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Laminar mixed convection heat transfer in a vertical circular tube under buoyancy-assisted and opposed flows

Hussein A. Mohammed *

Universiti Tenaga Nasional, College of Engineering, Mechanical Engineering Department, Km 7, Jalan Kajang-Puchong, 43009 Kajang, Selangor, Malaysia

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ABSTRACT

Laminar mixed convection heat transfer for assisted and opposed air flows in the entrance region of a vertical circular tube with the using of a uniform wall heat flux boundary condition has been experimentally investigated. The experimental setup was designed for determining the effect of flow direction and the effect of tube inclination on the surface temperature, local and average Nusselt numbers with Reynolds number ranged from 400 to 1600 and Grashof number from 2.0×10^5 to 6.2×10^6. It was found that the circumferential surface temperature along the dimensionless tube length for opposed flow would be higher than that both of assisted flow and horizontal tube [Mohammed HA, Salman YK. Experimental investigation of combined convection heat transfer for thermally developing flow in a horizontal circular cylinder. Appl Therm Eng 2007;27(8–9):1522–33.] due to the stronger free convective currents within the cross-section. The Nusselt number values would be lower for opposed flow than that for assisted flow. It was inferred that the behaviour of Nu_x for opposed flow to be strongly dependent on the combination of *Re* and *Gr* numbers. Empirical equations expressing the average Nusselt numbers in terms of Grashof and Reynolds numbers were proposed for both assisted and opposed flow cases. The average heat transfer results were compared with previous literature and showed similar trend and satisfactory agreement.

1. Introduction

The importance of the topic of mixed (free and forced) convection heat transfer in ducts of various cross-sections and orientations has motivated a large amount of research activity in the literature because of several applications in this area. Examples of these applications include solar energy systems, boilers, cooling of electronic devices, compact heat exchangers and the cooling core of nuclear reactors. Free convection can aid the forced flow or act in opposition to it. Knowledge of the heat-transfer characteristics under both conditions can guide the design of devices used in these applications [2]. The vast majority of the literature reviews correspond to the horizontal and vertical orientations of circular tubes [3–6]. For the vertical orientation with different geometries, most studies, e.g., [7–11], considered only buoyancy-assisted flows, i.e., upward flows with heating or downward flows with cooling. Under such conditions, the axial velocity increases near the duct walls and decreases in the core, with the possibility of flow reversal in the core region at high *Gr*/*Re* ratios. The occurrence of reversed flow for a particular geometry was also found to be strongly dependent on the thermal boundary condition imposed at the duct walls [12]. An early article by Eckert and Diaguila [13] analyzed simultaneous free and forced convection in a short vertical tube. Jackson et al. [14] presented a review of experimental and theoretical studies on mixed convection in vertical tubes. Studies of heated ascending laminar flow in vertical and inclined tubes with $Re < 2000$ indicate that the Nusselt number for mixed convection, Nu_M, is larger than the corresponding value for forced convection, Nu_F [12–16]. On the other hand, for heated descending laminar flow with $Re < 2000$, Nu_M is smaller than Nu_F [14]. Thus, for vertical tubes, when forced and free convection are in the same direction Nu_M is smaller than the corresponding Nu_F if the heating is weak and the mass flow rate relatively high (low values of the Richardson number and the buoyancy parameter). For high values of the Richardson number and the buoyancy parameter, Nu_M is larger than Nu_F. On the other hand, when forced and free convection are in opposite directions, Nu_M is always larger than Nu_F. For $Re > 2000$ relaminarization can occur and for these conditions Nu_M can be less than Nu_F [17,18]. This complicated behavior of Nu_M explains the lack of definitive information on this subject in heat transfer handbooks and textbooks. Therefore, the present study is concerned with the experimental investigation of laminar mixed convection in a heated vertical circular tube with buoyancy assisted and buoyancy opposed flows. Little prior works have experimentally dealt with laminar mixed convection in vertical tubes, particularly under buoyancy opposed flow conditions as will be proved in the following review.

* Tel.: +6 03 8921 2265; fax: +6 03 8921 2116.
E-mail address: hussein@uniten.edu.my

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Nomenclature

Nomenclature

A_s	tube surface area (m^2)
C_p	specific heat at constant pressure (J/kg °C)
D	tube diameter (m)
g	gravitational acceleration (m/s^2)
h	heat transfer coefficient (W/m^2 °C)
k	thermal conductivity (W/m °C)
L	tube length (m)
$\dot{m}$	mass flow rate (kg/s)
q	input heat flux (W/m^2)
$q_{conv.}$	convection heat flux (W/m^2)
T	air temperature (°C)
X	axial distance (m)

Greeks

θ	tube angle of inclination
β	thermal expansion coefficient (K^{-1})
μ	dynamic viscosity (kg/m s)
ν	kinematic viscosity (m^2/s)
ρ	air density (kg/m^3)

