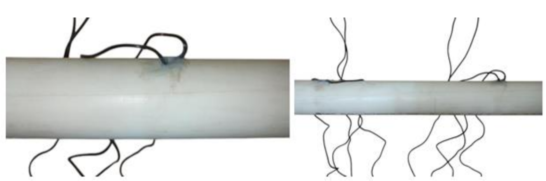
- The process began with the tubes being precisely cut to the required dimensions using appropriate tools to ensure smooth edges and precise lengths, essential for a perfect fit and leak-proof connections.
- Next, holes were carefully drilled into the inner and outer tubes at the designated locations for attaching the thermal sensors (thermocouples). Drilling accuracy was paramount to ensure proper alignment, an airtight seal to prevent leaks, and accurate temperature readings. The hole dimensions were matched to the probe diameters for a perfect fit. Next, the various heat exchanger components were assembled, either by precision welding (such as inert gas welding or a plastic flange device for plastic components) or by mechanical fastening such as threading, depending on material compatibility, pressure requirements, and ease of maintenance or disassembly.
- Once the primary structure was assembled, the thermal sensors were securely installed along the tubes, ensuring their optimal positioning for capturing representative temperature data.

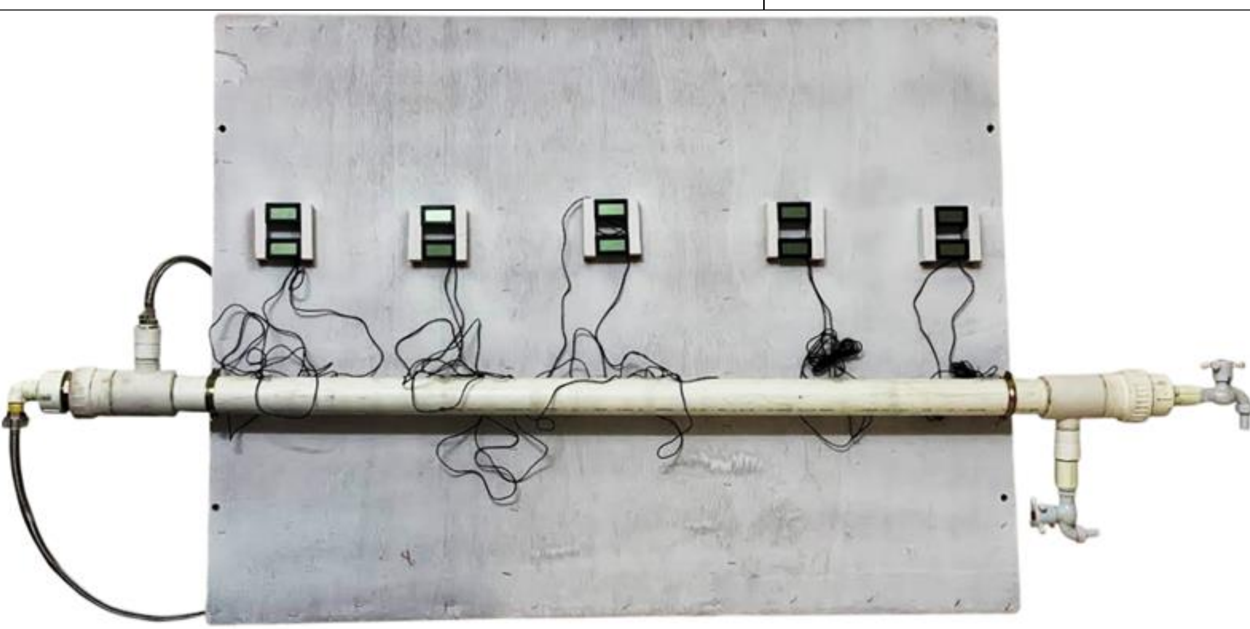
- A crucial final step consisted of rigorous leak and seal testing; the heat exchanger was filled with water and subjected to a pressure slightly above normal operating conditions. All joints and connections were thoroughly inspected for any signs of moisture for at least 30 minutes. Anydetectedleakswere immediately repaired before commissioning.

Through these systematic steps, a robust and accurate final model of the tubular heat exchanger was obtained, ready for experimental application in the university laboratory.

Table 3.1. Construction step of a tubular heat exchanger

Steps	**Explanation**
	Sections of the two pipes used in constructing the heat exchanger. Pipes are precisely cut to specific sizes using appropriate tools, such as power saws, pipe cutters, or hydraulic shears, to ensure smooth edges and accurate measurements. This step is essential for proper installation and leak-proof connections in construction applications
	Holes are drilled in both tubes to attach the thermometer. Holes are carefully drilled into both pipes at the designated locations to securely mount the thermometer. Precision is key to ensure proper alignment and airtight sealing, preventing leaks and accurate temperature readings. The hole size must match the thermometer's probe diameter for a snug fit.

	Some of the parts that were joined using a PPR welding device or by threading. In heat exchanger assembly, parts are joined either by precision welding (using inert gas welding or a plastic bridle device) or by mechanical fastening (using bolts/gaskets for ease of maintenance). The method depends on material compatibility, pressure requirements, and whether disassembly is necessary for cleaning or repair.
	Thermometers are securely mounted on copper pipe using specialized clamps or brackets, ensuring stability and optimal contact for accurate temperature readings. The placement of each thermometer is carefully selected to reflect specific points of interest along the pipe, allowing for precise temperature monitoring during fluid flow.
	the copper pipe is carefully inserted into the plastic pipe, ensuring proper fit for optimal thermal contact. thermal adhesives or insulating rings are sometimes used to enhance heat transfer and prevent leakage. this method is common in compact laboratory heat exchangers due to its insulating properties and lightweight design
	Placing thermometers along the plastic pipe. The thermometers were selected based on their resistance to chemical applications and plastic surfaces, considering the expected temperature range in the heat exchanger system.

<table>
<tr>
<td></td>
<td>Proper sealing and Test for leaks using water. After assembly, the heat exchanger is tested by filling it with water and applying pressure to check for potential leaks. It is important to ensure that: all joints and welds are properly sealed before testing; water pressure used is slightly higher than the normal operating pressure; all connections and joints are carefully inspected using paper towels to detect any moisture. The test lasts for at least 30 minutes under constant observation. Any leak, even minor, must be immediately repaired before the exchanger is used in laboratory applications.</td>
</tr>
<tr>
<td colspan="2"></td>
</tr>
</table>

The final form of the heat exchanger after installation. The image below shows the heat exchanger after the manufacturing and installation process has been completed in its position within the system. Its design takes into account both engineering and functional aspects to ensure thermal efficiency and ease of maintenance. The photo also displays all the mechanical connections and pipes attached to it, reflecting the final state of the device before operation.

3.3. Methodology

The experiment at ElOued University involved the design and testing of a tubular heat exchanger constructed using local materials. The primary objective was to investigate its thermal performance under various operating conditions. To achieve this, hot and cold water streams were circulated through the heat exchanger. Temperatures at various points along the exchanger were precisely monitored using thermocouples (or thermometers, as indicated in your detailed steps documentation), with readings recorded at regular 5-minute intervals to capture dynamic temperature changes and ensure data consistency.

