Thermal Performance Analysis of an Automotive Type Compact Heat Exchanger

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Abstract

Compact heat exchangers are one of the most important types of heat exchangers widely used in industrial and engineering applications. They are characterized by their small size and the large amount of heat exchange area per unit volume. Many techniques have been developed to enhance heat transfer rate through heat exchangers, one of which is increasing exchange area using fins with different forms and designs. In this study the heat transfer process through a locomotive compact heat exchanger of a type (FIAT PANDA 750) has been analyzed with a detailed description of all design parameters involved. The study revealed low performance characteristics of the tested heat exchanger which had not exceeded 65%. The study also achieved some interesting results leading to the determination of the most important thermal performance correlation represented by the Colburn-Reynolds chart which can be used in performance analysis and design process of this type of heat exchangers.

Keywords: Compact heat exchanger; thermal performance analysis; heat transfer enhancement.

1. Introduction

Heat exchangers are devices used to transfer thermal energy between two or more fluids at different temperatures. Heat exchangers are widely used in many engineering applications such as power plants, chemical processing, cooling of electronic devices and as radiators for most transport vehicles. Heat exchange process within the exchanger takes place by one or more of the well-known heat transfer mechanisms such as conduction, convection, radiation, evaporation and condensation. Each of these mechanisms is controlled by many variables that determine their dominance in the process of heat transfer within the exchanger. These variables can be classified into geometric variables (heat exchange area, size, weight), operating variables such as temperature difference, amount of thermal energy to be transferred, amount of energy necessary to pump fluids through the exchanger, variables that describe the physical properties of the operating fluids, flow dynamic variables that play an important role in determining the regime and flow nature of the operating fluids, and finally heat transfer variables that describe the thermal energy exchange process through the heat exchanger [1]. Therefore, the design process of the heat exchanger on a basis that takes into account the dominant thermal energy transfer mechanisms and their analysis is very important for the heat exchanger to meet the required tasks. Enhancing heat transfer process within heat exchangers becomes the main scientific research occupations in these days. Increasing the amount of heat transferred within the exchange unit in keeping its size unchanged will result in best thermal and economic performance characteristics for the heat exchanger.

In many engineering applications, the choice of the heat exchanger has to meet some constraints regarding its size and weight to satisfy some practical design requirements such as the case of the cooling cycle in the motor vehicles and most transport means in general. These functional characteristics and requirements led to the development of the compact heat exchangers which are the result of many scientific research works targeting the improvement of the thermal performance of heat exchangers. The main feature of the compact heat exchanger is its transfer density (heat transfer area per unit volume) starting from 700 $\left({}^{m^2}/{}_{m^3}\right)$, where the heat transfer area is increased by adding fins with suitable arrangements and design to the main flow passages [2]. These techniques belong to the passive control methods used to enhance heat transfer between fluid and solid surfaces. Differing from the active control procedures, there is no external energy input needed to modify the flow in the heat exchanger flow passages. The flow is modified through geometric modification of the fins surfaces and/or the solid boundaries of the flow passages [3]. Compact heat exchangers are employed for applications where the operating fluids are both gases or one of them is gas and the other is liquid. As mentioned above the main task of a compact heat exchanger is to perform heat energy transfer between fluids of low convective heat transfer coefficient with a reasonable performance and small size. Compact heat exchangers are classified depending on the fin configuration used into plate-fin or tube-fin heat exchangers [4]. As conventional heat exchangers, design and performance analysis of compact heat exchangers are realized via LMTD (Logarithmic mean temperature difference) and/or NTU (Number of transfer units) methods. For each design configuration of the compact heat exchangers; experimental investigations must be done to outline the relations between all variables involved in the process of heat transfer within the heat exchanger. The governing variables are gathered in dimensionless form and plotted in graphical charts to facilitate design, choice and performance analysis of compact exchangers of the same type. The main variables that control the heat transfer process in the compact heat exchanger are Reynolds number (Re) and Colburn modulus (J), knowing the values of these tow variables for a given operating condition permit conducting a complete thermal performance analysis for the compact heat exchanger [5]. The narrow passages formed between the fins make it difficult to conduct any kind of measurements in these passages since temperature measurements on the fin surfaces as well as that of the fluid passing through them are necessary to determine values of Re and J. In the present scientific paper, a methodology has been developed which can be used to determine the values of the dominating flow and heat transfer variables and conducting a complete thermal performance analysis of a compact heat exchanger. The studied heat exchanger is of a type (Fiat Panda Fire 750) with unknown thermal and design characteristics. The obtained results enabled to construct an important flow dynamic/heat transfer relation (Reynolds-Colburn), represented in a graphical form, which can be used for design and performance analysis purposes for any compact heat exchanger of the same type and in the permitted range of operating conditions.

