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3D CFD Study of the Effect of Inlet Air Flow Maldistribution on Plate-Fin-Tube Heat Exchanger

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Abstract**—***Plate fin and tube heat exchanger are used extensively in heating, ventilating, and air conditioning as well as in refrigeration systems. Non uniform inlet air flow distribution has a substantial effect on heat exchanger performance. This study presents the results of three-dimensional (3D) Computational Fluid Dynamics simulations aim to investigate the effect of inlet air flow maldistribution on the thermos hydraulic performance of heat exchanger. Validation of the computation results with experimental data found in the literature has a shown a very good agreement.*

Different computation test cases with variety of inlet air flow distribution on in line and staggered plate fin and tube heat exchangers were run to systematically analyse their effects on system performance. The CFD results confirmed the importance of the influence of inlet fluid flow non uniformity on heat exchanger efficiency. Results indicate up to 50% improvement or deterioration in the colburn j-factor are found compared to the baseline case of heat exchanger with a uniform inlet air velocity profile. The 3D CFD method employed by this study has great potential for use in, first, assessments of correlations centred on air flow maldistribution and, second, efforts to optimally design the headers of heat exchangers in order to minimise inlet flow maldistribution and maximise overall system performance.

Keywords**—** *3D CFD simulation, maldistribution, non-uniformity, reynolds number, prandtl number, fluid flow, hydrodynamics , thermal conductivity, boundary condition, fin thickness, fin pitch,colburn factor, nusselt number.*

I. Introduction

Heat Exchanger

A heat exchanger is a device used to transfer heat between one or more fluids. The fluids may be separated by a solid wall to prevent mixing or they may be in direct contact. They are widely used in spaceheating, refrigeration, air conditioning, power stations, chemical plants, petrochemical plants, petroleum refineries, natural-gas processing and sewage treatment. The classic example of heat exchanger is found in a 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 the heats the incoming air.

There are three primary classifications of heat exchangers according to their flow arrangements. In parallel flow heat exchangers, the two fluids enter the exchanger at the same end, and travel in parallel to one another to the other side. In counter-flow heat exchangers the fluids enter the exchanger from opposite ends. The counter current design is the most efficient, in that it can transfer the most heat from the heat medium per unit mass due to the fact that average temperature difference along any unit counter current exchangers are designed to maximize the surface area of the wall between the two fluids while minimizing resistance to fluid flow through the exchanger. The exchanger's performance can also be affected by the addition of fins or corrugations in one or both directions, which increase surface area and may channel fluid flow or induce turbulence. The driving temperature across the heat transfer surface varies with position, but an appropriate mean temperature can be defined. In most simple systems this is the "log mean temperature difference" (LMTD).Sometimes direct knowledge of the LMTD is not available and the NTU method is used.

Plate Fin – Tube Heat Exchanger

Plate fin tube heat exchangers are mainly used in heating, ventilating and air conditioning (HVAC), process engineering and refrigeration applications such as compressor intercoolers, fan coils and air-coolers. The plain plate fin configuration is the most popular fin pattern, owing to its simplicity, durability and versatility in application. The plain fin and tube heat exchanger usually consist of mechanically or hydraulically expanded round tubes in a block of parallel continuous fins and, depending on the application, the heat exchanger can be produced with one or more rows. During the past few decades many efforts have been devoted to heat transfer and friction characteristics of plate fin and tube heat exchanger. Among the entire extended fin surfaces, plain fin represents the simplest geometry. Though lower heat transfer performance is observed for plain fins as compared to the specially configured fin surfaces, these fin types are still widely used where low pressure drop characteristics are desired. In the case of a plain fin, for a turbulent flow, standard equations of turbulent flow in circular tubes may be used to calculate colburn factor (j) and friction factor (f). If the Reynolds number based on the hydraulic diameter is less than 2000, one may use theoretical laminar flow solutions for j and f. The experimental studies by kays and London provided an extensive data for the plain fin geometries. Correlations for the laminar flow have also been developed for many plain fin channel shapes. The cross sectional geometry of the plain fin channel can have very significant effect on the heat transfer and flow friction performance as shown by kays and London. The governing thermal resistance for heat exchangers is typically located on the air side, accounting for 85% or more of the total resistance practical applications. Consequently, the use of finned surfaces on the air side facilitates improvements to the overall thermal performance of heat exchangers.

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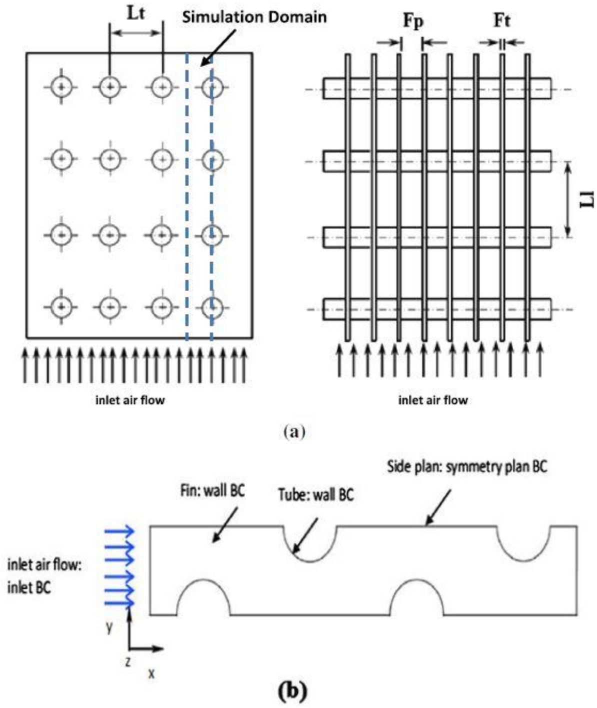

Modelled heat exchanger: (a) nomenclature and simulation domain. (b) Computational domain with boundary conditions.