The experimental methodology systematically explored the impact of flow arrangement and flow rates on heat transfer. Two main flow configurations were tested: co-current flow, where hot and cold water moved in the same direction, and counter-current flow, where they moved in opposite directions. Each configuration was initially tested with equal volumetric flow rates for both fluids. Subsequently, the experiment was repeated for both co-current and counter-current setups, but with the cold water flow rate doubled, allowing for a comprehensive analysis of how flow dynamics influence the heat exchanger's effectiveness. Figure 3.1 and Figure 3.2 show the tubular heat exchanger before and during the experiment

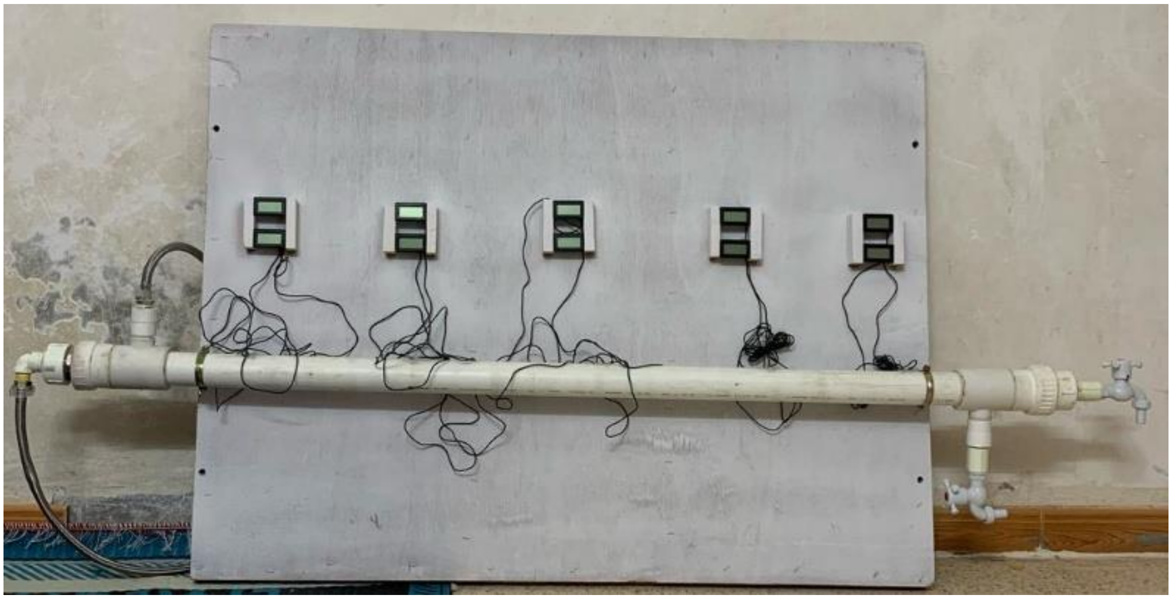


Figure 3.I.Heat exchanger before the experiment

Figure 3.II.Heat exchanger during the experiment

3.4. Results and discussion

3.4.1. Temperature profiles

3.4.1.1. Temperature Profiles for Co-current Flow

Figure 3.1 shows the temperature Profiles for Co-current Flow (Equal Flow Rates). This graph illustrates the temperature distribution along the length of the tubular heat exchanger for both the hot and cold water streams, operating in a co-current flow configuration. The heat exchanger consists of a copper internal tube with a 14 mm diameter and a plastic external tube with a 50 mm diameter, both 1 meter in length. In this experiment, both hot and cold water streams had an equal volumetric flow rate of 3.077×10^{-6} m³/s. As observed, the hot water temperature decreases from approximately 323.8 K at 0.25m to 319.5 K at 1.25m, while the cold water temperature increases from approximately 305.8 K at 0.25m to 310.5 K at 1.25m. This convergence of temperatures along the length is characteristic of co-current flow, indicating effective heat transfer between the fluids.

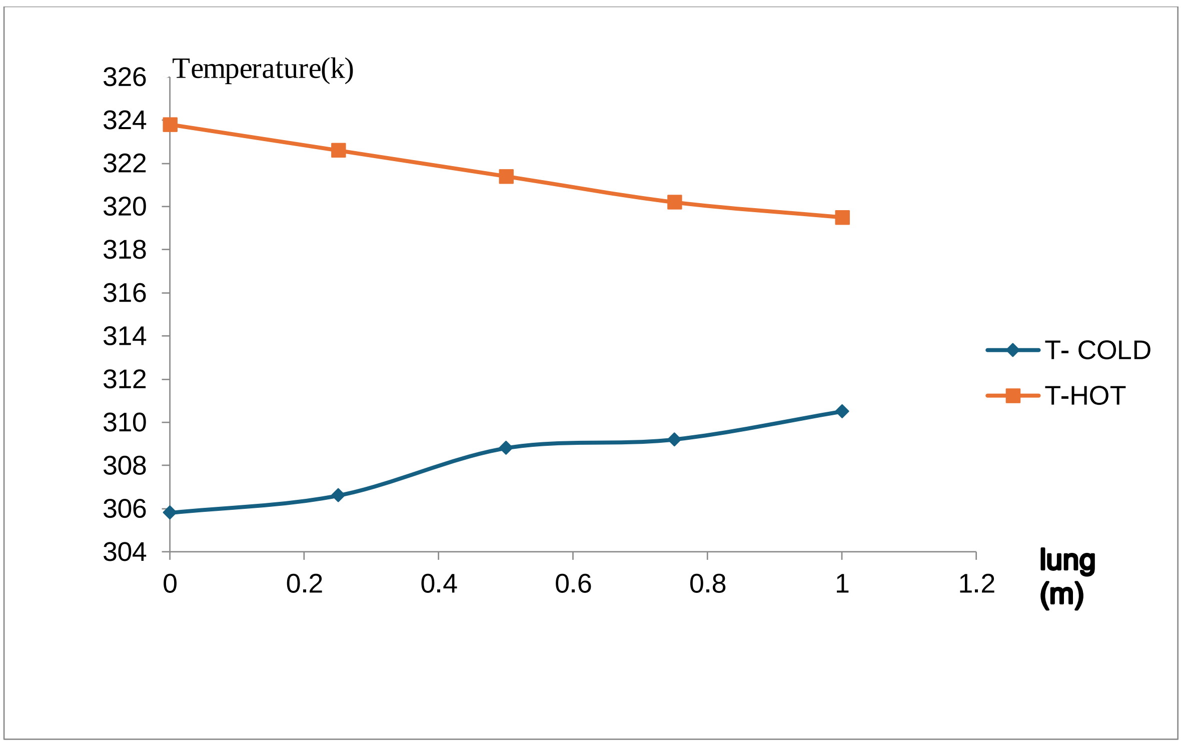


Figure 3.1. Temperature Profiles for Co-current Flow

3.4.1.2. Temperature Profiles for Co-current Flow (Doubled Cold Water Flow Rate)

Figure 3.2 presents the temperature profiles when the tubular heat exchanger (with 14 mm copper inner tube and 50 mm plastic outer tube, both 1m long) operates in a co-current configuration, but with a significantly altered flow rate balance. Here, the hot water flow rate remained at 3.077×10^{-6} m³/s, while the cold water flow rate was doubled to 6.014×10^{-6} m³/s. The plot shows how this increased cold fluid flow impacts the heat exchange. The hot water temperature decreases from approximately 320.4 K at 0.25m to 314.3 K at 1.25m, and the cold water temperature increases from approximately 303.4 K at 0.25m to 309.5 K at 1.25m. This configuration demonstrates a different temperature approach, reflecting the larger thermal capacity of the faster-flowing cold stream, which results in a smaller temperature rise for the cold fluid.

