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Numerical study of turbulent convection in inclined pipes with significant buoyancy influence

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ABSTRACT

Convection heat transfer in inclined pipes with significant influence of buoyancy is investigated numerically. V2F eddy viscosity turbulence model is used and, to isolate the effect of buoyancy, constant values are used for thermo-physical properties with Boussinesq approximation for the density variation with temperature in the momentum equations. This problem is particularly significant for better understanding of flow and heat transfer in supercritical fluids. It is found that the same mechanism that leads to impairment of turbulence production, and thus heat transfer, in a vertical pipe ($\alpha = 90°$) is present in inclined pipes; however it is less pronounced when $\alpha < 60°$. Secondary flows are observed as a result of buoyancy force leading to non-uniformity of local heat transfer coefficient along the pipe periphery.

1. Introduction

Queensland Geothermal Energy Centre of Excellence (QGECE) has been considering, among other ways, supercritical power cycles to maximize the power conversion efficiency in geothermal plants, which is a feasible route toward commercialization of enhanced geothermal energy (EGS) electricity generation [1–3]. The geothermal system of interest is a binary one. This kind of geothermal system consists of two loops: the *lower loop*, in which a *geothermal fluid*, e.g. brine, is sent down the geothermal well to get heated, then is drawn back to the surface to transfer its heat to the *working fluid* circulating in the *upper loop*. The upper loop is a closed power cycle, e.g. a Rankine cycle, in which heat is converted to the power. An on-going research program at QGECE is concerned with the performance of heat exchangers in the upper loop when at least one of the pressures in the cycle is above the critical value.

Fig. 1 shows the variation of specific heat capacity and density for CO_2 slightly above its critical pressure (7.39 MPa), as an example of a supercritical fluid. It is observed that even with a small temperature change, e.g. 10 °C, the density drops by a few times and, similarly, the specific heat reaches a peak whose value is larger by an order of magnitude. The temperature at which the specific heat capacity is maximum is called the 'pseudo-critical temperature'. Since very early studies [4–9], it has been found out that, due to this severe variation of thermophysical properties, heat transfer of supercritical fluids deviates from the prediction of conventional correlations in the vicinity of the pseudocritical temperature. In particular, when wall and bulk temperatures span the pseudocritical temperature, this deviation can be significant. The geothermal power cycles of interest work between the upper temperature of around 200 °C and lower temperature of 25 °C (or whatever ambient temperature is) [1], and considering that supercritical temperatures of a large number of potential working fluids – including CO_2 and many refrigerants – lies within this temperature range, a variety of scenarios can be contemplated in which the above mentioned temperature span occurs in one or more than one heat exchangers.

There are two major mechanisms by which heat transfer of supercritical fluids may be affected: first, the large difference between bulk and near-wall properties (especially density and specific heat capacity) that makes bulk-temperature correlations insufficient. Therefore, a large number of variable-property correlations, particularly derived for supercritical conditions, have been proposed by different researchers; see also [10–13]. Furthermore, the large Archimedes' force arising as a result of sharp variation of density near the pseudo-critical temperature will affect the flow field, and thus, heat transfer. It was well documented in the literature, by the end of the 70s, that heat transfer can be deteriorated in vertical tubes when the fluid receives heat from the surrounding wall and the flow is upward – a slight improvement was also observed for downward case [14]. Jackson and Hall [14] explained this observation based on the deformation of velocity profile, and thus shear stress profile, as a result of the significant density variation near the pseudo-critical point. According to those authors, hot fluid near the wall tends to move upward faster, compared

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Nomenclature

Latin symbols:

Bo	buoyancy parameter; see Eq. (13)
C_p	specific heat at constant pressure
$C_{\mu,\varepsilon,1,2,\eta,L}$	model constant
d	tube diameter
f	Production of turbulence velocity scale
G	mass flux
G_k	production of turbulence energy due to density fluctuation
$\bar{g}$	gravitational acceleration vector
Gr_q	Grashoff number
h	enthalpy
k	turbulence kinetic energy
L	length scale; see Eq. (10)
N_u	Nusselt number
p_k	production of turbulence energy due to shear
p	pressure
p_r	Prandtl number
q	heat flux
R	tube radius
r	radial coordinate measured from pipe centreline
S	strain tensor
T	Temperature
$\tilde{t}$	time scale; see Eq. (4)
$\overline{U}$	velocity vector
U	velocity magnitude
u	component of the velocity vector
$\bar{v}^2$	turbulence velocity scale
x,y,z	coordinates

