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Flow reversal of laminar mixed convection for supercritical CO_2 flowing vertically upward in the entry region of asymmetrically heated annular channel

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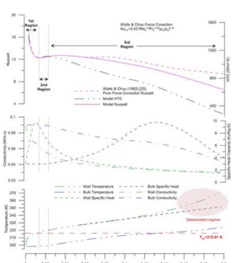
GRAPHICAL ABSTRACT



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ABSTRACT

Numerical investigation has been performed in order to determine the onset of flow reversal occurrence for buoyancy assisted flow of supercritical CO_2 through vertical annular channel of finite length with heated inner wall. The outer wall was considered adiabatic. Only steady state and laminar mixed convection cases were considered in order to study the involved heat transfer phenomena in a fundamental level. Results gave a clear insight of the flow reversal mechanism and highlighted buoyancy as the driving force of the aforementioned phenomenon. Furthermore, according to the results, two different flow reversal maps were constructed with the use of dimensionless parameters. Results clarifies that the dominance of free convection is vital for the onset of the flow reversal. More specifically, free convection must be higher from both conductive and forced convective heat transfer. In addition, mass flux suppresses the mentioned phenomenon, while heat flux aids the presence of flow reversal.

1. Introduction

The significance of combined natural and forced convection in ducts of various cross-sections and orientations has encouraged many researchers because of their practical industrial and engineering applications which include electronic equipment, boilers, solar collectors, compact heat exchangers, chemical processes and the cooling core of nuclear reactors. Since natural convection can aid the forced flow or act against it, the knowledge of the heat-transfer characteristics under both conditions can guide to design such apparatuses and to predict their off-design performance by aiding to obtain a precise description of the temperature, pressure and velocity profiles under all operating

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Nomenclature

Bu	Buoyancy number ($Gr/Re^{2.7}$)
c_p	Specific heat of fluid (J/Kg K)
d	Hydraulic diameter of annulus (m)
g	Acceleration due to gravity (m/s^2)
G	Mass flux (Kg/m^2 s)
Gr	Grashof number ($\rho_b{}^2\beta_b q\text{''} gd^4/\lambda_b\mu_b$
h	Convective heat transfer coefficient (W/m^2 K)
L	Channel length (m)
Nu	Nusselt number
p	Pressure (Pa)
Pe	Peclet number (Re Pr)
Pr	Prandtl number ($c_p\mu/\lambda$
q”	Heat flux (W/m^2)
r	Cylindrical coordinate radial direction characteristic (m)
R	Radius (m)
Re	Reynolds number ($\rho Ud/\mu$
Ri	Richardson number (Gr/Re^2)
T	Temperature (K)
t	Time (s)
U	Flow velocity (m/s)
U_0	Average flow velocity (m/s)
u	Velocity in x direction (m/s)
v	Velocity in y direction (m/s)
w	Velocity in z direction (m/s)
z	Cylindrical coordinate axial direction characteristic (m)

Greek letters

β	Volume expansion coefficient (1/K)
λ	Thermal conductivity (W/m.K)
μ	Dynamic viscosity (Pa s)
π_A	Acceleration number ($\frac{\beta}{c_p}\frac{q''}{G}$, defined by Cheng et al. [28])
ρ	Density (kg/m3)

Subscript

b	Evaluated at bulk
FC	Force convection
i	Inner
in	Inlet
o	Outer
pc	Pseudo-critical
w	Evaluated at wall

conditions [1]. Most of investigations in literature correspond to the horizontal and vertical orientations of circular tubes [2–4], in which for the vertical orientation, most studies [5–9], considered only buoyancy-assisted flows. For buoyancy-assisted flow through the vertical channel, the axial velocity increases near the wall region and decreases in the core region in which for high values of Gr/Re, could decrease to such extant that causes the flow to be inverted. It is also found that the thermal boundary condition applied to the duct walls has strong influence on the inversion of flow for particular geometry [10].