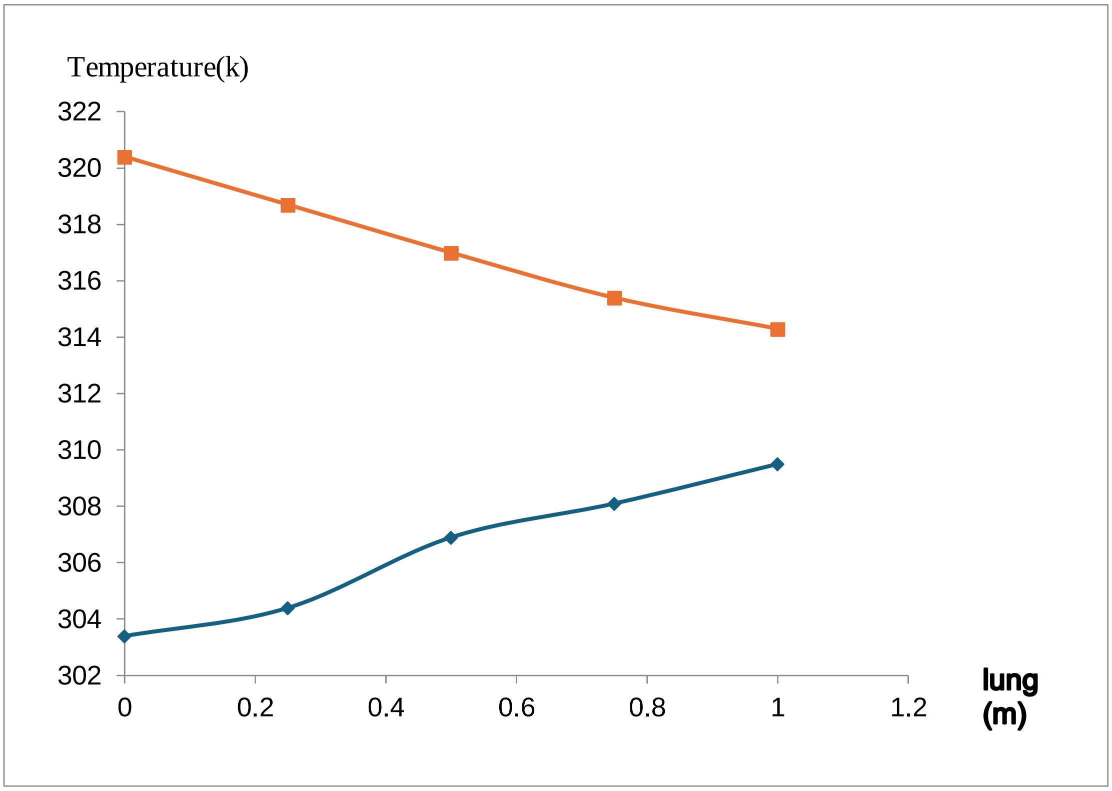


Figure 3.2. co-current with the cold water flow rate doubled

3.4.1.3. Temperature Profiles for Counter-current Flow (Equal Flow Rates)

Figure 3.3 displays the temperature variations of the hot and cold water streams along the heat exchanger operating in a counter-current flow arrangement. The heat exchanger configuration remains consistent with the 14 mm diameter copper inner tube and 50 mm diameter plastic outer tube, each 1 meter long. In this experiment, both hot and cold water streams maintained equal volumetric flow rates of approximately 3.077×10^{-6} m³/s. As is characteristic of counter-current flow, the hot water temperature decreases from approximately 315.0 K at 0.25m to 306.7 K at 1.25m, while the cold water temperature decreases from approximately 309.8 K at 0.25m to 301.0 K at 1.25m. The plot visually confirms that the hot fluid exits at a temperature lower than the cold fluid's inlet temperature (at 0m for cold fluid, which corresponds to 1m for hot fluid in counter-current flow), and vice-versa, indicating a highly effective heat transfer process.

