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ORIGINAL ARTICLE

Numerical investigation of transport phenomena properties on transient heat transfer in a vertical pipe flow

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Abstract Transient convection heat transfer is of fundamental interest in many industrial and environmental situations, as well as in electronic devices and security of energy systems. Transient fluid flow problems are among the more difficult to analyze and yet are very often encountered in modern day technology. The main objective of this research project is to carry out a theoretical and numerical analysis of transient convective heat transfer in vertical flows, when the thermal field is due to different kinds of variation, in time and space of some boundary conditions, such as wall temperature or wall heat flux. This is achieved by the development of a mathematical model and its resolution by suitable numerical methods, as well as performing various sensitivity analyses. These objectives are achieved through a theoretical investigation of the effects of wall and fluid axial conduction, physical properties and heat capacity of the pipe wall on the transient downward mixed convection in a circular duct experiencing a sudden change in the applied heat flux on the outside surface of a central zone.

1. Introduction

In nature, as well as within the human-made thermal systems, the time variable regimes are more commonly encountered, than the permanent regimes. Therefore transient flow problems are among the more difficult to analyze. Transient free convection heat transfer occurs for example, in nuclear reactors, space systems, environmental situation such as air conditioning systems, and human comfort in buildings. Hence there is a need for a more complete understanding of the phenomena. There is little experimental data available in the literature on the steady state and even less on the transient free convection. Heat transfer by convection is one of the modes that is often used in many industrial applications such as thermal and nuclear power plants or the gear of the buildings, electronic cooling in electronic equipment, cooling and distillation system in chemical processes and ventilation systems. Thus, the knowledge of the response of the systems, subjected to variable thermal and/or dynamical conditions allows to use rationally the energy, through a better system of regulation,

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Nomenclature

D	Tube diameter ($=2R_i$), m
f	Friction coefficient, kg/ms^2
g	Acceleration due to gravity, m/s^2
Gr	Grashof number ($=g\beta QD^4/v^2k_f$)
K	Wall-to-fluid thermal conductivity ratio ($=k_w/k_f$)
P	Dimensionless pressure ($=p + \rho_0 gz)/\rho_0 V^2$
Q_{wi}	Normalized interfacial heat flux ($=Q_i/Q$)
Q_i	Heat flux at the wall-fluid interface, w/m^2
R_i	Internal radius of the pipe, m
R_e	External radius of the pipe, m
$u*$	Dimensionless axial velocity ($=u/V$)
$v*$	Dimensionless radial velocity ($=v/V$)
V	average velocity at the inlet of the duct, m/s

Greek Symbols

τ	Dimensionless time ($=tV/D$)
η	Dimensionless radial coordinate ($=r/D$)
ξ	Dimensionless axial coordinate ($=z/D$)
Δ	Pipe thickness-to-diameter ratio ($=(R_e-R_i)/D$)
θ	Dimensionless temperature ($=(T-T_0)/QD/k_f$)

Subscripts

f	Fluid
w	Wall
w_i	Wall-fluid interface
0	Evaluated at the inlet temperature

Non-dimensional Numbers

Gr	Grashof number ($=g\beta QD^4/v^2k_f$)
Re	Reynolds number, [ρUD/μ]

and to avoid a fall of performance, to see a deterioration of the device, due to the appearance of thermal constraints.

The purpose of this work is to investigate the interaction between a downward flow and the pipe wall thickness subjected to a constant and uniform heat flux, during a transient regime in a vertical tube. The interest of such a process is, to acquire new data on the transient conjugated mixed convection in a vertical tube, as well as, to study the transient dynamic and thermal behavior of the flow in mixed convection in order to master the dimensioning of heat exchangers.

2. Transient heat transfer theory

There exist several types of convection: natural convection (or free convection), forced convection and mixed convection. The convection is said to be natural when it releases heat continuously and spontaneously due to the temperature differences that generate differences in density within the fluid mass. The forced convection is obtained while submitting the fluid to an increase in pressure by mechanical means such as pumps or fans. Finally, when the thermal sources (natural convection) and the mechanical sources (forced convection) coexist, this represents the mixed convection. A few works deal with the transient downward or upward mixed convection in a vertical duct, with or without the effect of axial wall and fluid conductions, while in the steady state these two kinds of mixed convection have received rather particular attention from researchers in the past decades. (Jackson and Cotton, 1989; Penot and Dalbert, 1983; Hanratty and Rosen, 1958) were among the first researchers who published experimental studies concerning the assisted or opposed mixed convection, in a vertical tube. (Carlos and Guidice, 1996) presented a numerical analysis of the effect of the entrance region on mixed convection in horizontal concentric cylinders. (Fusegi, 1996) investigated the combined effect of the oscillatory through-flow and the buoyancy on the heat characteristics of a laminar flow in a periodically grooved channel, while (Cheng and Weng, 1993) studied numerically the mixed convection flow and heat transfer processes in the developing region of a vertical rectangular duct with one heating wall. (Mortan and Bingham, 1989) investigated numerically and experimentally the mixed convection in a vertical circular duct subjected to constant temperature condition. (Wang et al., 1994) have presented a numerical analysis of upward and downward mixed convection in vertical and horizontal circular ducts with reversed flow. They have analyzed the effect of natural convection and fluid axial conduction on the fully developed laminar flow in a vertical channel, subjected to constant wall temperature. (Barletta and Rossi, 2004) have studied the non-axisymmetric forced and free convection in a vertical circular duct. (Bousedra and Soliman, 1999) considered the geometry of semicircular ducts and solved the problem of laminar fully developed mixed convection under buoyancy-assisted and opposed conditions. Their results are presented with a detailed assessment of the effects of inclination, Reynolds number, Grashof number and the thermal boundary conditions. Numerous researchers have also investigated the effects of the axial wall conduction on the steady combined forced and free convection in vertical parallel plates or pipes. (Hegg and Ingham, 1990; laplante and Bernier, 1997) have investigated the effect of opposed mixed convection and wall axial conduction on downward flow. (Nasredine and Galanis, 1998) have studied the effect of the axial wall conduction on the upward mixed convection. (Ouzzane and Galanis, 1999) have analyzed numerically the effects of the axial wall conduction and the non-uniform heat flux condition on the upward mixed convection in an inclined circular duct. They found that the calculated results for local parameters and for average variables are quite different, especially for high values of the Grashof number. In the transient regime, (Mai and El Wakhil, 1999) have studied the problem of upward vertical pipe flow with step change in the inlet temperature and velocity. Their results show a dissymmetry of the velocity profile and temperature between the positive and negative steps change. (Nguyan and Maiga, 2004) have studied the problem of 3D transient laminar mixed convection flow in vertical tube with negligible thickness under buoyancy effect and time dependant wall heat flux condition. Their results have shown that the flow seems to remain stable and unique for high Rashof numbers. (Azzizi et al., 2012) have developed a numerical model for transient heat transfer for gas flow in vertical pipes, while (Shih et al., 2010) present a comprehensive review of recent models covering transient heat