2. Material and Methods

This work aims to evaluate performance characteristics of an automotive type (air/water) compact heat exchanger installed in an experimental unit designed to study basic heat exchanger operations. The heat exchanger is of a type (FIAT Panda Fire 750) with unknown design and thermal performance characteristics. The main task encountered during this study was the determination of heat transfer variables that control the thermal exchange process through the heat exchanger. The overall heat transfer coefficient as well as the convective heat transfer coefficient in the finned side of the heat exchanger has to be determined. Based on this information and the known and measured design characteristics of the heat exchanger the thermal performance analysis can then be realized. The experimental procedure plans also to measure the effect of mass flow rate of both hot and cold fluids on the performance characteristics of the compact heat exchanger. The heat exchanger used has only the following known design characteristics:
Front exchange area ($A_{fr} = 0.0317\,m^2$); fin spacing ($s = 1.05\,mm$); material: round finned pipes of aluminum. Other design characteristics are measured such as: Fin thickness ($t = 0.15\,mm$); inner pipe diameter ($d_i = 0.86\,mm$); outer pipe diameter ($d_o = 0.95\,mm$).
Figure (2.1) shows a schematic diagram of layout and components of the experimental apparatus. The finned aluminum tubes are installed in a painted sheet steel tunnel (1). The air is supplied into the tunnel by a changeable speed fan (2) while the water flow is supplied by a variable speed motor driven pump (7). Water is heated by an electric resistance mounted in a tank feeding (10). The device is provided by temperature detectors installed in the inlet and outlet flow passages of both hot and cold fluids connected to digital temperature gages mounted on the control panel (14).
The digital temperature gauges give the inlet and outlet temperature readings for both hot and cold fluids. The water mass flow rate is obtained from the readings of the water flow meter (11) and the air mass flow rate is accessible through the readings of the differential manometer and the corresponding

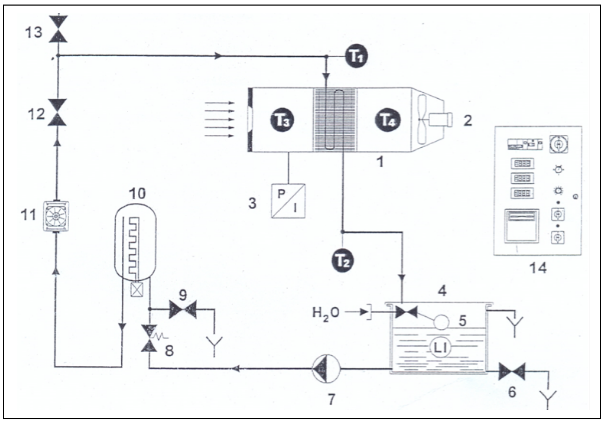

Figure 2.1: Layout and components of the experimental apparatus

flow rate value from the calibration diagram provided by the manufacturer. Temperature readings have been recorded for 10 equally spaced values of the cold fluid flow rate (air) and the procedure has been repeated for ten equally spaced values of the hot fluid flow rate (water).

3. Thermal Performance Analysis

Thermal performance analysis has been performed using some assumptions related to the nature of the problem and the available experimental facility. According to the small variations of physical properties of both hot and cold fluids in the operating ranges of temperature differences, these properties are assumed to be constant. The flow regimes of both cold and hot fluids were considered to be fully developed and the heat loss from the exchanger into the ambient surrounding due to the imperfect isolation of the tunnel walls have been neglected. The fouling resistance produced by deposit waste materials on the inner walls of the pipes have also been neglected. Table (3.1) shows the values of all physical properties of materials used.