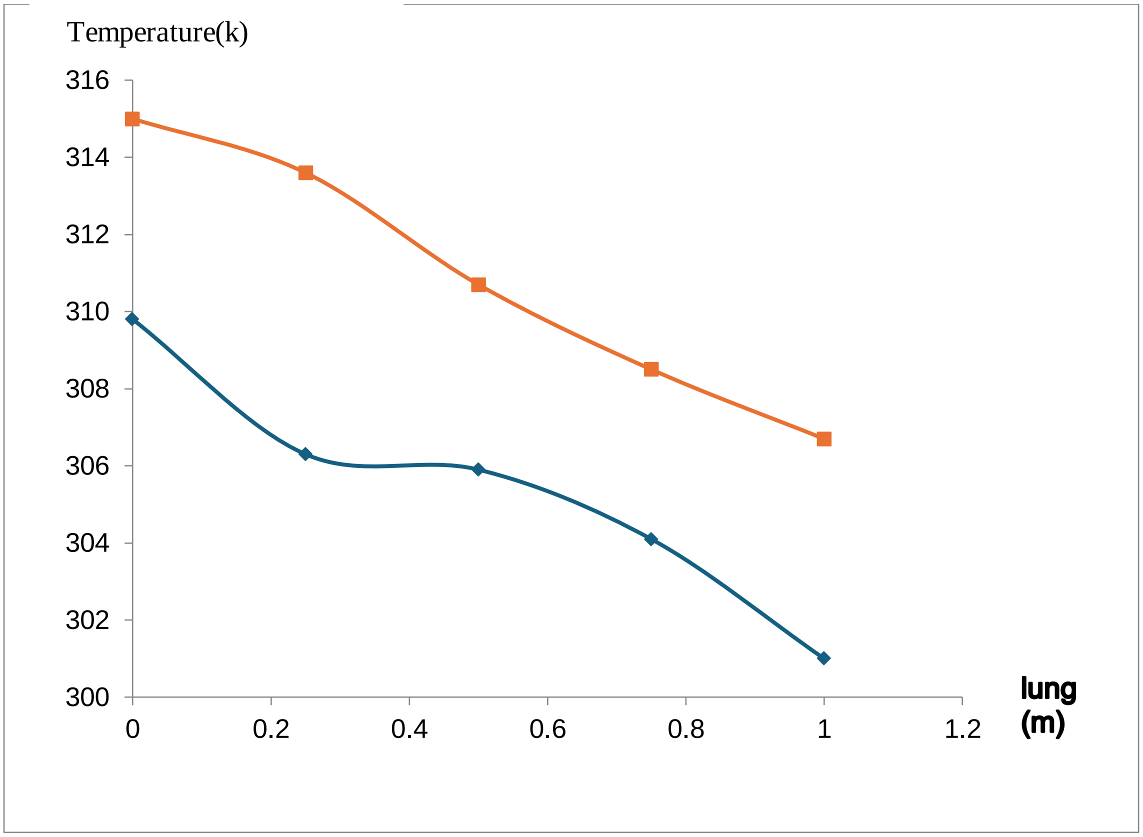


Figure 3.3. Counter-current Flow (Equal Flow Rates)

3.4.1.4. Temperature Profiles for Counter-current Flow (Doubled Cold Water Flow Rate)

Figure 3.4 presents the temperature profiles for the tubular heat exchanger in a counter-current configuration, similar to Experiment 3, but with the cold water flow rate doubled. The hot water flow rate was maintained at 3.077×10^{-6} m³/s, while the cold water flow rate increased to 6.014×10^{-6} m³/s. The plot shows the hot water temperature decreasing from approximately 314.5 K at 0.25m to 306.4 K at 1.25m, and the cold water temperature decreasing from approximately 306.2 K at 0.25m to 301.9 K at 1.25m. This demonstrates how increasing the cold fluid's velocity and thus its thermal capacity impacts the temperature gradients and the overall heat exchange effectiveness in a counter-current setup, allowing for a clearer analysis of performance under varied flow conditions.

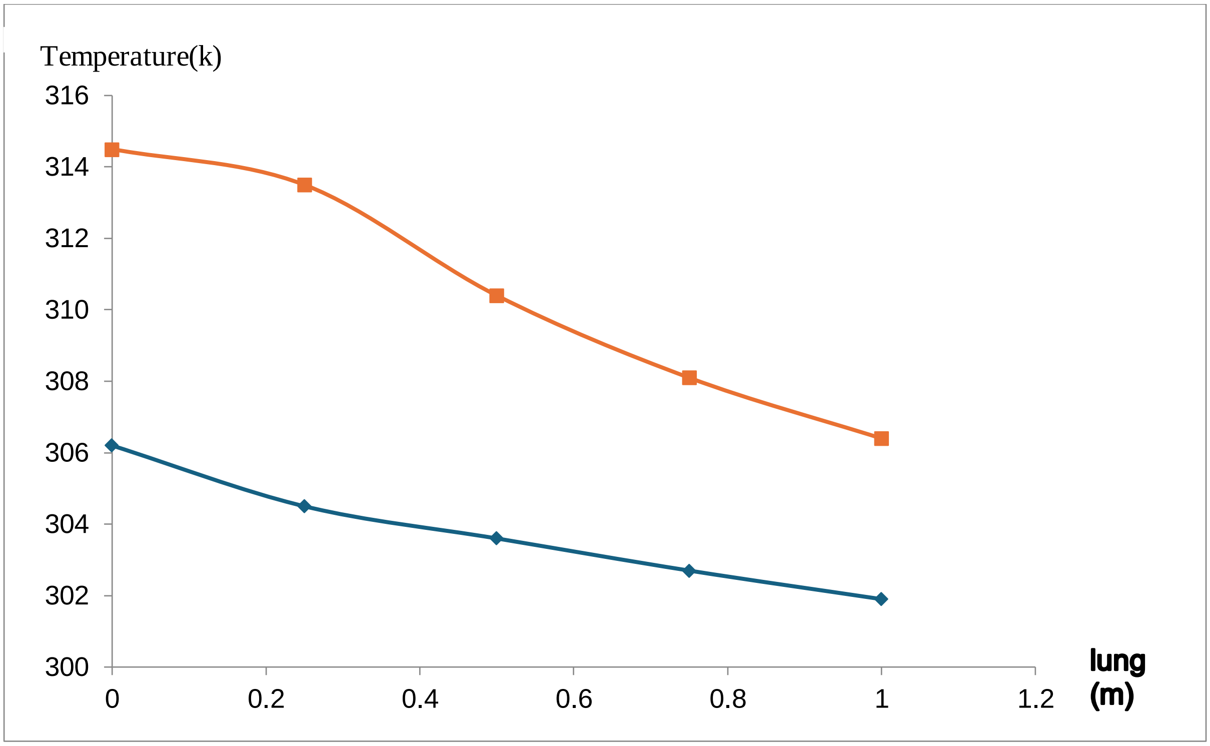


Figure 3.4.Counter-current with the cold water flow rate doubled

3.4.2. Cumulative heat transfer

Cumulative heat transfer represents the total heat energy exchanged between fluids from a specific reference point along the length of a heat exchanger, illustrating the progressive accumulation of heat loss from the hot fluid and heat gain by the cold fluid. Its importance lies in providing a clear visual and quantitative understanding of how efficiently heat exchange occurs at every section of the heat exchanger, which is crucial for identifying potential inefficiencies, verifying the experimental energy balance, and guiding design and optimization efforts by showing how effective heat transfer is built up along the device.

To draw the "Cumulative Heat Transfer" graphs, a systematic approach was followed, utilizing numerical data derived from the experimental measurements.

➢ **Data Preparation:**

- Temperature data for both hot and cold fluids were collected at specific measurement points along the heat exchanger's length.
- Mass flow rates for the hot and cold fluids in each experiment were obtained.
- Standard physical properties of water were used: density (ρ=1000 kg/m3) and specific heat capacity (cp=4186 J/kg·K).

- **Calculation of Mass Flow Rates ($\dot{m}$):**

- For each fluid in each experiment, the mass flow rate was determined using the formula: $\dot{m}=\rho\cdot Vdot$ (where Vdot is the volumetric flow rate).

