

Multiscale Simulation of compact heat exchanger thermal performance of heat exchangers

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Abstract:

Compact heat exchangers (CHEs) play a pivotal role in various thermal systems due to their high heat transfer surface area per unit volume. This study focuses on the performance analysis of compact heat exchangers to optimize efficient heat flow and energy utilization in industrial and commercial applications. The primary objective is to evaluate thermal performance parameters such as effectiveness, heat transfer coefficient, and pressure drop under varying flow conditions and configurations. Computational Fluid Dynamics (CFD) simulations, along with experimental data, are used to assess the thermal behavior of different compact geometries, including plate-fin and micro channel exchangers. The results reveal that enhanced surface area and turbulence generated by fins significantly improve the heat transfer rate while maintaining a reasonable pressure drop. The study concludes that optimal design and selection of compact heat exchangers can lead to substantial energy savings, reduced equipment size, and increased system efficiency in heat-critical processes.

1. Introduction

A heat exchanger is a system used to transfer heat between two or more fluids. Heat exchangers are used in both cooling and heating processes. The fluids may be separated by a solid wall to prevent mixing or they may be in direct contact. They are widely used in space heating, refrigeration, air conditioning, power stations, chemical plants, petrochemical plants, petroleum refineries, natural-gas processing, and sewage treatment. The classic example of a heat exchanger is found in an internal combustion engine in which a circulating fluid known as engine coolant flows through radiator coils and air flows past the coils, which cools the coolant and heats the incoming air. Another example is the heat sink, which is a passive heat exchanger that transfers the heat generated by an electronic or a mechanical device to a fluid medium, often air or a liquid coolant workhastobe done. Further more increasing the temperature difference

more than enough will cause unwanted thermal stresses on the metal surfaces between two fluids. This usually results in the deformation and also decreases the life span of those materials. As a result of these facts, increasing the heat transfer surfacearea generally is the best engineering approach.

Theabove requirements have been the motivation for the development of a separate class of heat exchangers known as Compact heat exchangers. These heat exchangers havea very high heat transfer surfacearea with respect to their volumeand areassociated with high heat transfer coefficients. Typically, the heat exchanger is called compact if the surfacearea density (β) i.e. heat transfer surfacearea per unit volumeis greater than $700 \text{ m}^2/\text{m}^3$ in either oneor more sides of two-stream or multi stream heat exchanger [R.K Shah, Heat Exchangers, Thermal Hydraulic 1980]. The compact heat exchangers are lightweight and also have much smaller footprint, so they are highly desirablein manyapplications.

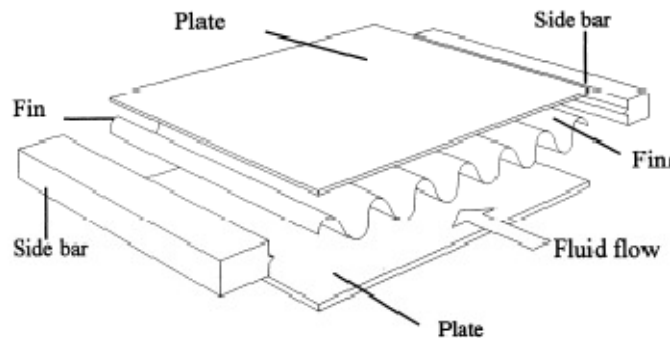


Figure 1 Exploded view of a plate fin heat exchanger

Platefin heat exchangers are generally, made from an alloy of aluminum or stainless steel. However, the process temperature and pressure dictates the choice of the material. Aluminum alloys are particularly suitable for low temperature applications because of their low weight and excellent ductility and increasing strength under such conditions. In general, the fins or secondary surfaces and the side bars are usually joined to the separating plate by using dip brazing technology or more recently vacuum brazing technique. The brazing material in case of aluminum exchangers is an aluminum alloy of lower melting point, while that used in stainless steel exchangers is a nickel based alloy with appropriate melting and welding characteristics.

In the vacuum brazing process, no flux or separate pre-heating furnace is required. The assembled block is heated to brazing temperature by radiation from electric heaters and by conduction from the exposed surfaces into the interior of the block. The absence of oxygen in the brazing environment is ensured by application of high vacuum (Pressure $\approx 10^{-6}$ Mbar). The composition of the residual gas is further improved (lower oxygen content) by alternate evacuation and filling with an inert gas as many times as experience dictates. No washing or drying of the brazed block is required. Many metals, such as aluminum, stainless steel, copper and nickel alloys can be brazed satisfactorily in a vacuum furnace.

