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Transient behavior of co-current parallel flow three-fluid heat exchanger ☆

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A B S T R A C T

Transient behavior of co-current parallel flow three-fluid compact heat exchangers with the effect of two-dimensional longitudinal heat conduction through the separating sheet and axial dispersion in fluids has been investigated numerically by using the Gauss–Seidel iterative technique for step excitation provided to hot fluid inlet temperature. The results reveal that the performance of the heat exchanger is affected when two-dimensional longitudinal conduction in separating sheets and axial dispersion in fluids are considered.

1. Introduction

Three fluid heat exchangers are used in variety of applications. They are used in air separation, ammonia gas synthesis, purification and liquefaction of gases, etc. [1]. Three fluid heat exchangers allow a more compact and economical design in various other applications also.

Co-current parallel flow three-fluid heat exchanger is one special case of a three-fluid heat exchanger where all the three streams flow in the same direction (Fig. 1a). Since they are used in various thermal engineering applications, their design and performance analysis are of great practical importance.

Analysis of three-fluid heat exchanger considering various aspects like design, effectiveness, thermal performance, and temperature distribution has been tried by many researchers. Sorlie [2] discussed the general concept regarding two-temperature effectiveness of a three-fluid heat exchanger for counter- and parallel-flow. Extending the work of Sorlie [2], Aulds and Barron [3] presented an analytical relationship between *NTU* and effectiveness for a general three-fluid heat exchanger. In his technical note, Sekulic [4] determined analytically the temperature distribution of the three fluids for all possible flow arrangement of a parallel-flow three-fluid heat exchanger with two-thermal communications. A single analytical expression has been given to determine the temperature cross for all combination of fluids involved and for all fluid flow arrangement. Four possible arrangements for parallel- and counter-flow three-fluid heat exchangers with two thermal communications were also presented by Sekulic and Kmecko [5]. A general analytical model for the design and analysis of single-pass parallel-flow three-fluid heat exchanger with three thermal communications for all flow arrangement considering steady state was developed by Ameel and Shrivastava [6]. They discussed the effects of six dimensionless design parameters on the temperature distribution of three fluid streams. Further, Ameel and Shrivastava [7] also proposed six different objective specific effectiveness definitions or figures of merit in terms of five engineering goals to access the overall performance. Saeid and Seetharamu [8] studied method the thermal performance of both co-current and counter-current parallel flow three-fluid heat exchangers using finite element. They found that the effectiveness of the three-fluid heat exchanger is always higher than that of the classical two-fluid flow heat exchanger. Krishna et al. [9] have investigated the effects of ambient heat in-leak to the cold fluid in the performance of the three-fluid parallel flow heat exchanger for cryogenic applications. A new Integral-Mean Temperature Difference (IMTD) formula for sizing and rating has been developed by Zhao and Yanzhong [10] for a parallel stream three-fluid heat exchanger. Bielski and Malinowski [11,12] obtained transient solution semi-analytically as well as analytically for the parallel-flow three-fluid heat exchanger considering step change in inlet temperature of central fluid without considering longitudinal conduction in wall. Barron and Yeh [13] obtained a numerical solution for temperature distribution and effectiveness considering the effects of longitudinal conduction for the parallel-flow three-fluid heat exchanger. Chiou [14] reveals that longitudinal wall conduction and axial dispersion in fluids affect the performance of the three-fluid parallel flow heat exchanger. Further Malinowski and Bielski [15] solved numerically the set of partial differential equations for transient temperature field in a parallel-flow three-fluid heat exchanger with three thermal communications between the fluids. In their analysis, they considered longitudinal conduction through walls and their thermal capacity. They verified their model with that of [11] by reducing to two thermal communications and without considering longitudinal conduction through the

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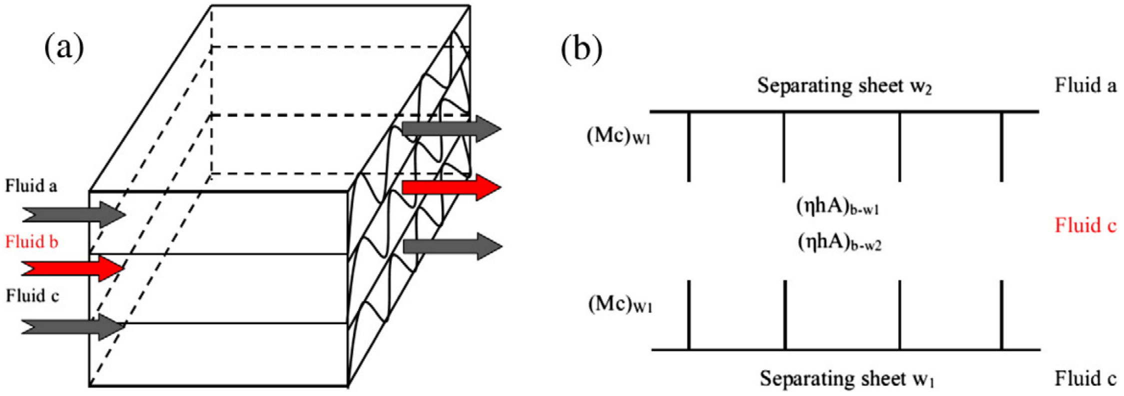

Fig. 1. (a) Schematic of co-current parallel flow three-fluid compact heat exchanger, and (b) distribution of convective resistance of central fluid '*b*' and the heat capacity of the separating sheet with fins.

walls. Roetzel and Luo [16] analytically investigated the cross-flow heat exchangers with axial dispersion in one fluid. Mishra et al. [17] investigated the transient behavior of the two-fluid cross flow heat exchanger by considering the effects of longitudinal conduction in wall and axial dispersion in fluids. Further, they [18] extended their work to investigate the dynamic behavior of three-fluid cross flow heat exchangers.