Dimensionless group

Gr	Grashof number
Gz	Graetz number ($Re \cdot Pr \cdot D/L$)
Nu	Nusselt number
Pr	Prandtl number ($=\mu \cdot C_p/\kappa$)
Re	Reynolds number
Ri	Richardson number ($=Gr/Re^2$)
Z	dimensionless axial distance ($=X/D \cdot Re \cdot Pr$)

Subscripts

a	air
F	forced
M	mixed
s	surface
x	local

Superscript

–	average

Morton [4] carried out a numerical study in which the governing elliptic partial differential equations were expressed in finite difference form and solved using a relaxation technique at constant wall temperatures. It was found that the numerical model was able to predict quite accurately the location, shape, and size of the recirculation regions observed in the experiments. Wang et al. [12] presented a numerical analysis for laminar flow at low Peclet number in the thermal entrance region of pipes by finite difference method. The effects of both hydrodynamic and thermal characteristics were systematically investigated. Zeldin and Schmidt [15] carried out experiments and presented numerical analysis to determine the influence of gravity on the hydrodynamics and thermal characteristics of forced laminar flow in a long tube maintained at uniform wall temperature and for air with $Re = 500$. Kemeny and Somers [19] carried out experiments to study the effect of properties variation on fully developed flow heat transfer and pressure drop in circular vertical tubes, with flow of water ($Pr = 4$) and oil ($Pr = 100$) as working fluids. Marner and McMillan [20] studied theoretically fully developed air flow in a vertical tube subjected to constant wall temperature. The tube was heated using a sudden change in wall temperature (a step function). Herbert and Sterns [21] obtained heat transfer coefficients for water heated upward and downward flows in vertical tubes for turbulent range. Their experimental results were agreed with those predicted by a modified Dittus–Boelter equation, but slightly lower. Brauer et al. [22] made numerical analysis to study the influence of free convection on forced convection for the following conditions: temperature-dependent fluid density, constant wall temperature and parabolic profile of axial velocity at the tube entrance for heating and cooling cases. Heggs et al. [23] investigated numerically the effects of wall heat conduction on a steady laminar combined convection water flow in a vertical pipe. Bernier and Baliga [24] presented numerically the results of conjugate conduction and laminar mixed convection in vertical pipes for upward flow and uniform wall heat flux for very low Re numbers between 1 and 10. Joye and Jacobs [25] investigated experimentally the flow patterns generated by buoyancy effects in mixed convection heat transfer to water in a steam jacketed vertical tube. In downflow heating, back flow of hot, large-scale turbulent eddies existed in both the boundary layer and the bulk flow near the entrance (top) of the heated section of the tube. Joye [26] studied experimentally mixed convection in a vertical tube with opposing flow for Re numbers ranged from about 700 to 25,000 at constant Gr numbers under constant wall temperature (CWT) conditions. Laplante and Bernier [27] studied numerically the effect of wall conduction on laminar mixed convection in vertical pipes for a downward flow and a uniform wall heat flux boundary condition. Celata et al. [28] confirmed experimentally the reduction in the heat transfer rate for mixed convection in vertical pipes for upward heat turbulent water cooled flow mainly due to buoyancy effect. Zghal et al. [29] identified the regimes of reverse flow for a vertical pipe with uniform heat flux at the fluid-solid interface. EzEddine et al. [30] presented numerically the interaction between thermal radiation and laminar mixed convection for ascending flows of emitting and absorbing gases in vertical tubes using different fluids of H_2O, CO_2 and H_2O–CO_2 mixtures. Su and Chung [31] presented a numerical study on the linear stability of mixed convection flow in a vertical pipe with constant wall heat flux with particular emphasis on the instability mechanism and the Prandtl number effect. Nguyen et al. [32] studied numerically the simultaneously developing upward transient, laminar and three dimensional flow of air inside a uniformly heated vertical tube that is subjected to a uniform but time-dependent heat flux at the tube wall. It was observed that the buoyancy forces have important effects on both the temperature and axial velocity of the fluid, in particular in the region near the tube wall where acceleration of the fluid appears obvious.

It can be noted from the above review that there is a lack in this topic. Therefore, the current work was performed to fulfill the existing gap in the experimental data. Thus, the purpose of present article was to experimentally investigate the tube inclination angle and the flow direction effects for buoyancy assisted and opposed laminar air flows mixed convection heat transfer through a vertical circular tube. The experimental results obtained, for a Reynolds number range from 400 to 1600, a Grashof number from 2.0×10^5 to 6.2×10^6, were presented and discussed. The results were compared with those for horizontal tube and with other inclination angles done by the same author in his previous work. The empirical correlations for the average heat transfer results were proposed for both assisted and opposed flow cases, and were compared with available literature.