Greek symbols

α	angle of pipe with horizontal plane
β	volumetric expansion coefficient
ε	dissipation rate of turbulence energy
θ	angle with y axis
λ	thermal conductivity
μ	kinetic viscosity
v	kinematic viscosity
ρ	density
σ	turbulent Prandtl number

Subscripts

ave	average value over a cross section
b	bulk value
Fc	forced convection
k	turbulent kinetic energy
r	radial component
ref	reference value
t	turbulence
$wall$	measured on the wall
z	axial component
θ	tangential component

to less heated fluid away from the wall, and that eventually leads to an 'M-shape' velocity profile. It leads to a reduction in the velocity gradient and shear stress in the near-wall region where 'the production of turbulence is mainly concentrated'. As a result, turbulence intensity reduces and a state of laminarization occurs near the wall with an adverse effect on heat transfer in a subsequent study, some 'buoyancy parameters' were defined to correlate the effects of buoyancy on the overall heat transfer [14,15]. Kurganov et al. [16,17] experimentally related the buoyancy-induced deterioration of heat transfer to the formation of the M-shape velocity profile in a tube.

Following the early works of Jackson and co-workers, other researchers tried to use the same approach, i.e. correlating buoyancy-affected Nusselt number with a buoyancy parameters using experimental data [18–23]. One important issue in the experimental works is how to distinguish the pure effect of buoyancy from other phenomena occurring on account of property variation.

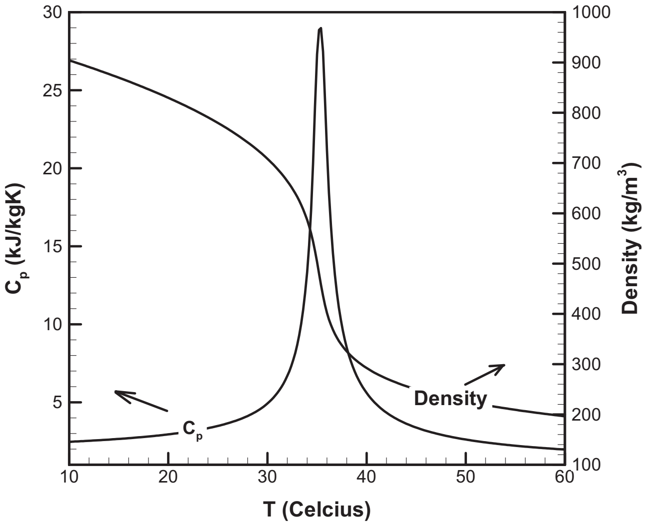

Fig. 1. Variation of specific heat and density for supercritical CO_2 in 8.12 MPa.

Several CFD works have also been published on this topic. Apart from a few DNS studies [24,25], the rest of numerical simulations have used RANS models. It has been shown that, due to complicated behavior of turbulent flow in the near-wall region, conventional eddy viscosity models (e.g. k–ε and k–ω) with standard wall functions are not effective in such problems, especially when large buoyancy forces are present [10,26,27]. Instead, many researchers preferred low-Reynolds number (LRe) k–ε models that solve momentum equation all the way down to the wall rather than overriding the near wall region using wall functions. Mikielevicz et al. [28] performed a thorough study on the capability of different turbulence models to find out which model gives the best results when heat transfer rate is high enough to influence the turbulence intensity. They suggested the Launder and Sharma (LS) LRe k–ε model [29] to be used for those conditions. Dang and Hihara [27] found LRe k–ε model of Jones and Launder (JL) [30] to be the most successful model for supercritical flows; however their study did not account for buoyancy or any other effect that might lead to the heat transfer deterioration. He et al. [31] found LS model 'slightly' better than other models when applied to supercritical flow inside a vertical mini tube where buoyancy effect is not significant. Jiang et al. [32,33] used various turbulence models including LS and LRe k–ε model of Lam and Bremhorst (LB) [34] for supercritical CO_2 flow in narrow vertical tubes for relatively small Reynolds numbers. LB model was also used by Lee [35] for supercritical water in horizontal rectangular ducts under gravity influence. Various LRe models were examined by Du et al. [36] and proven to successfully predict heat transfer of supercritical CO_2 in horizontal tubes with cooled walls. Those authors also argued that severe density variation can enhance heat transfer in horizontal tubes. Numerical studies of Bazargan and Mohseni