International Journal of Thermal Sciences 111 (2017) 18–29

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

Investigation of flow and thermal behavior in a pipe submerged in a hot fluid

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ARTICLE INFO

Article history:
Received 22 February 2016
Received in revised form
30 May 2016
Accepted 1 June 2016

Keywords:
Submerged pipe
Mixed convection
Temperature field
PIV
Buoyancy-inertial effects

ABSTRACT

Convection heat transfer through a pipe submerged in a stagnant fluid is experimentally studied over a range of flow and thermal conditions. The Reynolds number varied from 330 to 6670 while the Grashof number varied from 14,000 to 95,000. The ratio Gr/Re^2 ranged from 0.0003 to 0.6 implying that the inertial effects were more predominant than the buoyancy effects. The wall heating influenced the mean flow structure in both the streamwise and vertical directions at higher Gr/Re^2 values, where both velocity components peaked in the bottom region of the pipe. The Nusselt number values showed good agreement with the Gnielinski correlation in the turbulent regime at very low values of Gr/Re^2 as well as with theoretical values at low Reynolds numbers. However, in the turbulent regime, the Nusselt number decreased with an increase in Gr/Re^2. The results showed that the original flow regime (in the absence of heating) had a significant impact on the local temperature field as well as the mean flow structure. It was also concluded that at low Reynolds numbers when the contribution of buoyancy-driven flow (natural convection) was smaller than that of the inertia-driven flow (forced convection), the role of buoyancy was primarily limited to the initiation of instabilities in the laminar flow to trigger the transition into turbulence.

1. Introduction

Heat exchangers are vital to a wide variety of residential and industrial applications such as HVAC systems, automotive and aerospace sectors, power plants etc. A submerged pipe heat exchanger allows for heat to be exchanged between a primary fluid forced through a pipe that is completely immersed inside a secondary stagnant fluid with a mutually interacting thermal boundary. Submerged heat exchangers are also found in a wide variety of applications such as boilers, chemical and petrochemical processing, food processing, etc. Although widely used, the fundamental heat transfer mechanism present in such a heat exchanger is not well understood.

The thermo-fluid process inside an immersed pipe is expected to be different from other types of heat exchanger applications. Being immersed in a larger stagnant fluid domain, the pipe is exposed to an almost isothermal condition of the stagnant fluid. Hence, the fluid dynamics inside the pipe is expected to influence the thermal boundary conditions at the pipe wall and vice versa. Furthermore, the mode of convection heat transfer is also expected to play a role in the heat exchange between the pipe fluid and the surrounding stagnant fluid. There is however a scarcity of studies investigating the thermo-fluid process inside the pipe immersed in a stagnant isothermal fluid.

Mixed convection has a significant influence on the thermal and hydrodynamic structure present inside laminar flows [1,2]. Many studies have investigated the heat transfer rate during fully developed mixed convection through different geometries and experimental conditions including a large range of Reynolds (Re) and Grashof (Gr) numbers. The onset of unstable stratification is strongly dependent on the Grashof number and/or the Reynolds number [3]. This buoyancy-driven flow induces mixing which causes an enhancement of the heat transport from the thermal boundary layer to the bulk fluid. This rises the bulk fluid temperature which reduces the overall temperature gradient [4]. Mixed convection in channels and pipes are extensively studied and reported in the literature (for example see Jackson et al. [5] and Piva et al. [6]). However, a limited number of studies analyzed mixed convection in submerged pipes, which were mainly focused on numerical techniques to simulate this interactive boundary

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http://dx.doi.org/10.1016/j.ijthermalsci.2016.06.036
1290-0729/

Nomenclature

A	Pipe cross-sectional area, m^2
β	Thermal expansion coefficient, $^{\circ}C^{-1}$
D	Inner pipe diameter, m
f	Friction factor
g	Acceleration due to gravity, m/s^2
Gr	Grashof number
h	Convective heat transfer coefficient, $W/m^2\,^{\circ}C$
k	Thermal conductivity, $W/m^2\,^{\circ}C$
Nu	Nusselt number
Pr	Prandtl number
Q	Volumetric flow rate, $m^3/s,\ gpm$
q	Heat transfer rate, W
q''	Heat flux, W/m^2
R	Inner pipe radius, m
Re	Reynolds number
T_s	Average circumferential inner pipe surface temperature, °C
T_∞	Bulk temperature, °C
u	Mean streamwise velocity, m/s
$\overline{U}$	Cross-sectionally averaged mean streamwise velocity, m/s
v	Mean vertical velocity, m/s
ν	Kinematic viscosity, m^2/s
y	Vertical axis, m

condition. In addition, due to this scarcity of relevant experimental studies, the literature review is primarily comprised of studies that investigated thermo-fluid processes in channel or pipe flows subjected to different thermal boundary conditions that induce mixed convection heat transfer.