- **3. Calculation of Cumulative Heat Transfer ($Q_{cumulative}$):**

- The cumulative heat transfer represents the total heat exchanged from the inlet of the heat exchanger up to a given point.
- At **0 cm (0 m)**, the cumulative heat transfer for both hot and cold fluids is considered **0 W**, as this is the theoretical starting point of heat exchange within the system.
- For subsequent measurement points (0.25m, 0.50m, 0.75m, 1.00m), the cumulative heat transfer was calculated based on the temperature changes relative to a reference inlet temperature. While measurements began at 0.25m, the concept of cumulative heat transfer begins from the true inlet.
- **For the Hot Fluid (Heat Loss):** The cumulative heat lost by the hot fluid up to a certain point was calculated as: $Q_{cumulative,hot}=\dot{m}_{hot}\cdot c_p\cdot(T_{hot,inlet}-T_{hot,current})$ (Where $T_{hot,inlet}$ is the hot fluid temperature at the heat exchanger inlet, and $T_{hot,current}$ is the hot fluid temperature at the current length). This value increases as the hot fluid transfers heat and cools down.
- **For the Cold Fluid (Heat Gain/Change):** The cumulative heat change for the cold fluid up to a certain point was calculated as: $Q_{cumulative,cold}=\dot{m}_{cold}\cdot c_p\cdot(T_{cold,current}-T_{cold,inlet})$ (Where $T_{cold,inlet}$ is the cold fluid temperature at the heat exchanger inlet, and $T_{cold,current}$ is the cold fluid temperature at the current length).
    - In co-current flow, this value generally increases as the cold fluid heats up (heat gain).
    - In counter-current flow, depending on the reference point and direction of flow, the cold fluid's temperature might decrease along the axis of increasing length. This results in negative values for "heat change" relative to the 0.25m measurement point, indicating a heat loss in that specific direction of measurement.

- **Plotting using Matplotlib:**

- For each experiment, a distinct figure was generated.
- A line plot was created, with the length points (0 m, 0.25 m, 0.50 m, 0.75 m, 1.00 m) on the X-axis.
- The calculated cumulative hot fluid heat loss and cold fluid heat gain/change values were plotted on the Y-axis (Cumulative Heat Transfer in Watts).
- Markers were used to indicate the specific measurement points.
- Each plot included a descriptive title (e.g., "Figure V.1: Cumulative Heat Transfer (Co-current, Equal Flows)"), clear X and Y axis labels, and a legend to differentiate between the hot and cold fluid lines.
- A grid was incorporated for improved readability.

This methodology enabled a clear visualization of how heat transfer accumulated along the length of the heat exchanger under each specific experimental condition.

3.4.2.1. Cumulative Heat Transfer (Co-current, Equal Flows)

Figure 3.5 represents the total amount of heat energy transferred between the hot and cold water streams as they flow in the same direction through the heat exchanger, starting from the 0.25-meter mark, in an experiment where both fluids had equal mass flow rates. As depicted in the figure, the cumulative heat transfer values for both fluids increase progressively along the length of the heat exchanger: starting from 0.00 W for both at 0.25 meters, the hot fluid's cumulative heat loss reaches 15.48 W at 0.50 meters, then 30.95 W at 0.75 meters, 46.37 W at 1.00 meter, and finally 53.64 W at 1.25 meters; concurrently, the cold fluid's cumulative heat gain is 10.30 W at 0.50 meters, 38.64 W at 0.75 meters, 43.79 W at 1.00 meter, and 59.18 W at 1.25 meters. This consistent increase in cumulative heat transfer for both fluids along the length indicates continuous heat exchange, and the close proximity of the hot fluid's heat loss and the cold fluid's heat gain values suggests a reasonable energy balance within the system, illustrating the moderate heat transfer performance characteristic of this co-current, equal flow configuration which had an effectiveness of approximately 19.44%.

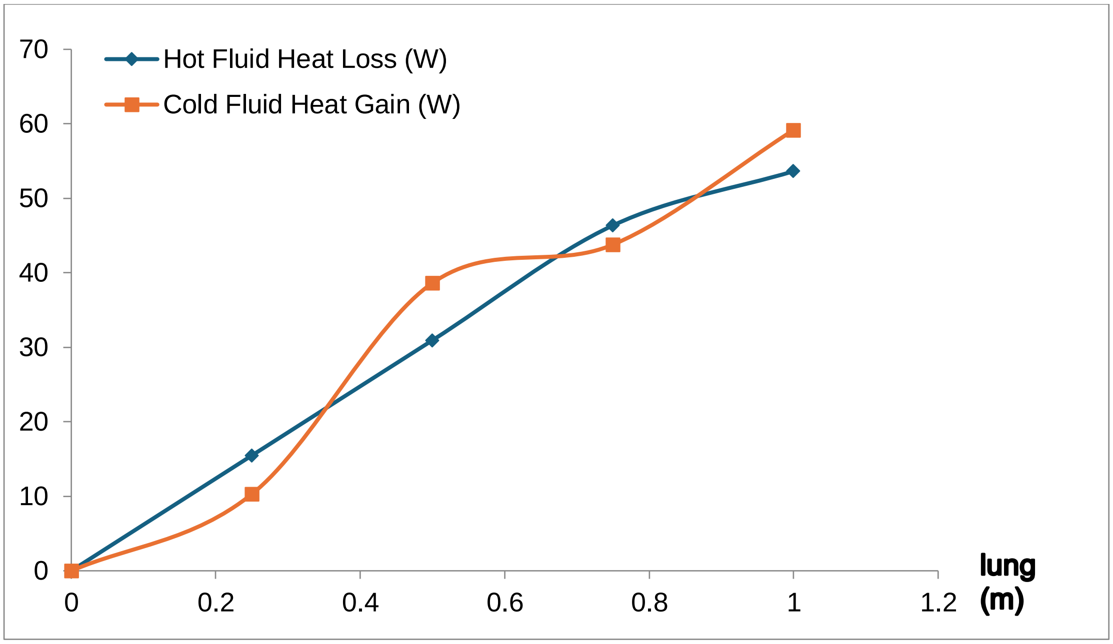


Figure 3.5.Cumulative Heat Transfer (Co-current, Equal Flows)

3.4.2.2. Cumulative Heat Transfer (Co-current, Doubled Cold Flow)

Figure 3.6 illustrates the total heat energy transferred between the hot and cold water streams when flowing in the same direction, with the cold fluid's flow rate significantly increased (doubled) compared to the hot fluid. As visible in the figure, both the cumulative heat loss from the hot fluid and the heat gain by the cold fluid increase along the heat exchanger's length. Starting at 0.25 meters with 0.00 W for both, the hot fluid's cumulative heat loss reaches 21.84 W at 0.50 meters, 43.68 W at 0.75 meters, 64.40 W at 1.00 meter, and 78.43 W at 1.25 meters. Concurrently, the cold fluid's cumulative heat gain is notably higher: 25.10 W at 0.50 meters, 87.78 W at 0.75 meters, 118.32 W at 1.00 meter, and 150.05 W at 1.25 meters. This pronounced increase in heat transfer compared to the equal flow rate case indicates that doubling the cold fluid's flow significantly enhances the overall heat exchange in this co-current configuration, contributing to a higher effectiveness (approximately 41.72%). The larger disparity between heat lost by the hot fluid and heat gained by the cold fluid, particularly at longer lengths (e.g., 64.40 W vs 118.32 W at 1.00m), also suggests a more substantial energy transfer and potentially highlights external heat losses or experimental nuances specific to this higher flow rate condition.

