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Numerical study of the effect of buoyancy on conjugate heat transfer in simultaneous turbulent flow in parallel pipelines

J. Serrano-Arellano [a,*], J.M. Riesco-Ávila [b], J.M. Belman-Flores [b], K. Aguilar-Castro [c], E.V. Macías-Melo [c]

[a] División de Arquitectura e Ingeniería en Energías Renovables, Instituto Tecnológico Superior de Huichapan – ITESHU-TecNM-SEP, Dom. Conocido S/N, El Saucillo, Huichapan, Hgo. C.P. 42411, Mexico
[b] Departamento de Ingeniería Mecánica, Universidad de Guanajuato, Carretera Salamanca-Valle de Santiago Km 3.5+1.8 Km, Comunidad de Palo Blanco, Salamanca, Gto. C.P. 36885, Mexico
[c] División de Ingeniería y Arquitectura, Universidad Juárez Autónoma de Tabasco, Av. Universidad s/n, Zona de la Cultura, Col. Magisterial, Vhsa, Centro, Tabasco, C.P. 86040, Mexico

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ABSTRACT

This paper presents a numerical study of conjugate heat transfer between two air flows circulating in parallel pipelines. We analysed the buoyancy effect generated by the temperature gradient, by coupling the movement produced by the air flow forced through the entrances of the input ducts. The buoyancy effect favours a rapid transition to turbulence. The governing equations were solved using the finite volume technique. The variables were the Reynolds number in a range from 10 to 1000, and the aspect ratio values of 5, 25, and 50. The results show the importance of buoyancy on the performance of the heat exchanger. Furthermore, it was found that at low Reynolds numbers, buoyancy did not favour heat exchange effectiveness of increasing heat across the length of the channels. Furthermore, when the Reynolds value is 1000, we conclude that heat transfer is not affected by the buoyancy. Therefore, efficiency of heat exchange depends mainly on the length of the channels.

1. Introduction

Heat exchange between two or more fluids is widely applied in industry through heat exchangers. Heat exchangers are used to cool electronic equipment, electromechanical systems, and chemical processes of distillation, evaporation, and solar collectors, among other applications. The basic principle of the heat exchanger is to transfer part of the thermal energy contained in the hot fluid to a cold fluid. A wall separates these fluids. Water and air are among the most common fluids in the heat exchangers, the latter being an advantage when the equipment has restrictions concerning contact with water. Studies on heat exchangers have a degree of complexity when we consider using a differential model. In this case, we must solve the equations of continuity, momentum, and energy simultaneously, and additionally couple them to a solid heat conductor. So it is only possible to solve the system numerically. However, in the literature we found several models for solving systems of heat exchangers, which were experimental, analytical, or numerical. We found that the effect of buoyancy was not considered in most of the works reviewed. In this regard, we discuss in detail this type of system based on our literature review.

Among early studies of laminar flow in a horizontal channel we find the experiment by Osborne and Incropera [1], which takes into account the effect of buoyancy on the flow within the channel. The authors found a strong influence of the buoyancy effect on the bottom plate, but a weak influence on the upper plate. Furthermore, they found that the forced flow dominated heat transfer near the upper plate. However, the authors found mixed convection. A more recent analysis of heat transfer in a channel study was performed by Mahmud and Fraser [2]. This study involved a channel system with two parallel plates in which a fully developed forced flow convection is considered, and to resolve the problem they employed an analytical model. To increase the effectiveness of heat transfer systems, the variable recycled energy at the end of the duct has been incorporated into the input stream. Recycled energy has been applied to parallel plate systems or double parallel plates [3–5]. Another type of study analyses the heat transfer in double channel exchangers in counterflow. This type of study is normally at a macro level and generally does not consider axial heat transfer, but rather focuses on the analysis of the development of flow in the inlet channel. For example, the study presented by Vera and Liñán [6], in which the authors present an exact solution for laminar flow, which is proposed to be used as a benchmark in numerical

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* Corresponding author. Tel.: +52 01 (761) 724 80 79/724 80 80.
E-mail addresses: jserrano@iteshu.edu.mx (J. Serrano-Arellano), riesco@ugto.mx (J.M. Riesco-Ávila), jfbelman@ugto.mx (J.M. Belman-Flores), karla.aguilar@ujat.mx (K. Aguilar-Castro), edgar.macias@ujat.mx (E.V. Macías-Melo).

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Nomenclature

Cp	specific heat at constant pressure, J/kg K
C_C	specific heat of cold fluid, J/kg K
C_H	specific heat of hot fluid, J/kg K
C_m	specific heat of the conductive wall, J/kg K
$C_{1\varepsilon}, C_{2\varepsilon}, C_{3\varepsilon}, C_\mu$	constants of the turbulence model
g	acceleration due to gravity, m/s^2
h_{ext}	convective heat transfer coefficient, W/m^2 K
H_i	aperture height at the mixture inlet, m
Hx	cavity width, m
Hy	cavity height, m
n	normal direction
Nu	average Nusselt number
P	fluid pressure, N/m^2
Pr	Prandtl number, $Pr = \upsilon/\alpha$
$q_{(A\ or\ B)\ conv}$	convection heat flux towards the interior of the channel, W/m^2
$q_{(A\ or\ B)\ cond}$	conductive heat flux towards the interior of the solid, W/m^2
Re	Reynolds number, $Re = (u_{inlet})(\rho)(H_i)/\mu$
$S\varphi$	source term
T	temperature, °C or K
$T_{average}$	average temperature of the mixture (Air–CO_2) inside the cavity, °C
T_m	temperature of the conductive wall, °C
T_{inlet}	temperature of the mixture (Air–CO_2) at the inlet, °C
T_{outlet}	temperature of the mixture (Air–CO_2) at the outlet, °C
u_{inlet}	velocity in the horizontal direction at the inlet, m/s
v	velocity in the vertical direction, m/s
t	thickness of the solid wall, m
x, y	coordinate x or y