2. Literature Survey

Heat exchangers constitute the most important components of many industrial processes and equipment's covering a wide range of engineering applications. Increasing awareness for the effective utilization of energy resources, minimizing operating cost and maintenance free operation have led to the development of efficient heat exchangers like compact heat exchangers.

R.K Shah[15] in his elaborate discussion over the classification of heat exchangers has defined the "compact heat exchangers" as one having a surface area density of more than $700 \text{ m}^2/\text{m}^3$. Such compactness is achieved by providing the extended surfaces i.e. fin on the flow passages which work as the secondary heat transfer area.

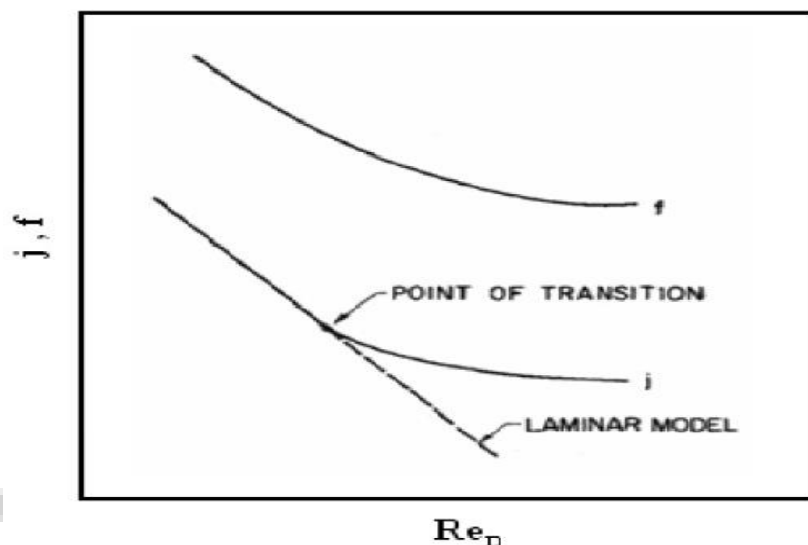


Figure 2 typical j and f characteristics

Four different flow regimes (Figure. 1 and 2.) were identified by Joshi and Webb [2] from their experiment. The flow was found to be laminar and steady in the first regime. In the second regime the oscillating flow structures were found in the transverse direction. The flow oscillated in the wake region between two successive fins in the third regime. And in the fourth regime the effect of vortex shedding came into picture. The laminar flow correlation of Joshi and Webb started to under predict the j and f factors at the second regime. So they assumed the Reynolds number at that point as the critical Reynolds number to identify the transition from laminar to turbulent.

3. Experimental Setup and Procedure

Our air supply system consists of a Twin screw rotary compressor which is a positive displacement machine that uses two helical screws known as rotors to compress the gas. The rotors comprise of helical lobes affixed to a front and rear shaft. One rotor is called the male rotor and it will typically have three bulbous lobes. The other rotor is the female rotor and this has valleys machined into it that matches the curvature of the male lobes. Typically the female rotor has five valleys. In a dry running rotary screw compressor, timing gears ensure that the male and female rotors maintain precise alignment. In oil flooded rotary compressor lubricating oils bridge the space between the rotors, both providing a hydraulic seal and transferring mechanical energy between the driving and driven rotors.

