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Theoretical and experimental studies of crossflow minichannel heat exchanger subjected to external heat ingress

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HIGHLIGHTS

- Theoretical model of crossflow heat exchanger with known ambient heat leak amount.
- Numerical technique of partitioning exchanger into smaller segments.
- Experimental validation of model by testing of crossflow minichannel heat exchanger.

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ABSTRACT

The effect of heat in-leak, an unavoidable phenomenon occurring due to the temperature difference between the system and its surroundings, has been studied for two-stream crossflow minichannel heat exchangers with unmixed fluids. Assuming that the amount of heat in-leak is known, an analytical expression for the normalised temperature difference between hot and cold fluids has been derived in terms of dimensionless parameters. The analytical results, in conjugation with the area partitioning of crossflow heat exchanger both in x and y directions, have been used for predicting the outlet fluid temperatures. On the experimental part, one of the end plates in a crossflow-type multistream, minichannel heat exchanger has been subjected to deliberate external heat input given electrically. The variation in the exit fluid temperatures has been recorded as a function of this external heat in-leak entering the exchanger through one of its outer surfaces. Experimental data obtained is employed to validate the fluid exit temperatures predicted by the developed model under the same conditions of external heat ingress.

1. Introduction

Thermal communications between the atmosphere and the fluid stream(s) in a heat exchanger are inevitable. The effect of this energy exchange can be severe depending on the difference in temperature between the fluid streams and the surroundings. Appropriate and adequate insulation is essential, particularly when used for cryogenic as well as high temperature applications. If the heat in-leak is not taken into account, this may result in erroneous experimental and theoretical computation for efficient heat exchanger systems [1]. For example, external heat in leak causing a deterioration of 2.5% in heat exchanger effectiveness may result in ultimately 15% reduction in liquid yield for an air liquefaction system [2].

Crossflow heat exchanger analysis is a well documented subject investigated by many researchers for long time [3–11]. Historically, Bowman et al. [12] have synchronised the results of Nusselt and Smith and transposed them into curves for various arrangements of crossflow heat exchangers. While their proposed technique is mainly suitable for the design of heat exchangers (with known terminal temperatures), performance prediction of heat exchangers using this technique becomes tedious with iterative calculations. On the other hand, heat exchanger performance prediction becomes easier with the effectiveness-NTU method proposed by London and Seban [13]. Kays and London [14] presented effectiveness-NTU charts for various arrangements of crossflow heat exchangers with the help of Mason's solution [15]. Mason provided equations to predict theoretical temperature difference between the exchanger fluids at any distance in the single pass, crossflow heat exchanger with unmixed fluids. The complete procedure has been presented in the book of Kern and Kraus [16].

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Conventional heat exchanger analysis involving thermal interaction with the surroundings is also not uncommon. But most of them are related to either counter-current or co-current configurations. One of the early mathematical solutions to the one-dimensional temperature distribution problems of two-stream counterflow heat exchanger subjected to external heat in-leak has been given by Barron [2]. The governing equations have been developed when either of the fluid is subjected to heat in-leak. The effectiveness-NTU plots depict an increase in performance degradation with increasing heat exchange with the ambient. Thermal interaction of the outer fluid with the environment in a double-pipe heat exchanger has been formulated by Prasad [17], for both co-current and counter-current arrangements. Simultaneous heat in-leak in hot as well as the cold fluid in counterflow heat exchanger has been theoretically analysed by Ameel and Hewavitharana [18]. They have discussed the undesirable condition of temperature cross that may develop in an exchanger due to excessive ambient heat exchange. This study has been further extended by Ameel [19] to study co-current heat exchangers under similar condition of heat in-leak to both exchanger fluids. It has also been shown that, under same operating conditions of ambient interaction, the performance of a parallel-flow heat exchanger is poorer than that of a counterflow one. Al-Dini and Zubair [20] have also provided closed-form solutions for ambient thermal interaction with either of the fluids for parallel-flow heat exchanger. Typical to cryogenic temperatures, effect of ambient heat in-leak in conjunction to axial conduction has been studied by Gupta and Atrey [21]. Parametric studies have been conducted with variation in ambient conduction ratio, heat capacity ratio and temperature conditions. Experimental validation of the model for specified conditions in a coiled tube-in-tube heat exchanger has been done and compared to the mathematically predicted values. They have concluded that at cryogenic temperatures, severity of performance degradation due to ambient heat in-leak is higher. Gupta et al. [22] have further looked into the exergy analysis of the mathematical model developed by Gupta and Atrey [21].

