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Two-stream cross flow heat exchangers in thermal communication with the surroundings – A generalized analysis

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ABSTRACT

Thermal interactions of heat exchanger fluids with the surroundings are difficult to limit. It becomes a necessity to determine the effect of these interactions on exchanger performance when the demand of heat exchanger effectiveness is very high, like in case of cryogenic applications. In the present article, effect of heat in-leak in two-stream cross flow exchangers has been studied and compared with the two other type of flow arrangements, namely counter-current and co-current. Mathematical model involving mutual heat exchange between hot and cold fluid streams and their individual thermal interactions with ambient have been considered through overall heat transfer coefficients. Parametric studies have been made with different non-dimensional parameters and essentially generating effectiveness-NTU type of plots for balanced exchangers. Various heat exchange possibilities depending on the relative temperature difference between fluids and ambient have been considered.

1. Introduction

Heat exchanger performance is susceptible to ambient heat in-leak, especially when the difference in temperature between the ambient and the process fluids is high. Although this phenomenon is prevented by the measure of insulation, but possibility of ineffectiveness caused due to heat in-leak cannot be ruled out. Virtually, the conduction resistance of an insulating material cannot be infinite leading to a definite amount of ambient heat loss. Similarly heat transfer may occur by convection between the fluid and the exchanger wall and between exchanger wall and ambient. Heat loss due to radiation is also present because of the temperature gradient between the working fluid and the ambient. Therefore, while designing the heat exchangers, the aim must be to maximize these resistances in order to minimize the heat lost to the ambient. Though one can probably avoid considering the effect of heat in-leak in heat exchangers handling fluids near ambient temperature, omission of the same may prove expensive for applications demanding high effectiveness heat exchangers, for example, used in cryogenic systems [1,2].

The secondary effect of heat in-leak in cryogenic heat exchangers has been studied by many researchers. Early researchers, such as Wood and Kern [3] and Hausen [4], formulated the governing equations for heat exchanger interaction with the surroundings. Barron [5] and Chowdhury and Sarangi [6] solved the governing equations to determine the two stream counter-flow heat exchanger performance when there is thermal interaction with either one of the exchanger fluids and the environment. Barron [5] found that with heat transfer from ambient, the hot and cold fluid thermal interaction reduces. This effect is more pronounced when cold fluid is subjected to ambient heat in-leak rather than the hot fluid. Chowdhury and Sarangi [6] introduced effective NTU as a function of exchanger performance. Higher the difference between effective NTU and design NTU, higher is the rate of heat loss to the ambient. Prasad [7,8] gave analytical solutions for incremental temperatures and amount of ambient heat transfer in double pipe heat exchangers with counter-flow as well as parallel-flow configuration. Ameel and Hewavitharana [9] developed a mathematical model for counter-flow heat exchangers with heat leakage to both exchanger fluids, expressing it in terms of dimensionless conductance ratios as used by Barron [10]. They illustrated that in the condition of large amount of heat in-leak and high number of heat transfer units, the fluid temperature profiles cross one another. Narayana and Venkatarathnam [11] studied the performance of counter-flow heat exchanger when only the cold end is in thermal interaction with the ambient. Gupta and Atrey [12] compared the experimental results for heat in-leak in counter-flow heat exchanger with numerical predictions and established a good fit between the two. They also predicted the exchanger performance, under the combined influence of longitudinal heat conduction and heat in-leak, in terms of degradation factor for varying number of heat transfer units and heat capacity ratio. Gupta et al. [13] extended the same study using second law of thermodynamics expressing the performance

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Nomenclature

A_h	heat exchanger surface area between hot fluid and ambient (m)
A_c	heat exchanger surface area between cold fluid and ambient (m)
C	specific heat capacity at constant pressure (J/kg K)
C_R	heat capacity rate ratio (C_h/C_c)
m	mass flow rate (kg/s)
n	number of segments
NHL	no heat in-leak
NTU	number of heat transfer units
N_a	number of transfer units for hot fluid defined by $U_0x_0y_0/m_hC_h$
N_b	number of transfer units for cold fluid defined by $U_0x_0y_0/m_cC_c$
q	heat transfer rate from hot fluid to cold fluid in infinitesimally small area (W)
Q	heat transfer rate from hot to cold fluid stream (W)
Q_h	ambient heat in-leak to hot fluid (W)
Q_c	ambient heat in-leak to cold fluid (W)
R_h	hot fluid conductance ratio defined in Eq. (6)
R_c	cold fluid conductance ratio defined in Eq. (6)
T	temperature of hot fluid (K)
T_a	temperature of ambient (K)
t	temperature of cold fluid (K)
U_0	overall heat transfer coefficient (W/m^2 K)
U_h	overall heat transfer coefficient between ambient and hot fluid (W/m^2 K)
U_c	overall heat transfer coefficient between ambient and cold fluid (W/m^2 K)
WHL	with heat in-leak
x', y'	length coordinates of coordinate system used for mathematical analysis
x_0, y_0	heat exchanger length along x' and y' axes respectively (m)
x, y	dimensionless parameters for heat exchanger length defined by $x = x'/x_0$ and $y = y'/y_0$

