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Numerical study of turbulent flow in asymmetrically heated horizontal channel

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ABSTRACT

Low Reynolds number turbulent flow of Helium in a horizontal channel subjected to asymmetric heating was studied using a low-Reynolds number turbulence model. The study was conducted for inlet Reynolds number ranging from 4000 to 10,000, non-dimensional wall heat flux ranging from 0.001 to 0.005, and ratio of top wall heat flux to bottom wall heat flux ranging from 0 to 1. The results from the study were used to obtain laminarization criterion as a function of inlet Reynolds number, non-dimensional wall heat flux, and ratio of top wall heat flux to bottom wall heat flux. The developed laminarization criteria which is based on the ratio of turbulence production to turbulence dissipation predicts a reduction in the Nusselt number as compared to the constant property turbulent flow results, ranging from as much as 45% reduction for inlet Reynolds number of 4000 to 22% reduction for inlet Reynolds number of 10,000.

1. Introduction

Inert gas coolants, such as Helium or Nitrogen, are commonly used in heat exchangers for nuclear reactor applications as they provide safety, chemical inertness, and high thermal efficiency benefits. In such heat exchangers, as the coolant flow rate is kept low to provide a higher outlet temperature, the flow is in the low Reynolds number turbulent flow regime. Furthermore, due to large heating rates, there are significant variations in the thermo-physical properties of the gases used. For example, the Reynolds number at the exit of the High Temperature Engineering Test Reactor (HTTR) cooling channel in Japan is around 3500 [1].

For low Reynolds number turbulent flow subjected to increased heating, the flow field may change to a laminar-like state at local Reynolds number representing turbulent flow. This transition from turbulent to a laminar-like flow regime is referred to as laminarization [2]. Laminarization leads to deterioration of heat transfer due to thickening of the thermal boundary layer and may lead to as much as 40% reduction in heat transfer [3]. Thus, a thorough understanding of flow and thermal behavior for laminarized flow is required to predict the thermo-hydraulic performance for design, optimization, and operation of such heat exchangers.

Laminarization of flow caused by heating is due to variations in acceleration, buoyancy, and thermo-physical properties of the fluid. Turbulent internal flow through pipe or channel is characterized by the formation of low-speed coherent structures or streaks in the near-wall region. These streaks move away from the near-wall region and oscillate before finally breaking up in a time-cyclic way leading to increased momentum exchange between the near-wall region and the core region. This phenomenon of the steaks cyclically moving and finally breaking up is referred to as turbulent burst. For heated flows, the reduction in density causes the bulk flow to accelerate which reduces the turbulent bursting rate near the wall. The reduced turbulent bursting reduces the momentum exchange leading to a reduction in heat transfer.

Similarly, the variation in fluid density caused by heating introduces a buoyancy effect that reduces turbulence generation within the boundary layer which in turn causes a reduction in heat transfer. On further heating of the fluid, the buoyancy effects cause secondary flows which increases mixing and the heat transfer is enhanced.

Based on similarity with external boundary layer flow, previous investigators [4–7] have proposed an acceleration parameter to characterize the laminarization and to develop laminarization criterion. Bankston [4] investigated laminarization of hydrogen and Helium flow through circular tubes with Reynolds number ranging from 2350 to 12,500. A modified form of acceleration parameter was developed by relating the change in bulk velocity in the tube to

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Nomenclature

A_c	channel cross-sectional area
Bo	Buoyancy parameter $[=Gr/Re^{3.425}Pr^{0.8}]$
c_p	specific heat at constant pressure
g	gravitational acceleration $(=9.81\ \mathrm{m/s^2})$
G	mass flux $[=\dot{m}/A_c]$
Gr	Grashof number $[=gD_h^4 q_w/\nu_b^2 \lambda_b T_b]$
h	heat transfer coefficient $[=q_{w,i}/(T_{w,i}-T_b)]$
H	channel height
k	turbulence kinetic energy
$\dot{m}$	mass flow rate
N	ratio of wall heat flux $[=q_{w,1}/q_{w,2}]$
Nu	Nusselt number $[=h2H/\lambda]$
p	pressure field
Y_k, Y_b	production terms in transport equation for turbulence kinetic energy and buoyancy, respectively.
Y	turbulence production rate $[Y=Y_k+Y_b]$
Pr	molecular Prandtl number
P^+	non-dimensional pressure drop $[=\rho_{in}(p_{in}-p)/G^2]$
Pr_t	turbulent Prandtl number
q_w	heat flux at wall
q_w^+	non-dimensional wall heat flux $[=q_w/(Gc_{p,in}T_{in})]$
y, z	spatial coordinates in cross-stream and stream-wise direction, respectively
Re	Reynolds number $[=\rho w 2H/\mu]$
T	temperature
v, w	velocity components in cross-stream and stream-wise direction, respectively
$\langle v'w' \rangle$	Reynolds shear stress
W	non-dimensional axial velocity $[=w/w_b]$