Coutier and Greif [7] modeled the velocity and temperature fields in the cross-sectional plane of a horizontally immersed pipe during mixed convection. Heat was transferred from the internal flow of warmer fluid to the surrounding fluid. Limited experimental analysis was also conducted in order to verify the theoretical temperature results. These results were then compared to the cross sectional results of an immersed tube with isothermal wall condition of comparable Gr/Re^2 values [8]. It was found that the differing thermal boundary conditions had a largely noticeable effect on the resulting velocity and temperature fields. For the case where the boundary was exposed to natural convection, the fluid tended to slide down the side walls from the top to the bottom of the pipe as it cooled by convection. In the case of isothermal boundary conditions, this active fluid was not able to reach the same depths as it slid down the side wall due to the larger wall temperature in the bottom region of the pipe. Therefore, the buoyant forces in the lower regions of the pipe were weaker in the case of isothermal boundary conditions. It was also found that in the case of natural convection around the boundary, the rising plumes of fluid were impeded by the thermal boundary layer in the upper-center region. This induced a small circulation in the upper-center of the tube, which was not found in the case of isothermal boundary conditions.

Hussain and Hussein [9] numerically simulated natural convection in the cross-sectional plane surrounding an immersed isothermal pipe to study temperature and velocity fields surrounding the immersed pipe. The Rayleigh number varied from 10^3 to 10^6. It was found that the hot pipe induced rising plumes of fluid near its surface, which then rose to the top of the outer encasement and began to fall along the encasement wall. This induced two symmetric vortex cells on either side of the pipe. With increasing Rayleigh number, the vortices were forced into the upper region, increasing the local fluid tangential velocity which in turn, largely effected the temperature fields. Faghri and Sparrow [10] studied mixed convection in a horizontal pipe subjected to external natural convection and radiative heat transfer around its boundary. Their analysis was focused on the variation in the heat transfer coefficient along the axial length of the pipe. It was found that the average Nusselt number along the pipe had a weak dependency on the variation of the external convection coefficient. Instead, it was the bulk and wall temperature distributions that noticeably varied with a change in external convective conditions.

Bulk properties of mixed convection in uniformly heated horizontal pipes and channels have been extensively analyzed. Patil and Babu [11] investigated the convective heat transfer in a square duct with uniform thermal boundary conditions for water and ethylene glycol. They observed mixed convection in water at Re $<$ 1050 while, for ethylene glycol, the mixed convection was observed at Re $<$ 480 and it was argued that this difference was due to the higher Prandtl number of ethylene glycol that reduces the thermal boundary layer thickness. They concluded that at a given Reynolds number, the average Nusselt number throughout the duct is positively correlated with Gr/Re^2 and Prandtl number (Pr). Mixed convection in a horizontal pipe exposed to uniform heat flux boundary conditions was experimentally analyzed by Barozzi et al. [12] and Mohammed [13], and numerically by Shome and Jensen [14]. They focused on the change in Nusselt number with a change in distance from the inlet of the heat exchanger. It was found that as the distance increased, the Nusselt number rapidly decreased due to the decrease in the temperature difference between the bulk fluid and the tube surface. This decrease was found to be dependent on the Reynolds, Prandtl, and Rayleigh numbers. It was also found that an increase in the circumferential heat flux increased the Nusselt number. A similar study was also conducted by Peyghambarzadeh [15], confirming the change in Nusselt number with distance from the inlet as examined in the previous study. Wang et al. [16] investigated the effect of mixed convection in horizontal and vertical pipes with uniform heat flux conditions and low Peclet numbers. They found a reverse flow in the top region of a horizontal tube as the buoyancy effects become large. This effect was found to decrease the circumferentially-averaged Nusselt number.

Experimental investigations of mixed convection in non-uniform thermal boundary conditions with noninvasive visualization techniques are also plentiful. Mixed convection in the region immediately adjacent to the bottom heating wall of a channel during forced convection was conducted by Gajusingh and Siddiqui [17]. They investigated the effect of heat transfer in the near wall region for originally laminar and turbulent flows using particle image velocimetry (PIV) technique. It was concluded that strong buoyancy forces generate turbulence in originally laminar flow. In the case of originally turbulent flow, the buoyant forces in the near wall region dampens local turbulent fluctuations. They argued that the unstable stratification generated by bottom heating enhances turbulence in originally laminar flows, but decreases its magnitude in originally turbulent flows. Elatar and Siddiqui [18,19] experimentally investigated mixed convection in a channel subjected to heating through bottom at low Reynolds numbers and large Grashof numbers where the buoyancy-to-inertia ratio (Gr/Re^2) ranged