Thermal analysis process of compact heat exchangers differs slightly than that encountered in the case of conventional heat exchangers. There are many geometrical, heat transfer and flow dynamic variables that should be determined first, which are indispensable in analyzing thermal behavior and performance of this type of heat exchangers. Geometric variables such as the free flow area (A_{ff}), the hydraulic diameter of finned flow passages (D_h), the overall heat transfer area (A_t), the total fin area and the heat

Table 3.1: Physical properties of fluids and materials used

Physical property	Symbol	Value at room temp
Water density	ρ_w	$992.8\ (^{kg}/_{m^3})$
Water viscosity	μ_w	$6.72 \times 10^{-4}\ (^{kg}/_{m.s})$
Prandtle No. (air)	Pt_{air}	0.6907
Air viscosity	μ_{air}	$1.875 \times 10^{-5}\ (^{kg}/_{m.s})$
Air heat capacity	Cp_{air}	$1.0075\ (^{kJ}/_{kg\,^\circ K})$
Water heat capacity	Cp_w	$4.1778\ (^{kJ}/_{kg\,^\circ K})$
Water conductivity	K_w	$0.62997\ (^{W}/_{m\,^\circ K})$
Aluminum conductivity	K_{al}	$237\ (^{W}/_{m\,^\circ K})$

exchanger volume are indicative tools used to classify and analyze compact heat exchangers [6]. Table (3.2) gives calculated values of these geometric variables during the current study.

Table 3.2: Geometric variables of the tested compact heat exchanger

Geometric Variable	Symbol	Value
Free flow area	A_{ff}	$0.015206\,m^2$
Frontal exchange area	A_{fr}	$0.0317\,m^2$
Total exchange area	A_t	$2.68178\,m^2$
Total fins area	A_f	$2.195\,m^2$
Hydraulic diameter (finned side)	D_h	$0.001212\,m$
Total volume	V	$0.0013339\,m^3$
(A_{ff}/A_{fr})	σ	0.48
(A_t/V)	α	2010
(A_f/A_t)		0.818

As mentioned earlier the dominant heat transfer mechanism in most heat exchanger devices is convection, where the convective heat transfer coefficient plays an important role in determining the quantity of heat transferred between operating fluids. Therefore, to perform thermal performance analysis of the compact heat exchanger it was necessary to determine the values of the convective heat transfer coefficient of the hot fluid, which flows through circular pipes (internal pipe flow) and of the cold fluid which flows through the finned passage of the heat exchanger. Internal flow convective heat transfer coefficient can be determined easily as the flow regime in the pipe was known. The problem arises in determining the convective heat transfer coefficient of the cold fluid in the finned flow passage since the local fins surface temperature as well as that of the external tube walls could not be measured. To overcome this difficulty, the overall heat transfer coefficient has been computed for each case using heat energy balance equation based on the logarithmic mean temperature difference (ΔT_m) as follows:

$$q = U \times A \times \Delta T_{lm} \tag{3.1}$$

The term ($U \times A$) is used to compute the overall thermal resistance which is equivalent to the sum of all convective and conductive heat transfer resistances imposed on the heat flux in the heat exchanger. Therefore, the overall heat transfer resistance equation is given by:

$$R_t = \frac{1}{U\ A} = \frac{1}{\eta_{o,c}\ h_c\ A_c} + R_w + \frac{1}{h_h\ A_h} \tag{3.2}$$

Where $\eta_{o,c}$ is the total fins efficiency of the cold finned passage, h_c is the convective heat transfer coefficient in the finned passage, A_c is the heat transfer area of the finned passage with fins surface area included, R_w is the conductive heat transfer resistance of the aluminum tube walls, h_h is the convective heat transfer coefficient of the hot water flow in the pipes, A_h is the inner exchange surface area of the tubes. In this equation, there are two unknowns, the convective heat transfer coefficient in the finned passage as well as the total fins efficiency which are in turn depends on the value of h_c according to the following expressions:

$$\eta_o = 1 - \frac{A_f}{A_t}\,(1 - \eta_f) \tag{3.3}$$

Where η_f is the single fin efficiency, and can be calculated as follows:

$$\eta_f = \frac{tanh\,(R_m\ \tau_t\ \phi)}{(R_m\ \tau_t\ \phi)} \tag{3.4}$$

$$R_m = \sqrt{\frac{2\ h_c}{k\ t}}$$

And ϕ is a geometric variable given by

$$\phi = (F - 1) - (1 - 0.35\ ln\ F)$$

$$F = \left(\frac{P}{2\pi\ \tau_t}\right)$$

Where P is the single fin perimeter and τ_t the outer tube radius with fin thickness included [7].
These two coupled equations (3.2, 3.3) have to be solved iteratively to get the values of (h_c) and the corresponding value of (η_o) for each case [7]. As the convective heat transfer coefficients were computed for the hot and cold sides, the corresponding dimensionless flow dynamic and heat transfer variables necessary for thermal performance analysis were also computed. These variables with their mathematical expressions are given in the Table (3.3).

Table 3.3: Dimensionless variables involved in the process of thermal performance

Quantity	Symbol	Math Expression
Reynolds No. (Air flow)	Re_{air}	$\left(\frac{G\ D_h}{\mu_{air}}\right)$
Reynolds No. (Water flow)	Re_w	$\left(\frac{\rho\ V\ D}{\mu}\right)$
Mass velocity	G	$\left(\frac{\dot{m}_{air}}{A_{ff}}\right)$
Prandtl No.	Pr	$\left(\frac{\mu\ C_p}{k}\right)$
Nusselt No.	Nu	$\left(\frac{h\ D}{k}\right)$
Colburn modulus	J	$St\ Pr^{2/3}$
NTU	NTU	$\left(\frac{A\ U}{C_{min}}\right)$
Effectiveness	ε	$\left(\frac{q}{q_{max}}\right)$
Stanton no.	St	$\left(\frac{h_c}{G\ C_{pair}}\right)$

The thermal performance of heat exchangers could be measured using dimensionless variable known as heat exchanger effectiveness or coefficient of thermal performance, which plays an important role in design and selection of the appropriate heat exchanger type [8]. As an example of its importance, in [Barron, 1985] have been shown that cryogenic plants based on Linde–Hampson cycle cease to produce liquid if the effectiveness of the heat exchanger in this cycle is below (0.869) [4]. The coefficient of thermal performance (effectiveness) measures the ability of the heat exchanger to perform a particular heat transfer objective for a given range of operating conditions. The calculated values of the effectiveness have been traced versus NTU (Number of transfer units) which is an indicative variable of the exchange capacity of the heat exchanger and also versus the relative heat capacity (C_{min}/C_{max}) of the operating fluids. The convective heat transfer coefficient of the finned flow passage which is given by the Col-

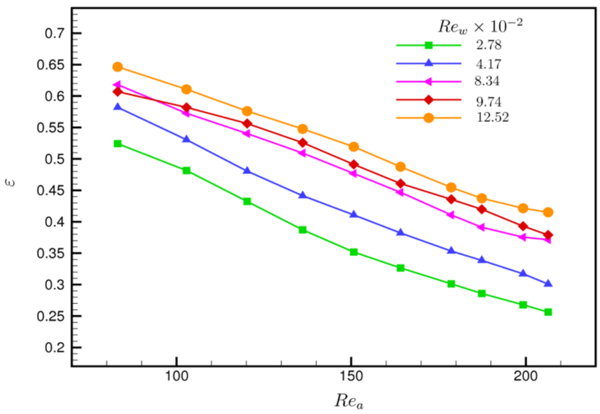

Figure 4.1: Effectiveness vs hot and cold flows Reynolds number

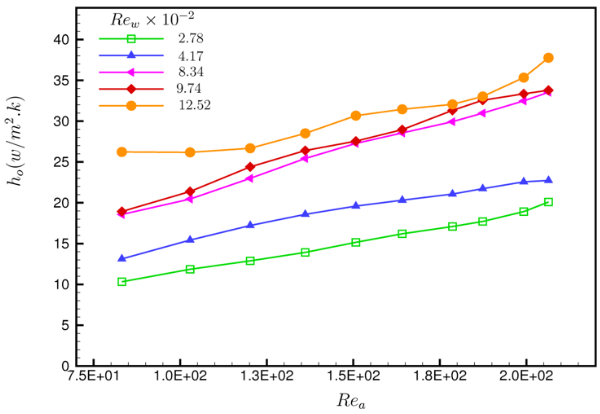

Figure 4.2: Effect of varying hot and cold flows Reynolds number on the convective heat transfer coefficient in the finned side

burn modulus are usually presented as a function of Reynolds number.