II. DESCRIPTION

The design of these type of heat exchangers is based on the assumptions that inlet flow and temperature distribution values remain uniform and steady across exchanger cores. However this assumptions generally does not hold true under real operating conditions, due to various reasons, one of these reason is mainly related to the flow non-uniformity, it is divided to two flow mal-distribution, and they are gross mal-distribution and passage to passage mal-distribution. The gross flow mal-distribution is mainly associated with improper heat exchanger entrance configuration, such as poor design of header and distributor configuration. The passage to passage flow mal-distribution occurs in a highly compact heat exchanger caused by various manufacturing tolerances, frosting of condensable impurities.

The study on the effect of flow mal-distribution on heat exchangers performance have been extensively researched, but the majority of the studies have been restricted to experimental or analytical design due to their complexity. Previous research has typically sought to access the effect of flow non-uniformity on heat exchanger performance via reference to specific flow mal-distribution models. Performance reductions up to 30% have been reported for non-uniform operating conditions. These relatively minor mal-distribution values are concerning because they produce non-negligible decreases in heat transfer performance and in some case, they may even affect the mechanical functioning of the heat exchanger itself.

III. DESIGN AND PARAMETERS AND NOMENCLATURE IMPORTANT

The major nomenclature of plain fin is shown in fig. Figures shows the main geometric parameters such as longitudinal tube pitch (Ll) and transverse tube pitch (Lt), fin pitch (Fp), fin thickness (Ft), wavy height (Wh), wavy angle (Wa), and tube diameter (D). Longitudinal pitch (Ll) is defined as the centre distance between two tubes in a plate fin and tube heat exchanger in the direction of flow. Transverse pitch (Lt) is the measure of the centre distance crosswise in a plate fin and tube heat exchanger. Fin pitch (Fp) is defined as the gap between two parallel plates in a plate fin and tube heat exchanger. Wavy angle (Wa) is an important parameter in the wavy fin and heat exchanger. Wavy angle is the inclination of the fin plate from the flow axis. Inlet flow has significant effects on the heat transfer and pressure drop performance. Almost all the previous numerical investigations assume that the inlet flow is normal to the heat exchanger face. In some recent studies the effects of inlet flow angle for the wavy fin and tube heat exchanger are explored in details.

In fluid mechanics, the Reynolds number Re is a dimensionless number that gives a measure of the ratio of inertial forces to viscous forces and consequently quantifies the relative importance of these two types of forces for given flow conditions. The dimensionless Reynolds number is an important parameter that describes whether flow conditions lead to laminar or turbulent flow. In the case of flow through a straight pipe with a circular cross section, Reynolds number of less than 2300 are generally considered to be of a laminar flow. There is no theorem relating relating to Reynolds number to turbulence, flows with high Reynolds number usually becomes turbulent. While those with low Reynolds number usually remains laminar. At very low speeds the flow is laminar, i.e. the flow is smooth (though it involves vortices on a large scale). As the speed increases, at some point the transition is made to turbulent flow. In turbulent flow, unsteady vortices appear on many scales and interact with each other.

The local heat transfer coefficient h is defined in terms of heat flux Q and logarithmic mean temperature difference LMTD as

$$h = \frac{Q}{A.LMTD}$$

IV. PREVIOUS EXPERIMENTS & OBSERVATIONS

Fleming set up a flow mal-distribution model in paired-channel heat exchangers and investigated the effect of flow mal-distribution on performance deterioration.Based on the experimental data from wind tunnel experiments,

Chiou et al. - Chiou set up a continuous flow distribution and studied the thermal performance deterioration in cross-flow heat exchangers. Mueller and Chiou summarised various types of flow mal-distribution, and discussed the reason leading to flow mal-distribution.

Ranganayakulu et al. – Ranganayakulu and seetharamu investigated the combined effects of wall longitudinal heat condition, inlet flow uniformity and temperature nonuniformity on the thermal performance of a two fluid cross-flow plate fin heat exchanger using finite element method.

The results showed that the performance may be reduced by 30% under non-uniform operating conditions.

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Lalot et al. – He used CFD to study the gross flow maldistribution in an electrical heater. They presented the effect of flow non-uniformity on the performance of heat exchangers, based on the study of flow maldistribution in an experimental electrical heater. They found that reserve flows would occur for the poor header design and the perforated grid can improve the fluid flow distribution. Their results indicated also that the flow maldistribution leads to a loss of effectiveness of about 25% for cross-flow exchangers.