Situation of ideal plug flow or no axial dispersion ($Pe = \infty$) rarely exists in a practical situation. The presence of nonuniformities in the fluid streams in the form of eddies, circulation, back flow, etc. deviates ideal plug flow model to the case where thermal dissipation effect becomes predominant and has to be considered. The influence of axial dispersion is significant [16] when $Pe < 20$. A smaller value of Pe denotes that the flow is highly dispersive. So a realistic value of Pe up to 10 has been considered in this study so as to analyze the effects of axial dispersion. For a small value of NTU ($NTU = 1$), the responses of counter flow, parallel flow and cross flow heat exchangers are almost similar for a two fluid heat exchanger. The responses are significantly different in the case of the parallel flow heat exchanger as NTU is 4 or higher [19]. Considering the mentioned facts, realistic values of Pe up to 10 and NTU up to 8 have been considered in the present study, which is also very common in heat exchangers having compact passages.

A very few literature have been found that deals with the effects of longitudinal wall conduction and axial dispersion in fluids together on heat exchanger performance. Transient behavior of co-current parallel flow three-fluid compact heat exchanger with two-thermal communications has been numerically investigated in this article. The energy conservation equations have been developed considering longitudinal heat conduction in separating sheets and axial dispersion in fluids. The governing equations along with appropriate boundary conditions have been solved by using the Gauss–Seidel iterative technique. Step excitations in temperature of central (hot) fluid have been provided and the performance has been investigated for the effects of longitudinal conduction in separating sheets and axial dispersion in all the three fluids.

2. Mathematical formulation

A direct transfer co-current parallel flow three-fluid compact heat exchanger is shown schematically in Fig. 1(a). One fluid is flowing between the two separating sheets and other two fluids are on the either side of it. Following assumptions have been made.

1. All the fluids are single phase, unmixed without any internal source of heat.
2. Heat exchange with the surroundings is negligible.
3. The thermo-physical properties of the fluid streams and the walls are independent of time, temperature and space.
4. Two-thermal communication is assumed to exist.
5. The central fluid is assumed either the hottest or the coldest.
6. Perfect transverse mixing of fluids in each flow passage and thus no variation in velocity and temperature of fluid streams along perpendicular to flow direction.
7. The heat transfer area is distributed uniformly on each fluid side.
8. The primary and secondary areas of the separating plates have been lumped together, so the variation of wall temperature is two-dimensional.
9. Transverse conduction through fins between adjacent separating sheets is neglected. This implies that there will be a temperature extremum in the fin temperature profile [20].
10. The thermal resistances on both sides, comprising film heat transfer coefficients of primary and secondary surface and fouling resistance, are constant and uniform.
11. Transverse thermal resistance of the separating sheets in a direction normal to it is considered negligible.

The process of energy exchange in a three-fluid heat exchanger becomes more complex compared to that in a conventional heat exchanger due to the presence of third fluid. The central fluid stream exchanges heat simultaneously with two adjacent streams. The exact distribution of this thermal energy plays an important role in steady state as well as in transient behavior of heat exchanger. This distribution depends upon the conditions of all the three fluids and the total area associated with them. As the thermo-physical properties of the top and the bottom fluid streams may be different in a general situation, it is likely that the two separating sheets will have different temperatures, and the fins in the central passage will have an asymmetric temperature profile. This indicates that the central stream may transfer heat to the top and the bottom separating sheets at different rates. To take care of this phenomenon it is assumed that part of the secondary surface is associated with the top separating sheet ($w1$), and the rest is associated with the bottom separating sheet ($w2$). This idealization is depicted in Fig. 1(b).

Assuming that $(\eta hA)_{b\_w1}$ and $(\eta hA)_{b\_w2}$ are the convective conductance associated with the top and the bottom separating sheet respectively, the following relationship (Eq. (1)) can be obtained.

$$\frac{1}{(\eta hA)_{b\_w1}}+\frac{1}{(\eta hA)_{b\_w2}}=\frac{1}{(\eta hA)_{b}} \tag{1}$$

A non-dimensional parameter ϕ may be introduced as in Eq. (2)

$$\frac{(\eta hA)_{b\_w1}}{(\eta hA)_{b}}=\frac{1}{\phi}\text{ and }\frac{(\eta hA)_{b\_w2}}{(\eta hA)_{b}}=\frac{1}{(1-\phi)} \tag{2}$$

Proceeding with the same logic it may be assumed that the total thermal capacity of the separating sheets is also distributed amongst