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Buoyancy induced heat transfer deterioration in vertical concentric and eccentric annuli

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ABSTRACT

Turbulent convection heat transfer of upward fluid flows in vertical annular channels with uniformly heated inner wall and adiabatic outer wall is investigated numerically. Two concentric geometries with outer-to-inner diameter ratios of 2.4 and 3 as well as two eccentric geometries with identical outer-to-inner diameter ratio of 2.4 and eccentricities of 0.25 and 0.5 are investigated. Heat transfer deterioration, similar to that of a circular pipe, is observed. The range of buoyancy parameter, over which deterioration is observed, is close to that of circular pipes. Moreover, it is observed that when the value of eccentricity increases, the deterioration phenomenon becomes less pronounced and recovery of heat transfer coefficient occurs earlier, i.e. at lower buoyancy parameters compared to concentric annuli.

1. Introduction

Variation of the thermophysical properties can significantly affect transport phenomena in fluid flows. A good example is the case of fluids at pressures slightly higher than critical pressure when rapid variations in the values of specific heat, density, viscosity and thermal conductivity against temperature is present [1]. In such fluid flows, if the fluid exchanges heat with a solid wall, property variations can be significant in the normal-to-wall direction. If one intends to correctly account for heat transfer coefficient in such flows, correction factors are required for the wall-to-bulk values of thermal properties [2,3].

Variation of density can affect heat transfer also in a rather indirect manner, which is, causing significant buoyancy forces thereby changing the fluid velocity field. A notable phenomenon stemming from this boost of buoyancy force is what commonly referred to as “heat transfer deterioration” or briefly “deterioration”. Deterioration, which is simply a sudden reduction in the value of heat transfer coefficient, is likely to occur whenever the regime is turbulent, the flow direction is vertical and in the same direction as the buoyancy force adjacent to the wall, i.e. upward heating or downward cooling. In 1979, Jackson and Hall [4] explained this phenomenon as the indirect impact of buoyancy on the production of turbulence kinetic energy by deforming the velocity profile in a channel. According to their explanation, in an upward flow, heated fluid near the wall tends to move upward faster because it is lighter. As a result, the velocity profile differs from that of no-buoyancy flow so that the velocity gradient decreases in the near-wall region where turbulence production would have been significant. It reduces the level of turbulence intensity and, consequently, heat transfer is deteriorated. This theory was later supported by flow structure observations of Kurganov and Kaptilnyi [5]. Aiming to predict the onset of deterioration, Jackson et al. [6] introduced a buoyancy parameter (Bo) to quantify the buoyancy effect:

$$Bo = \frac{Gr}{Re^{3.425} Pr^{0.8}} \tag{1}$$

where

$$Gr = \frac{\rho_b^2 g \beta_b q_w D_h^4}{\mu_b^2 \lambda_b} \tag{2}$$

Reynolds number should be similarly defined based on hydraulic diameter D_h. For Reynolds number, the properties are calculated in bulk temperature. When the above buoyancy parameter reaches a certain threshold, sudden decrease in the value of heat transfer coefficient, or Nusselt number, is observed. It must be noted that with very high values of buoyancy parameter, heat transfer starts to recover as a result of free convection becoming dominant. This ‘deterioration’ and ‘recovery’ sequence can be seen in Figure, which will be further discussed in Section 3.

In order to better study deterioration phenomena and its dependence on the above mentioned buoyancy parameter or similar ones, a number of experimental studies have been conducted.

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Nomenclature

Latin symbols
Bo buoyancy parameter
C_p specific heat at constant pressure ($W\,kg^{-1}\,K^{-1}$)
$C_{\mu,\varepsilon,1,2,\eta,L}$ model constant
D diameter (m)
e eccentricity
f production of turbulence velocity scale (s^{-1})
G_k production of turbulence energy due to density fluctuation ($m^2\,s^{-3}$)
$\vec{g}$ gravitational acceleration vector ($m\,s^{-2}$)
Gr Grashoff number
h enthalpy ($J\,kg^{-1}$)
k turbulence kinetic energy ($m^2\,s^{-2}$)
L length scale (m); see Eq. (12)
l distance between tube centers (m)
Nu Nusselt number
P_k production of turbulence energy due to shear ($m^2\,s^{-3}$)
p pressure (Pa)
Pr Prandtl number
q heat flux ($W\,m^{-2}$)
Re Reynolds number
r radial coordinate measured from pipe centreline (m)
S strain tensor
T temperature (K)
$\tilde{t}$ time scale (s); see Eq. (6)
$\vec{U}$ velocity vector
U velocity magnitude ($m\,s^{-1}$)
$\bar{v}^2$ turbulence velocity scale (m^2)
x, y, z Coordinates (m)