The pioneer's works on the reversal flow phenomenon and the flow instability in laminar mixed convection flow inside vertical channel carried out by Hanratty et al. [11], Scheele and Hanratty [12] in late fifties; and they observed experimentally the existence of reversal flow in the fully developed region at low values of Reynolds numbers for buoyancy-assisted case and they also presented some analytical solution to the observed phenomena. Morton [13] performed a numerical study by using relaxation technique for constant wall temperature boundary condition in order to solve fully elliptical governing equations which were expressed in finite difference form. It was shown that the numerical model was able to predict correctly the shape, size, and location of the recirculation regions observed in the experiments. By using a technique, which made visualization of fluid flow phenomena possible, Bernier and Baliga [14] observed experimentally the presence of recirculation cells and laminar-turbulent transitions at low values of Reynolds number in a closed-loop thermosyphon. They [15] also numerically presented the results of conjugate conduction and laminar mixed convection for upward fluid flow in vertical pipe with uniform heat flux boundary condition, for low values of Reynolds numbers ranging from 1 to 10. Wang et al. [10] numerically investigated the problem of mixed convection with flow reversal in the thermal entrance region of horizontal (3D study) and vertical (axially symmetric 2D flow) pipes at low Péclet number; and also the effect of axial conduction. They found that the reversed flow appears at immediate to the tube wall for the cooling case and the pipe center for the heating case, both at relatively high value of Gr/Re ratio. They also identified the regime of reversed flow occurrence for various Prandtl numbers and in the Pe–Gr/Re coordinate map, for both cases. Moutsoglou and Kwon [16] performed numerical study for both cases of buoyancy-assisted and opposed flow in vertical channels for laminar mixed convection in developing zone and solved the parabolized equations with uniform temperature or heat flux boundary conditions. On account of using a parabolic formulation of the governing equations, they only managed to determine only one onset for reversed flow occurrence which is the critical buoyancy parameter, Gr/Re ratio. They also demonstrated that in case of buoyancy-assisted flow, local bulk Nusselt numbers exceed its corresponding zero buoyancy values while exhibiting valleys and peaks particularly at high buoyancy intensities, but for latter case, their values diminish to below their corresponding values in absence of buoyancy forces. Nesreddine et al. [17] and Zghal et al. [18] carried out a numerical investigation of laminar mix convection in vertical tube with uniform heat flux boundary condition that applied to heated section, by using of fully-elliptic model and considering wide range of value for Reynolds and Richardson numbers and also length of heated section which is preceded and followed by adiabatic sections. The Results illuminated that, there may exist five different flow regimes with or without bidirectional flow depending on the combination of mentioned parameters. The conditions that cause the inversion of flow as well as the importance of the upstream axial diffusion of heat and momentum have also been demonstrated and the results have been mapped on the Péclet–Richardson numbers plane for different lengths of the heated section. Nguyen et al. [19] in numerical investigation of transient laminar mixed convection in vertically heated tube by applying heat flux at constant rate to its wall, studied structure of the flow and the thermal field for a simultaneously developing flow and its transient behaviors under strong and time-dependent heating condition (i.e., high Grashof number), in both case of buoyancy-opposed and assisted flow, based on the Boussinesq’s assumptions and by using a fully 3D-transient model, in order to analyze the occurrence of reversed flow and more importantly, to determine its association with the onset of flow instability which may or may not have exist. They showed that the resulted reversed flow region with increase in time has significantly increased in size and intensity and spread into the upstream region, and also the flow structure appeared to conserve its axisymmetrical characters even for cases with very high Grashof numbers; but they failed to demonstrate whether there is any link between flow reversal and onset of flow instability or not. Although they observed that for Grashof number below critical value (value that initiate flow reversal), the flow structure remain stable and unique (depend on heat flux rate) but for beyond critical values, the convergence become an extremely slow and rather tedious which they believed to be due to a possible form of flow