Greek symbols

θ	dimensionless parameter for temperature difference defined by θ'/θ_0
θ_0	temperature difference between fluids at entry defined by $T_i - t_i$ (K)
θ'	temperature difference between the exchanger fluids at any point (x',y') in heat exchanger defined by $T(x', y') - t(x', y')$ (K)
θ_a	dimensionless ambient temperature difference defined in Eq. (7)
ε	heat exchanger effectiveness
ϕ_a	dimensionless ambient heat transfer defined by Eq. (34)

Subscripts

avg	average of inlet and outlet
c	cold fluid
h	hot fluid
i	inlet
o	outlet

deterioration in terms of irreversibility number for counter-flow heat exchanger. Nellis [14] investigated the effects of heat loss from the exchanger fluids due to radiation, a common mode of heat loss in cryogenic applications. Expression for exchanger effectiveness directly in terms of ambient heat flux value has been derived by Nellis and Pfotenhauer [15] for counter-flow heat exchanger. They also illustrated the effectiveness deterioration under the condition of heat in-leak to either of the fluids against no heat in-leak case. Ameel [16] and Al-Dini and Zubair [17] investigated the effect of heat in-leak in parallel-flow heat exchangers. Ameel [16] concluded that the effect of heat in-leak in parallel-flow heat exchanger is more severe than in counter-flow heat exchanger. Similar to the study of Nellis and Pfotenhauer [15], Al-Dini and Zubair derived a closed-form solution for parallel-flow heat exchanger when the amount of ambient heat flux is known. They studied the variation in actual effectiveness, based on both hot and cold fluids, at different heat capacity ratios with heat in-leak to either of the exchanger fluids. Ghosh et al. [18] expressed heat in-leak in two stream counter-flow heat exchanger as a special case of multistream heat exchanger with heat in-leak. They also presented the effect of external heat load on three-stream and four-stream plate fin heat exchanger [19]. Mathew and Hegab [20–24] have extensively studied microchannel counter flow and parallel flow heat exchangers in thermal interaction with the ambient. They developed a mathematical models considering ambient heating as well as cooling. Very recently [24], they have experimentally validated the theoretical models by supplying known amount of uniform heat flux on the external surface of the heat exchanger. Seetharamu et al. [25] and Krishna et al. [26] have presented the thermal interaction of hot and cold fluid with the ambient as a special case of three-fluid heat exchangers, ambient being considered as the third fluid.

Based on the literature survey it has been observed that the effect of ambient heat in-leak on cross flow heat exchangers is yet to be studied in details. Although recently Dixit & Ghosh [27] have studied this effect when the ambient heat flux is known, a more generalized approach with known external resistance needs focus. Cross flow heat exchangers may not offer the best thermal performance, but this limitation is often compensated by the ease of fabrication, particularly in case of plate fin type of heat exchangers [28]. This type of exchanger is frequently used in cryogenic air separation systems, chemical industries, automobile and aerospace sectors to name a few [29]. The divergence of cross flow heat exchanger performance, when in thermal interaction with the surroundings, has been taken under study in the present paper.

2. Mathematical modeling

Fig. 1(a) shows a two-stream, cross-flow heat exchanger with unmixed fluid in thermal interaction with the surroundings. According to Fig. 1(a), the hot and cold fluids are at temperatures below that of ambient, typical to cryogenic applications. However, the analysis stands equally valid for the other possible form of thermal interaction between the fluids and the surrounding.

Prior to the formulation of governing equations, following assumptions may be noted:

a. Steady-state conditions prevail.
b. The fluid temperatures at inlet of the exchanger are uniform. Fluid streams are not undergoing any phase change.
c. Fluid temperature variation in third dimension (along z-axis within channel height) has been neglected.
d. Rate of flow and specific heat of each fluid is constant.