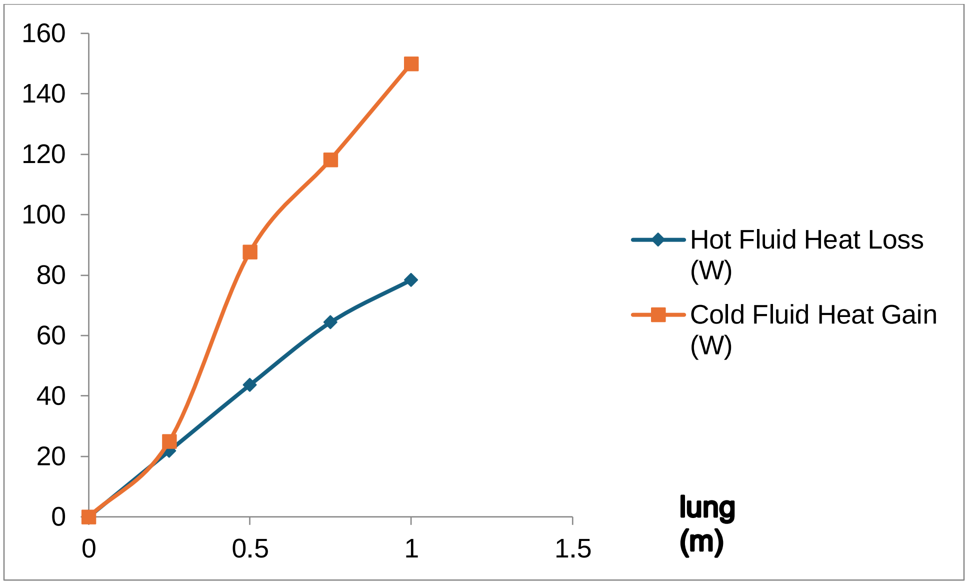


Figure 3.6.Cumulative Heat Transfer (Co-current, Doubled Cold Flow)

3.4.2.3. Cumulative Heat Transfer (Counter-current, Equal Flows)

Figure 3.7 shows the heat exchange when hot and cold fluids flow in opposite directions with equal mass flow rates. This figure demonstrates the superior performance typically observed in counter-current heat exchangers. Starting at 0.25 meters with 0.00 W for both fluids, the hot fluid's cumulative heat loss increases significantly along its flow path, reaching 18.06 W at 0.50 meters, 54.49 W at 0.75 meters, 83.72 W at 1.00 meter, and a substantial 104.99 W by 1.25 meters. For the cold fluid, the "Cumulative Heat Change" is represented by negative values, which is characteristic of counter-current flow when the length axis increases in the direction of the hot fluid; this indicates that as the cold fluid flows in the opposite direction (from 1.25m towards 0.25m), its temperature decreases when measured at progressively increasing points from 0.25m, thus showing a 'loss' relative to its temperature at 0.25m (e.g., -45.02 W at 0.50 meters, -73.42 W at 1.00 meter, and -111.45 W at 1.25 meters). The larger magnitudes of cumulative heat transfer for the hot fluid in this configuration, compared to co-current flows, underscore the enhanced efficiency of counter-current operation, which resulted in a higher effectiveness of approximately 55.96%.

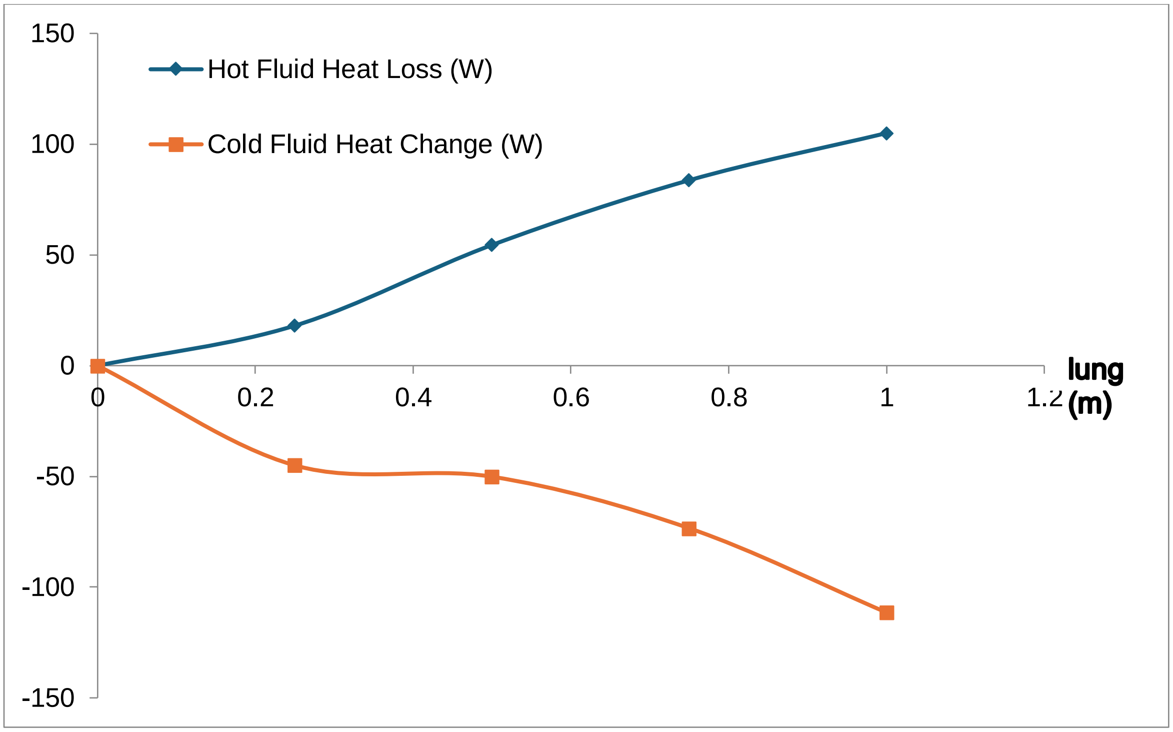


Figure 3.7.Cumulative Heat Transfer (Counter-current, Equal Flows)

3.4.2.4. Cumulative Heat Transfer (Counter-current, Doubled Cold Flow)

Figure 3.8 illustrates the heat exchange in a counter-current configuration where the cold fluid's flow rate has been doubled. This setup maintains the characteristic efficiency of counter-current flow. Starting at 0.25 meters with 0.00 W for both fluids, the hot fluid's cumulative heat loss consistently increases, reaching 12.87 W at 0.50 meters, 52.88 W at 0.75 meters, 82.43 W at 1.00 meter, and a substantial 105.00 W at 1.25 meters. Concurrently, the cold fluid's "Cumulative Heat Change" is represented by negative values (e.g., -42.82 W at 0.50 meters, -76.84 W at 0.75 meters, -94.75 W at 1.00 meter, and -108.97 W at 1.25 meters). These negative values indicate that as the cold fluid flows opposite to the increasing length axis, its temperature decreases relative to its measurement at 0.25m. Despite the doubled cold flow, the hot fluid's overall heat loss magnitude remains remarkably similar to the equal-flow counter-current case, confirming the already high effectiveness of this flow arrangement (approximately 56.10%), with the additional cold fluid serving to absorb more heat but not drastically alter the effectiveness itself.