Greek symbols
β volumetric expansion coefficient (K^{-1})
ϵ dissipation rate of turbulence energy ($m^2\,s^{-3}$)
φ non-dimensional temperature
θ angle with y axis in x–y plane (rad)
λ thermal conductivity ($W\,m^{-1}\,K^{-1}$)
μ kinetic viscosity (Pa s)
ν kinematic viscosity ($m^2\,s^{-1}$)
ρ density ($kg\,m^{-3}$)
σ turbulent Prandtl number

Subscripts
ave area-averaged on a periphery
b bulk value
FC forced convection
h hydraulic
i inner
mean mass-averaged over a cross section
o outer
ref reference value
t turbulence
w measured on the wall
z axial component

Watts and Chou [7] derived a correlation to predict deterioration based on the buoyancy parameter for supercritical water in circular pipes. Similar studies have been done for circular pipes with CO_2 [1,8].

Attempts have also been made to simulate deterioration phenomenon numerically. As this phenomenon is closely related to the mechanism by which turbulence energy is produced, the right choice of turbulence model is crucial here. A widespread choice for this problem has been low Reynolds variations of k–ε model [9–11]. However more careful studies have recently revealed that this class of two-equation models may not be as loyal to the physics of problem as their results suggest. The same references recommend a more elaborated four equation model of k–ε–v^2–f [12] to be the best choice within the category of eddy viscosity models [10,13–15].

A big difficulty with the study of deterioration is that deterioration is only one of the phenomena arisen as a result of rapid property variations so it is not easy to distinguish the pure effect of buoyancy on heat transfer when real fluids are studied. To tackle this problem, a number of researchers adopted constant property assumption along with Boussinesq approximation for the calculation of buoyancy term in the momentum equation [13,16]. This computational approach facilitates study of the pure effect of buoyancy on transport phenomena in turbulent flows.

A careful literature review reveals that most of the references (numerical or experimental) have studied the deterioration phenomenon using a circular pipe in vertical direction as the geometry, with exception of [17], studying it an inclined circular pipe. Few researches have been done on the heat transfer of supercritical fluids in ‘concentric’ annular pipes [18–20], none of them has studied the effect of buoyancy – isolated from other effects. On ‘eccentric’ annular pipes, however, no research has been reported so far.

The present paper, aims to investigate the deterioration phenomenon in both concentric and eccentric annuli using Boussinesq assumption in order to isolate the effect of buoyancy, as described above. The focus of this study will be on the effect of buoyancy parameter on heat transfer and the trend of deterioration phenomenon with the eccentricity of the annulus.

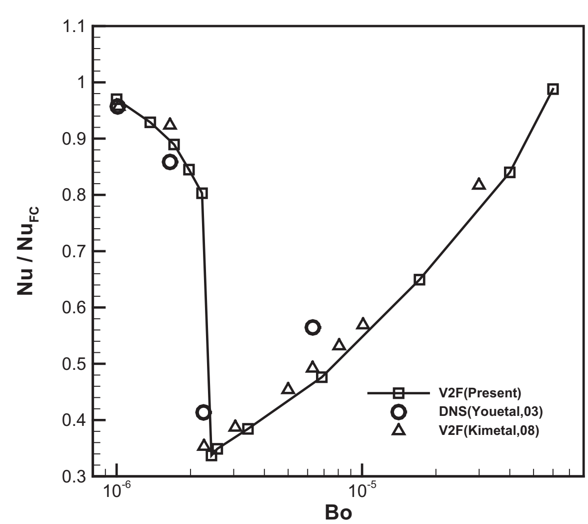

Fig. 1. Comparison of the present solution with DNS data of [16] and a separate CFD simulation [13] using the same turbulence model. The Nusselt number is for upward flow in a circular pipe with $Re = 5300$. Boussinesq assumption has been adopted in all three studies. The deterioration occurs at $Bo = 2 \times 10^{-6}$ followed by a recovery zone (monotonic increase in Nu/Nu_{FC}).