Greek symbol

α	thermal diffusivity, m^2/s
β	coefficient of thermal expansion, $\beta = 1/T_{prom}$, K^{-1}
Γ	diffusion coefficient
ε	dissipation of turbulent kinetic energy, m^2/s^3
$\bar{\varepsilon}_t$	overall effectiveness coefficient for temperature distribution
$\bar{\varepsilon}_C$	overall effectiveness coefficient for contaminant distribution
κ	turbulent energy kinetic, m^2/s^2
λ	thermal conductivity of the mixture (Air–CO_2), W/m K
λ_m	thermal conductivity of the conductive wall, W/m K
μ	dynamic viscosity of the mixture (Air–CO_2), kg/m s
μ_t	turbulent viscosity
υ	kinematic viscosity of the mixture (Air–CO_2), m^2/s
ρ	density of the mixture (Air–CO_2), kg/m^3
σ_t	turbulent Prandtl number
ϕ	dependent general variable (u, v, P, T)

codes. In a subsequent study by Quintero et al. [7], carried out analytically and numerically to compare both results, the authors propose the study as a base to build a model that addresses the effect of axial conduction between the parallel plates. The effect of axial heat flow in heat exchangers has been addressed in different studies, mainly mini channels or micro channels. In this context, we found studies analysing this effect in systems with parallel-flow or dual channel plates. Such studies are generally proposed analytical models to determine the heat transfer coefficients. For example, the study presented by Maranzan et al. [8], in which a dimensionless number (M), is proposed for measuring the axial heat transfer in the channel. In another study conducted by Mathew and Hegab [9], the authors propose a condition of constant heat flux in the outer walls of the channels. Axial temperatures and effectiveness of flow channels are predicted. In subsequent studies, the authors modify the boundary condition of imposed heat flux on the outer walls and now consider the interaction with the outside, the system was solved for parallel flow and counterflow respectively [10,11]. Finally, the authors performed the experiment [12] to verify the numerical results.

Among the numerical studies we can cite Al-Bakhit and Fakheri [13], this was a numerical study of simultaneous parallel flow in rectangular channels. The authors vary parameters to determine the impact that it has on heat transfer, taking into consideration the coefficient of constant heat transfer. The authors found significant changes in the developed flow region, which were presented to smaller values of the Graetz number to 0.3. Mushtaq et al. [14], examined the effect of axial heat conduction between flows. The authors considered different parameters such as the thickness of the conductive wall, the hydraulic diameter, longitudinal variation, and thermal conductivity. They concluded that all parameters studied affected axial heat conduction, but after a ratio value of 10 for thermal conductivity, the axial driving tends to zero. Furthermore, Al-Nimr et al. [15] determined the hydrodynamic performance and heat transfer flow between parallel plates. They analysed the effect of various parameters such as the Knudsen number, heat capacity ratio, effectiveness, and number of transfer units on the performance of heat transfer. Similarly, Shakir et al. [16] analysed the effects of parameters such as Reynolds number, thermal conductivity, Knudsen number, and aspect ratio. A further study to predict the thermal performance of parallel flow channels is by Kok-Cheong and Fashli [17], in which the authors considered a heat sink. For example, one application of such configurations of a heat exchanger is the parallel flow of a solar heater. Hernández and Quiñonez [18] show analytical models representing the values of local temperature on the plate or any point along the collector.

According to our literature review of the most relevant literature, we could not find a study for rectangular parallel pipelines where the effect of buoyancy was studied at different Reynolds numbers in a turbulent flow regime. Thus, this paper is intended to provide greater clarity in the process of heat transfer in a heat exchanger parallel flow in rectangular channels. Analysis of a system under these conditions was proposed considering the effects caused by temperature gradients in the convective motion via buoyancy forces that have not been studied previously. Therefore, this study will provide a better understanding of the phenomenon of heat exchange processes. We herein discuss basic parameters that characterise the system, which are the Reynolds number, the aspect ratio, and the effectiveness of the exchanger. Moreover, we consider the parameter buoyancy.

2. Physical and mathematical formulation model

The principle of operation of the heat exchanger occurs with the convective motion of the fluid within the channel, the convective fluid motion increases or decreases the conduction of heat through the wall between the two channels. The development of this process begins with the entrance of the hot fluid from the lower channel at a given speed and temperature. Temperature change occurs as the fluid particles make contact with the upper surface, and the temperature tends to decrease. We found lower temperature values near the wall. This decrease in temperature of the fluid particles will propagate throughout the rest of the fluid through the