In the aforementioned literature, it is assumed by the authors that the ambient overall heat transfer coefficient (or, in other words, ambient conductance ratio) is known. Alternatively, a constant ambient heat flux that is being subjected to the exchanger fluids may also be known. This has been studied by Nellis and Pfotenhauer [23] for counter-current heat exchangers. These authors have pointed out that with ambient thermal interaction, heat exchange between hot and cold fluid is not equal and therefore hot fluid effectiveness and cold fluid effectiveness should be separately defined.

Thermal interaction of multi-stream heat exchangers with the surroundings has also been taken up by few researchers. Krishna et al. [24] have analysed three-fluid tubular heat exchanger for cryogenic applications, with the cold fluid subjected to ambient heat interaction. The solution to the developed mathematical model has been obtained by finite element method. Ghosh et al. [25,26] have studied the heat leakage into a multi-stream plate fin heat exchanger. The complete heat exchanger has been assumed to be divided into stacks of overlapping two-stream heat exchangers. Simulation of variations in temperature profile of a three-stream and four-stream plate fin heat exchanger in interaction with the surroundings has been graphically shown.

Literature for miniature heat exchangers subjected to ambient heat in-leak from the atmosphere are even more limited, this technology being recently developed. As per the nomenclature of Kandlikar and Grande [27], heat exchangers with hydraulic diameters above 3 mm are considered conventional while exchangers with hydraulic diameters in the range of 200 μm–3 mm and 10 μm–200 μm have been termed as minichannel and microchannel heat exchangers respectively. However, the terms minichannel and microchannel are frequently used interchangeably. Mathew and Hegab [28–32] have extensively studied counter-current as well as co-current microchannel heat exchangers in thermal interaction with the ambient. These microchannel heat exchangers have hydraulic diameters less than 1 mm. Mathematical model for one-dimensional parallel-flow microchannel heat exchangers subjected to uniform external heat flux has been developed in Ref. [28]. The solutions to this model are in form of equations that can be used to predict the variations in fluid axial temperatures and determine the hot and cold fluid effectiveness, for balanced as well as unbalanced flow conditions. Similar to the effects of heat in-leak in a conventional heat exchanger, in case of microchannel parallel flow heat exchanger Mathew and Hegab [28] have found a decrease in hot fluid effectiveness and an increase in cold fluid effectiveness with increasing ambient heat flux. For higher values of heat in-leak, temperature cross over has also been observed. This mathematical model [28] has been experimentally validated in Ref. [29]. The parallel-flow microchannel heat exchangers have been fabricated in silicon having triangular ($D_h = 278.5$ μm) and trapezoidal ($D_h = 279.5$ μm) channel cross-sections. Deionized water has been used as the test fluid and the external heating has been generated using a thin film heater. Then again, in case of known ambient thermal resistance, instead of the heat flux, modified model for parallel-flow microchannel heat exchangers has been formulated by Mathew and Hegab in Ref. [30]. In addition to the results obtained in earlier model [28], Mathew and Hegab [30] also found that at certain operating heat in-leak conditions, effectiveness of one of the fluids is maximum at a particular *NTU*. They suggested that the heat exchanger be operated at this peak *NTU* to minimize the heat in-leak effect if unavoidable. In lines to the mathematical model in Ref. [28] for parallel flow microchannel heat exchanger, effect of ambient heat flux for counterflow microchannel heat exchangers has been presented by Mathew and Hegab in Ref. [31]. Experimental validation of this model has been lately done by the same authors [32]. The procedure followed in manufacture and testing of silicon counterflow microchannel heat exchangers is similar to that of the exchanger fabricated in Ref. [29].

Recently, Dixit and Ghosh [33] have studied the effect of thermal interaction with the surroundings in two-stream crossflow heat exchangers with unmixed fluids in a generalised way. Thermal interaction between the exchanger and the environment has been considered through an overall external conductance, defined separately for the hot and cold fluids. Heat flow also depends on the temperature difference between the process streams and the ambient temperature. However, there are instances when the assumption of constant external heat flux exposure for the terminal fluid streams makes the heat exchanger analysis convenient [26] for diverse engineering applications mentioned by Nellis and Pfotenhauer [23]. As for example, a multistream heat exchanger when envisaged as a combination of several thermally interlinked two-stream heat exchangers stacked as a pile, knowledge of heat input to each unit would be necessary [26]. Since the postulation of constant heat flux is applicable in the heat exchanger of sufficiently small cross-section, one has to divide the exchanger into a large number of small segments so that its validity is extended to each individual section. Moreover, experimental validation of the mathematical model developed for predicting fluid outlet temperatures in a crossflow heat exchanger experiencing external heat influx can be carried out easily by mimicking the ambient heat flux through electrical heat input of known amount. Consequently, the analysis reported in Ref. [33] has been extended for the specific case where the amount of external heat flux is known. Furthermore, crossflow minichannel heat exchanger has been experimentally