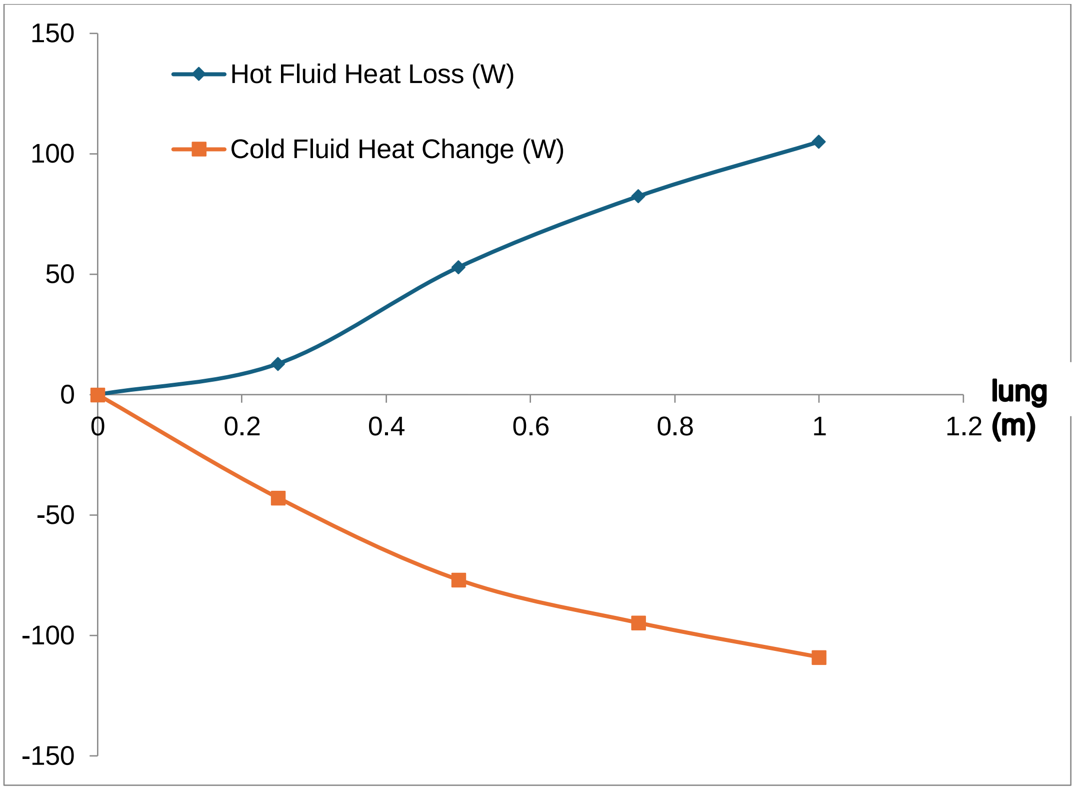


Figure 3.8.Cumulative Heat Transfer (Counter-current, Doubled Cold Flow)

Note: For the Counter-current cold fluid, the "Heat Change" values are negative because the cold fluid's temperature decreases as length increases from the 0.00 m measurement point, indicating a heat loss relative to that initial measurement point.

3.4.3. Comparison of Heat Exchanger Effectiveness

Experiment 1 (Co-current, Equal Flows): ϵ=0.1944 (19.44%)

This relatively low value indicates that your co-current heat exchanger, with equal flow rates, is not highly effective. Only about 19.44% of the maximum possible heat transfer is being achieved. This is typical for co-current flow, as the temperature difference between the fluids diminishes along the length, limiting further heat transfer.

Experiment 2 (Co-current, Doubled Cold Flow): ϵ=0.4172 (41.72%)

By doubling the cold water flow rate, the effectiveness significantly increased from 19.44% to 41.72%. This shows that increasing the mass flow rate of the cold fluid (which likely increased its heat capacity rate, potentially making it the Cmax fluid) improved the heat transfer. The larger amount of colder fluid absorbs more heat, leading to a better performance in this co-current setup.

Experiment 3 (Counter-current, Equal Flows): ϵ=0.5596 (55.96%)

Switching to a counter-current configuration with equal flow rates dramatically improved the effectiveness to 55.96%. This is a key finding! Counter-current flow inherently allows for a more uniform temperature difference along the entire length of the heat exchanger, leading to much more efficient heat transfer compared to co-current flow.

Experiment 4 (Counter-current, Doubled Cold Flow): ϵ=0.5610 (56.10%)

When the cold water flow rate was doubled in the counter-current setup, the effectiveness remained very high, showing a slight increase to 56.10%. This reinforces that counter-current is a highly effective mode of operation. The effect of doubling the cold flow rate is less pronounced on effectiveness in this already efficient configuration compared to its impact in co-current flow. This suggests that the system was already operating close to its optimal effectiveness for these conditions in counter-current mode.

In summary, the effectiveness values provide a powerful metric to compare different heat exchanger designs and operating conditions, allowing you to quantitatively assess how well your heat exchanger is transferring heat. Higher effectiveness means better performance.

3.5. Discussion

This study investigated the thermal performance of a double-pipe heat exchanger under varying flow arrangements and mass flow rates, specifically focusing on co-current and counter-current configurations with equal and doubled cold fluid flow rates. The key performance indicators evaluated were temperature profiles, fluid flow regimes (Reynolds number), and heat exchanger effectiveness.

3.5.1. Impact of Flow Arrangement (Co-current vs. Counter-current):

The most significant factor influencing the heat exchanger's performance was the flow arrangement.

- **Co-current Flow (Experiments 1 & 2):** In this configuration, both hot and cold fluids flow in the same direction.

- **Experiment 1 (Co-current, Equal Flows):** With hot and cold mass flow rates of approximately 0.003077 kg/s, the heat exchanger achieved an effectiveness (ϵ) of 0.1944 (19.44%). The cumulative heat transfer plots (Figure V.1) showed a moderate increase in heat exchange along the length, with the hot fluid losing 46.37 W and the cold fluid gaining 43.79 W by the 1.00m mark.
- **Experiment 2 (Co-current, Doubled Cold Flow):** Doubling the cold fluid mass flow rate to approximately 0.006014 kg/s significantly improved the effectiveness to 0.4172 (41.72%). This represents a 114.6% increase in effectiveness compared to Experiment 1. The cumulative heat transfer (Figure V.2) also showed a notable increase, with 64.40 W lost by the hot fluid and 118.32 W gained by the cold fluid at 1.00m. This highlights that a higher flow rate for the cold fluid in co-current mode can improve performance by maintaining a larger overall temperature driving force.