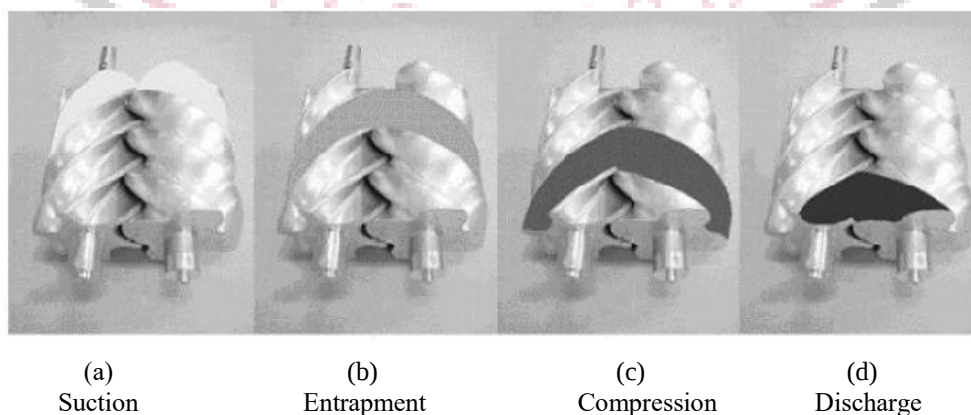


Figure 3 working mechanism of Twin Screw Compressor

4. Types of Double Pipe Heat Exchangers

Design of heat exchanger involves two types of problem – (a) Sizing and (b) Rating. Sizing involves the determination or we can say selection of type of heat exchanger, flow arrangement, material of heat exchanger and physical dimensions of the heat exchanger to meet the specified heat transfer and pressure drop requirements. Whereas, Rating of the heat exchanger consists of finding the thermal performance parameters like, effectiveness, heat transfer coefficient and pressure drop of an already designed heat exchanger whose dimensions are known to us. We are working on the rating problem. Since the outlet temperatures are not known for the rating problem, the average fluids mean temperatures have to be projected first. The heat transfer coefficient and the effectiveness of the plate fin heat exchanger are found based on different correlations existing in literature. The outlet temperatures and the average fluid temperatures are calculated from the effectiveness value and then compared with the values assumed earlier. The above procedure is carried out until the calculated values of the mean fluid temperatures matches with the assumed values. Following steps show the detailed rating procedure:

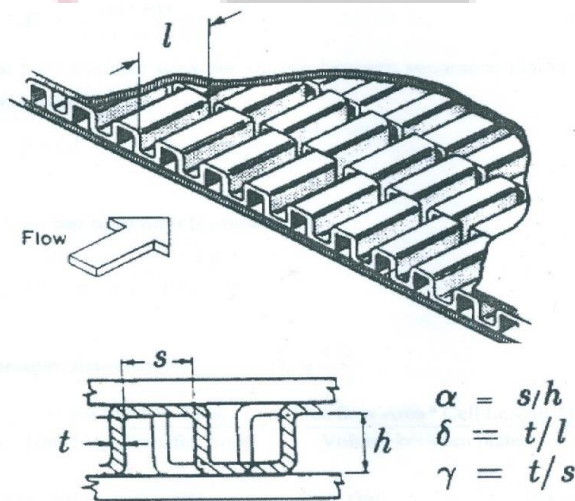


Figure 4 Geometry of Typical Offset Strip Fin Surface

5. Performance Analysis

The main aim of present work is to calculate the performance parameters like, effectiveness, overall heat transfer coefficient of the plate fin heat exchanger. In order to find the performance of present heat exchanger a number of experiments were carried out at different mass flow rates and at different hot fluid inlet temperature under balanced flow.

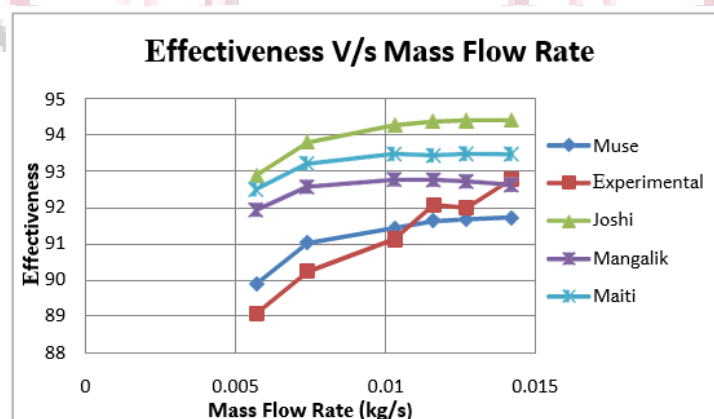


Figure 5 Variation of effectiveness with mass flow rate (hot inlet temperature=96°C)

Figure 5 shows “the variation of effectiveness obtained experimentally as well as with theoretical correlations and that obtained with simulation software Aspen with mass flow rate. It is seen that in both the cases effectiveness increases with mass flow rate. Experimental hot effectiveness first increases, then becomes almost constant for certain mass flow rates and then again increases. However from two figures it can be seen that the value of experimental effectiveness is more when hot inlet temperature is 96°C as compared to effectiveness value when hot inlet temperature is 66°C ”. So it can be concluded that with increase in hot inlet temperature effectiveness increases.