4. Results and Discussion

Thermal performance results are given in the form of mathematical or graphical correlations of various thermal and geometric parameters that control the heat energy exchange through the heat exchanger. The most important correlations which specify the capacity of a heat exchanger to fulfill certain required thermal objective are the effectiveness- NTU relation, effectiveness- Relative capacity relation and the Colburn-Reynolds relation [9, 10]. Therefore, in the foregoing discussions, results are presented in a graphical form monitoring the effect of changing Reynolds number of the cold and hot flows on the effectiveness, overall heat transfer coefficient, finned side convective heat transfer coefficient, effectiveness- NTU relation, effectiveness- Relative capacity relation, and Colburn-Reynolds relation.

Figure (4.1) presents the effect of changing Reynolds number for both cold and hot fluids flow on the effectiveness of the compact heat exchanger. It shows an increase in the thermal performance with increasing water flow rate and a decrease with increasing air flow rate. The performance reaches its maximum values at high water flow rate levels. These results confirm that the studied heat exchanger has a moderate thermal performance since it could not realize more than 65% of the thermal energy available at the best operating conditions. It can be noticed that the better thermal performance occurs at low levels of air flow rate.

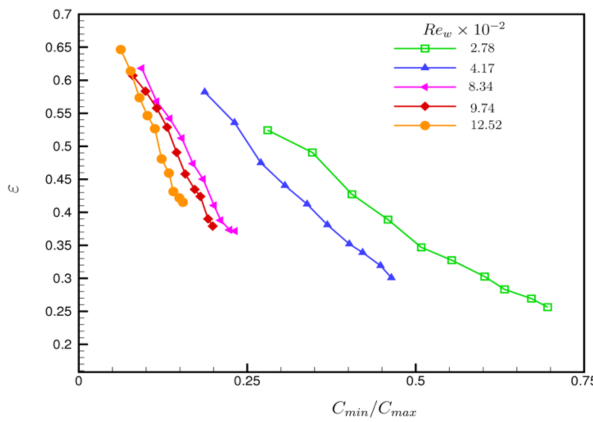

Figure 4.3: Effectiveness – Relative capacity relation for different hot fluid Reynolds number

As shown in Figure (4.2), at low water flow rates there is no significant changes in the convective heat transfer coefficient (h_c) and the same trends are observed for low flow rate levels of cold fluid (air). However the value of (h_c) increases rapidly as both flow rates were increased and it reaches a maximum value of ($37.7815\ W/m^2\ K$) at the highest flow rate level of both fluids. The variations of (h_c) follow a linear relationship as well.

Figure (4.3) shows the relative heat capacity ratio versus cold and hot fluids Reynolds number. The relative capacity increases as Reynolds number increases in the cold side and decreases in the hot side. It should be noted for all tested levels of both fluids flow rates that the cold fluid (air) was the minimum heat capacity fluid in the heat exchanger. The increase in the relative capacity ratio reduces the thermal performance of the heat exchanger and the