- **Counter-current Flow (Experiments 3 & 4):** In this configuration, the hot and cold fluids flow in opposite directions.
  - **Experiment 3 (Counter-current, Equal Flows):** With equal mass flow rates of approximately 0.003077 kg/s for both fluids, the effectiveness dramatically increased to 0.5596 (55.96%). This is a 187.9% improvement compared to the co-current equal flow (Experiment 1). The cumulative heat transfer (Figure V.3) showed a greater magnitude of heat exchange along the length (e.g., 83.72 W hot fluid heat loss at 1.00m), despite the cold fluid's temperature decreasing along the measured length (resulting in negative cumulative change relative to 0.25m for the cold fluid).
  - **Experiment 4 (Counter-current, Doubled Cold Flow):** Doubling the cold fluid mass flow rate to approximately 0.006014 kg/s in the counter-current setup resulted in an effectiveness of 0.5610 (56.10%). This represents a marginal increase of only 0.25% over Experiment 3's effectiveness. The cumulative heat transfer (Figure V.4) also showed a high rate of heat exchange (e.g., 82.43 W hot fluid heat loss at 1.00m).

3.5.2. Fluid Flow Regimes (Reynolds Number)

The calculated Reynolds numbers indicate that the fluid flow within the heat exchanger was predominantly in the **laminar regime** for all experiments, as all Reynolds numbers were well below 2300 (the typical threshold for turbulent flow in pipes).
The Reynolds number (Re) is a dimensionless quantity used to predict fluid flow patterns. It helps determine whether the flow is laminar (smooth and orderly), transitional, or turbulent (chaotic and irregular).
The formula used to calculate the Reynolds number for flow in a pipe is:

$$Re = \frac{\rho\, v\, D}{\mu} \tag{16}$$

Where:

- ρ (rho) = Density of the fluid (for water, approximately 1000 kg/m³)
- v = Average velocity of the fluid (m/s)
- D = Inner diameter of the pipe (for your setup, 0.014 m)
- μ (mu) = Dynamic viscosity of the fluid (for water, approximately 0.001 Pa·s or kg/(m·s) at typical operating temperatures)

so,
Figure 3.10 presents a hierarchical classification of heat exchangers, illustrating the diverse types based on their operating principles and structural configurations. At the highest level, it distinguishes between regenerative heat exchangers, which involve intermittent heat transfer through a temporary storage medium, and recuperative heat exchangers, which facilitate continuous heat transfer across a separating wall. The diagram further breaks down recuperative exchangers into those with direct fluid contact and the more common indirect contact types, which are then subdivided by surface characteristics (primary or augmented) and specific designs, notably including tubular exchangers. The tubular category is further detailed into single-tube and shell-and-tube designs, highlighting their various configurations. Finally, the figure also notes the fundamental flow arrangements employed in heat exchangers, such as counter-current, parallel (co-current), and cross-flow, providing a comprehensive overview of how these devices are categorized in the field of thermal engineering.
As a brief conclusion:

- **Experiment 1:** Hot fluid Re = **487.6**, Cold fluid Re = **487.6**
- **Experiment 2:** Hot fluid Re = **487.6**, Cold fluid Re = **952.1**
- **Experiment 3:** Hot fluid Re = **487.6**, Cold fluid Re = **487.6**
- **Experiment 4:** Hot fluid Re = **487.6**, Cold fluid Re = **952.1**

Despite the laminar flow, which generally implies lower heat transfer coefficients compared to turbulent flow, significant heat exchange was still observed, particularly in the counter-current configuration.

3.6. Conclusion

The experimental results unequivocally demonstrate that the counter-current flow arrangement is significantly more effective for heat transfer in this double-pipe heat exchanger compared to the co-current arrangement. The effectiveness values of **~56%** for counter-current flow are substantially higher than the **~19-42%** observed for co-current flow. While increasing the cold fluid's flow rate improved co-current performance, it yielded only a negligible gain in the already highly efficient counter-current setup. The consistent laminar flow regime across all experiments suggests that further improvements in heat transfer might require modifications to induce turbulent flow or increase the heat transfer area, but the fundamental advantage of counter-current over co-current for maximizing effectiveness in this system is clear.

References

No references

General conclusion

This master's project successfully culminated in the design, construction, and experimental validation of a tubular heat exchanger, meticulously crafted using readily available local materials at El Oued University. The overarching objective of establishing this heat exchanger as a versatile test bench within the university's laboratory has been demonstrably achieved. Beyond merely assembling a device, this work involved a comprehensive understanding and practical application of fundamental heat transfer and fluid dynamics principles, ensuring the system's functionality and its capability to provide empirical data.

The experimental phase, which systematically explored both co-current and counter-current flow configurations under varying flow rates, yielded several key results:

- **Overall Objective Achieved:** A functional tubular heat exchanger was successfully designed, constructed using local materials, and validated as a test bench for El Oued University's laboratory. This approach minimized costs and maximized the direct involvement in the design and fabrication process.
- **Impact of Flow Arrangement:**
  - **Counter-current flow consistently demonstrated superior performance** compared to co-current flow.
  - **Effectiveness in Counter-current Flow:** Reached up to **0.5610 (56.10%)**, indicating significantly higher heat transfer efficiency.
  - **Effectiveness in Co-current Flow:** Ranged from **0.1944 (19.44%)** to **0.4172 (41.72%)**.
- **Impact of Doubling Cold Flow Rate:**
  - In **co-current flow**, doubling the cold fluid flow rate (from approximately 3.077×10^{-6} m3/s to 6.014×10^{-6} m3/s) significantly **increased effectiveness by 114.6%** (from 0.1944 to 0.4172). This highlights the benefit of increasing flow to enhance heat transfer in this configuration.
  - In **counter-current flow**, doubling the cold fluid flow rate yielded only a **marginal increase of 0.25%** in effectiveness (from 0.5596 to 0.5610), suggesting that the counter-current arrangement is inherently highly efficient and less sensitive to increased flow rates for effectiveness improvements under these conditions.
- **Cumulative Heat Transfer:**

    - **Higher magnitudes of actual heat transfer** were observed in counter-current configurations (e.g., hot fluid losing over 82 W by the 1.00m mark) compared to co-current flows (hot fluid losing around 46-64 W by the 1.00m mark). This directly supports the higher effectiveness values in counter-current flow.
- **Fluid Flow Regimes (Reynolds Number):**
    - All experiments operated within the **laminar flow regime**.
    - Calculated Reynolds numbers for both hot and cold fluids ranged from approximately **280 to 547**, confirming the non-turbulent nature of the flow.

This project's success is not just about the experimental results but also about the establishment of a permanent, functional test bench. The heat exchanger now stands as a valuable resource, capable of facilitating diverse future studies including investigations into overall heat transfer coefficients, the impact of varying fluid properties, pressure drop characteristics, and the efficacy of different insulation materials. It significantly enhances the laboratory's capacity for practical coursework, student projects, and research initiatives in experimental thermodynamics and fluid mechanics education, providing a tangible platform for students to deepen their understanding of heat transfer phenomena through direct experimentation and validation of theoretical models.