5.1 Variation of Overall thermal Conductance with Mass flowrate

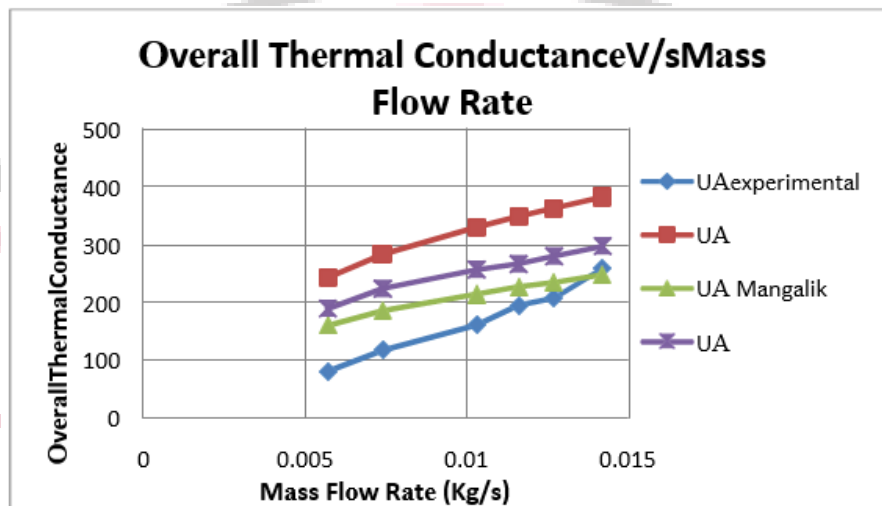


Figure 6 Variation of overall thermal conductance with mass flowrate (hot inlet temperature of 96°C)

Figure 6 and 7 show the variation of overall thermal conductance with mass flow rate for hot inlet temperature of 96°C and 66°C respectively. It can be seen that the theoretical as well as experimental overall heat transfer coefficient increases with increasing mass flow rate. It is due to the fact that with increasing mass flow rate the Reynolds number increases and as a result Colburn factor (j) also increases which is directly proportional to heat transfer coefficient, so overall thermal conductance increases.

5.2 Variation of Hot and Cold Effectiveness with Mass Flow Rate

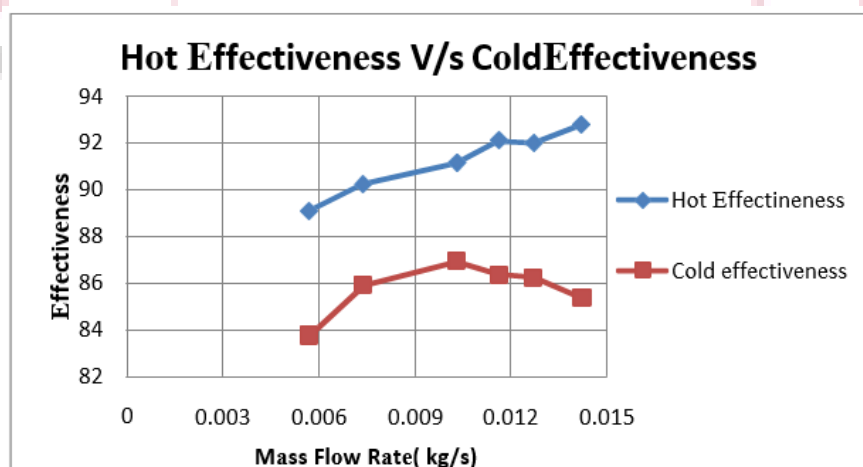


Figure 7 Variation of Hot and Cold effectiveness with mass flowrate (hot inlet temperature of 96°C)

Conclusion

The hot test is conducted to determine the thermal performance parameters of the available plate fin heat exchanger at different mass flow rates and two different hot inlet temperatures of 96 and 66°C. An average effectiveness of 91% is obtained. It is found in both the cases that the effectiveness and overall thermal conductance increases with increasing mass flow rate. It is also found that hot fluid effectiveness increases with flow rate of the fluid and agrees within 4% with the effectiveness value calculated by different correlations and that obtained by using the simulation software, Aspen. Also the pressure drop increases with increasing mass flow rate and experimental values are more as compared to theoretical results because the losses in pipes and manufacturing irregularities have not been taken into account.

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