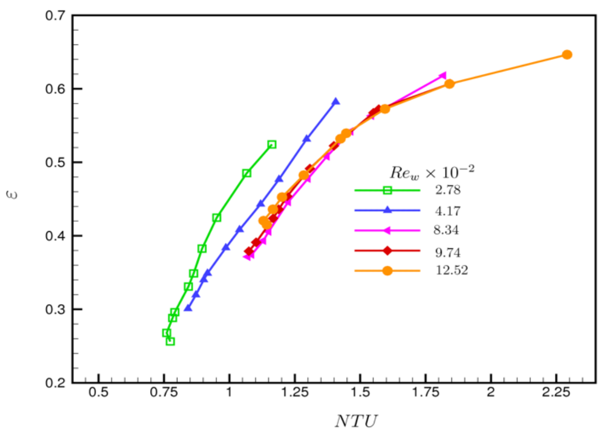

Figure 4.4: NTU effectiveness relation for different hot fluid Reynolds number

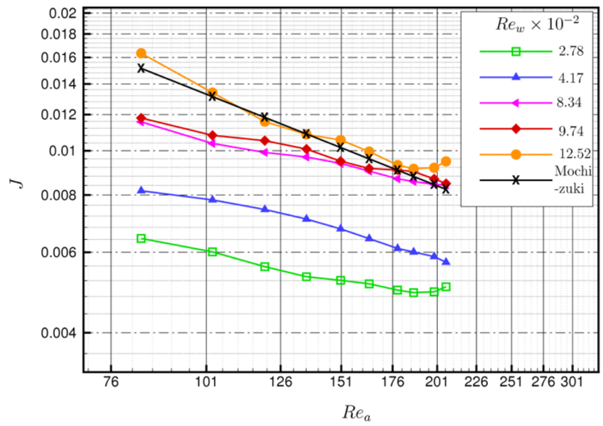

Figure 4.5: $Re_{air}-$ Colburn chart for different hot fluid Reynolds number

best performance occurs at highest levels of hot fluid Reynolds number and lowest levels of cold fluid flow rates.

By definition, NTU parameter is related to the exchange area and the overall heat transfer coefficient of the heat exchanger and it is used to calculate the amount of heat exchanged through the exchanger when the LMTD is not permitted. NTU effectiveness relation is used also in design and selection of an appropriate heat exchanger device. Figure (4.4) traces the evolution of effectiveness-NTU relation for different values of hot fluid Reynolds number; it shows that as NTU increases the effectiveness of the heat exchanger also increases. Increasing Reynolds number of both the cold and hot fluids contributes to the augmentation in the effectiveness and NTU values. It is expected from these results that the effectiveness could be improved if the volume and hence the exchange area of the heat exchanger were increased.

Thermal and flow dynamic characteristics of the compact heat exchanger are summarized in some graphical charts which express the correlation between the most dominating variables in the energy exchange process through the exchanger. These variables are the Colburn modulus and Reynolds number, the first one gives the convective heat transfer coefficient while the second determines the flow dynamic regime in the finned side of the heat exchanger. It is obvious from the resulting chart Figure (4.5), that the Colburn modulus decreases with increasing Reynolds number of the cold flow in the finned passages while it increases slightly with increasing Reynolds number of the hot flow inside the tube banks. Due to the lack of resources that could provide mathematical correlations for Colburn-Reynolds relation of the same type of compact heat exchangers used in this study, the graphical Colburn-Reynolds relation obtained has been validated qualitatively with Mochizuki et al correlation reported in [4], which suggests the following relationship:

$$J = 1.37\left({}^{1}/{}_{D_h}\right)^{-0.25} \sigma^{-0.184}\, Re^{-0.67} \qquad (4.1)$$

Although proposed graphical and mathematical correlations do not provide any information about some possible influence resulting from flow rate variation in the pipes on the convective heat transfer coefficient and hence on J values in the finned flow passage, an acceptable agreement have been found between this correlation and values of J at high Re_w cases.

5. Conclusion

Compact heat exchangers are widely used in most engineering and industrial applications due to their high thermal performance and small size as well as their low operating and maintenance costs. In this paper, a comprehensive study of the thermal and design characteristics of a heat exchanger have been presented. The compact heat exchanger is of a locomotive radiator type FIAT PANDA with unknown design and thermal performance characteristics. Characteristic design parameters have been determined and then used for the process of thermal performance analysis. The effectiveness of the compact heat exchanger has been determined for wide range of Reynolds number of both cold and hot fluid

flow. The results show low value of the heat exchanger effectiveness which does not exceeded 65% in the best operating condition. The convective heat transfer coefficient in the finned side has been also determined for the same range of Reynolds number. The compact heat exchanger thermal performance chart (Colburn-Reynolds) have been produced which can be used to determine the quantity of heat that could be exchanged under nominal design operating conditions. An unexpected effect of the inner flow Reynolds number on the convective heat transfer coefficient in the finned cold flow side has also been reported, which should be verified in a future work.

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