Greek symbols

ε	turbulence dissipation
λ	thermal conductivity
μ	dynamic viscosity
ν	kinematic viscosity
Θ	non-dimensional temperature $[=(T_{w,2}-T)/(T_{w,2}-T_{in})]$
ρ	fluid density
σ	turbulent Schmidt number

Subscripts

b	evaluated at bulk condition
in	evaluated at inlet
w	evaluated at wall
1, 2	evaluated at top wall and bottom wall of channel, respectively

Abbreviations

DNS	direct numerical simulation
LES	large eddy simulation
RANS	Reynolds averaged Navier Stokes equation

a change in the bulk temperature, to predict the onset of laminarization. In addition, an additional parameter to predict the heated length of the tube that is required for laminarization was also proposed. McEligot et al. [5] also proposed a similar acceleration parameter to predict laminarization for flow through a heated vertical tube. The acceleration parameter was proposed for the case of uniform wall heat flux boundary condition and as well as extended to the case of variable heat flux boundary condition. Variable property effects were included through the power law variation of viscosity and specific heat with temperature. Lee et al. [6,7] experimentally investigated the heat transfer deterioration for ascending flow of gases in heated vertical tubes and suggested that the flow laminarizes when the acceleration parameter, defined as $k_v=(\nu_b/w_b^2)/(\mathrm{d}w_b/\mathrm{d}z)$, exceeds the threshold value of 2.5×10^{-6}. In addition, they also suggested that deterioration in heat transfer due to buoyancy effects occur when the Buoyancy number, defined as $Bo=Gr/(Re^{3.425}Pr^{0.8})$, exceeds the threshold value of 6×10^{-7}.

The effect of buoyancy on flow laminarization has been studied extensively [8–10] and these investigations have proposed parameters to assess the impact of buoyancy on heat transfer. The study by Jackson et al. [8] showed that the effect of buoyancy on laminarization is negligible for Bo values less than 6×10^{-7}. Cotton and Jackson [9] numerically investigated the effect of buoyancy on flow laminarization for both ascending and descending flows in heated vertical tubes using the Launder Sharma variant of the low-Reynolds number $k-\varepsilon$ turbulence model. Their results show that the numerical predictions agree well with the test data for ascending flow but major discrepancies with the test data were observed for strongly buoyancy-dominated descending flow. Jackson and Li [10] experimentally studied vertical flow of air through a heated tube for both uniform wall temperature and uniform wall heat flux conditions. Their results show significant deterioration of heat transfer due to buoyancy effects on turbulence with the effect much larger for the case of uniform wall temperature than for the case of uniform heat flux condition.

The inlet velocity profile and the inlet turbulence intensity level influence the breakdown of laminar flow. Minkowycz et al. [11] found that the breakdown of laminar flow and the subsequent onset of transition in flow through channels is greatly influenced by the shape of the inlet velocity profile and the level of inlet turbulence intensity. The authors found that in addition to the laminar and fully developed turbulent flow regimes, there is a third regime which is intermittently laminar and turbulent and which particularly occurs for high levels of turbulence intensity. The heat transfer coefficient for uniform wall heat flux and uniform wall temperature boundary conditions was found to be around the same for fully developed laminar flow and fully developed turbulent flow; however, for the intermittent regime the heat transfer coefficients differed from each other by as much as 25% [12].

Laminarization in gas flowing vertically upwards through a tube and subjected to high heating rates has been a subject of many experimental [7,13,14] and numerical investigations [13–18]. The experimental study of Lee et al. [7] used flow of Helium, Nitrogen, and Carbon Dioxide through a heated vertical tube whereas the experimental studies by Perkins [13] and by Shehata and McEligot [14] used flow of air through a heated vertical tube. The numerical studies for study flow laminarization involved use of LES [15], DNS [16,17], and RANS based eddy viscosity turbulence models [18–20]. Both the experimental and numerical studies have presented distribution of local quantities (such as velocity, temperature, and turbulence variables) and global quantities (such as average Nusselt numbers and non-dimensional pressure drop values). In addition, laminarization criteria using flow acceleration parameters and based on attenuation of turbulent kinetic energy and Reynolds shear stresses have been proposed to predict the onset of flow laminarization. In contrast to flow of gas through heated vertical