NG et al. – Used CFD modelling to generate the velocity profiles for the numerical NTU thermal performance analysis, but no hydrodynamics performance effects were presented.

Zhang & Li, Wen & Li, Sheik Ismail et al. – Using CFD to design various flow dispersion baffles in order to improve flow distribution into the heat exchanger.

Types	Brief Description	Major Findings
1 chevron plate heat Exchanger	Heat transfer and pressure drop characteristics of Al2O3/water and MWCNT/water Nano fluids flowing in a chevron-type plate heat exchanger were experimentally investigated	Heat transfer seemed to be improved by using Nano fluids at constant Reynolds number
2 Shell and tube heat exchanger	An improved structure of ladder type fold baffle is proposed to block the triangular leakage zones in original heat exchangers with helical baffles	The Shell side heat transfer coefficient and overall heat transfer coefficient are improved by 22.3-32.6% and 18.1-22.5% respectively
3 Plate heat exchanger	A heat exchanger device using nanofluids needs to operate at best nano particle loading to get the maximum heat transfer performance	The thermal performance factor TEF enhances by 18.6-23.2%
4 Brazed plate heat exchangers	A new model for refrigerant boiling inside Brazed plate heat exchangers (BPHEs) based on a set of 251 experimental data	The new model was compared against a set of 505 experimental data obtained by different laboratories with different plate geometries
5 Fin tube heat exchangers	Obtained the critical operating conditions which prevent frosting in the fin tube heat exchanger of air source heat pumps	The critical operating conditions can be used to prevent various operating strategies to prevent frosting in ASHPs

V. Experimenting on CFD

The use of Computational Fluid Dynamics (CFD) simulations aiming to investigate the effects of flow mal-distribution on heat exchanger performance has become common. This approach allows for the construction of realistic computational models to which a wide variety of potential physical conditions can be applied without needing to build expensive test rigs or large scale prototypes.

In the previous works they mainly concentrated on the effects of flow non-uniformity on the heat exchanger performance using simplified 2d or 3d modelling. The focus with these design in on flow uniformity entering the heat exchanger with the gaol to maximize the thermal performance but the hydrodynamics aspect was not always presented, such as the pressure drop penalties associated with the baffle design or the effect of flow mal-distribution on the performance taking into account the coupling of fluid flow and heat transfer.

VI. Review on Experimental Studies

Plate Fin Tube Heat Exchanger

There have been a number of studies on the pressure drop and heat transfer characteristics of bare tube banks in cross flow. Most of the earlier studies were experimental in nature and an excellent review is given. The overviews of different researchers have been discussed considering the pattern of the heat exchanger. A comprehensive number of investigational studies have been reported in the literature on the thermal and hydraulic individuality of the plate fin patterns. Following literature assessment briefly summarize a selected number of articles for the plain fin and tube heat exchanger configurations. Available experimental information on the plate fin and tube heat exchanger has been presented reviewed and correlated in the literature

VII. Recommendation for Future Research

Flat tubes are vital component in various technical applications like modern heat exchanger, automotive radiators, automotive air conditioning evaporators and condensers. In comparison to round tube heat exchanger. In comparison to the round tube heat exchangers, flat tube heat exchangers are expected to have smaller air-side pressure drop and improved air-side heat transfer coefficients. For the above reasons, the Optimum spacing (e.g., tube-to-tube, fin-to-fin) with the maximum overall heat conductance (heat transfer rate) and minimum pressure drop needs more focus and research in the future. In addition, more works are needed to develop the thermos-fluid correlations in tubes of this shape.

In most of the study, for the fin and tube heat exchanger, circular tube is used as the flow passage for the liquid. The effect of the heat transfer and the friction characteristics were investigated for the laminar and turbulent flow regime. This circular tube can be replaced by the rectangular or elliptical tube as it affects the flow area. So it can be considered for the future study from the point of interest. The numerical investigation for the turbulent flow range can be considered using Reynolds Stress Turbulence Model or other suitable model. The different fluid flow can be allowed for the heat exchanger in place of air flow. This will affect the heat transfer and friction performance of the heat exchanger. The wavy fin investigated in different studies can be replaced by using sinusoidal type fin to show the effects of heat transfer and pressure drop performance.

VIII. Conclusion

Non uniformity of the inlet airflow in heat exchangers is of first order importance and has crucial influence on their efficiency because it can be intensify longitudinal wall heat conduction and the maldistribution of interior temperature. In this study, 3D CFD simulations have been carried out to investigate the effect of the inlet airflow maldistribution on the thermo-hydraulic performance in heat exchanger used in air handling units.

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The CFD model was first validated against the experimental data available in the literature. Very good agreement between the numerical results and the experiments was found. This implies that the model used in the present study is reliable and can predict the thermal performance satisfactory for heat exchangers.

Moreover, the present investigation with respect to inlet flow maldistribution demonstrates that 3D CFD simulation is a valuable tool for analysing, designing and optimising heat exchangers. Finally, the result of this study have significant contribution on the optimum design of header and distributor configurations of heat exchanger to minimize maldistribution.

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