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Experimental and numerical study of mixed convection with flow reversal in coaxial double-duct heat exchangers

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Abstract

Velocity vectors in a vertical coaxial double-duct heat exchanger for parallel ascending flow of water under conditions of laminar mixed convection have been determined experimentally using the particle image velocimetry technique. The measured velocity distributions for large annular flow rates, resulting in an essentially isothermal environment for the stream in the inner tube, are in very good agreement with corresponding numerical predictions. For flow rates of the same order of magnitude in the inner tube and the annulus, and corresponding temperature differences of about 20 °C, experimental observations show that flow reversal occurs simultaneously in both streams over large axial distances for both heating and cooling of the flow in the inner tube.

Keywords: Velocity measurements; Mixed convection; PIV; Heat exchangers

1. Introduction

The double tube heat exchangers with parallel- or counter-flow in a vertical or horizontal position are still very much in use today, notably in the agricultural and food industries (pasteurisation) or in the solar heating of swimming pools. Applications with large temperature differences and small mass flow rates give rise to mixed convection, that is to say flows in which the effect of forced convection and of natural convection due to buoyancy are equally important. Nevertheless, few studies have dealt with the conjugate problem of mixed convection in such a geometry.

On the other hand, a large number of studies have dealt with mixed convection in single ducts with simple thermal conditions at the walls (namely, T or isothermal walls and H or uniform heat flux). Thus, Hallman [1] obtained analytically the fully developed velocity and temperature profiles for laminar flow in a vertical pipe with uniform wall heat flux. A considerable number of numerical studies have been conducted mostly for laminar flow conditions. Significant results have been obtained by Wang et al. [2] and Zghal et al. [3] who described zones of flow reversal while Su and Chung [4] have performed a linear stability analysis of such flows. Analogous studies for a vertical annulus have been carried out by Iannello et al. [5] and Aung et al. [6]. Behzadmehr et al. [7] have established numerically the critical Grashof numbers for transition from laminar to turbulent conditions and relaminarization of fully developed mixed convection in a vertical pipe with uniform wall heat flux. Experimental evidence of the differences between mixed and forced convection flow fields in single pipes has been provided by Mori et al. [8] and Zeldin and Schmidt [9] who used Pitot tubes and thermocouples to measure the fluid's axial velocity and temperature. However, these results are limited to a few cross sections of the pipe and do not provide an overall and continuous picture of the flow field. Furthermore, the presence of sensors within such a flow causes unwanted disturbances which may be of the same order as the buoyancy induced phenomena. This

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Nomenclature

D, D_h	tube, hydraulic diameter (m)
g	acceleration of gravity (m s^{-2})
Gr_t	inner tube Grashof number $= \rho_{to}\beta_{to}D_h^2 (T_{to} - T_{ao})/\mu_{to}$
Gr_a	annulus Grashof number $= \rho_{ao}\beta_{ao}D_h^2 (T_{to} - T_{ao})/\mu_{ao}$
k	thermal conductivity (W/m K)
L	length (m)
r, z	radial, axial coordinates (m)
Re	Reynolds number $= \rho_o V_o D_h/\mu_o$
Ri	Richardson number ($Gr\ Re^{-2}$)
T	temperature (K)
v_r, v_z	radial, axial velocity components (m s^{-1})
V	average axial velocity (m s^{-1})
p	pressure (Pa)

Greek symbols

β	coefficient of thermal expansion (K^{-1})
μ	dynamic viscosity (Pl)
ρ	density (kg m^{-3})

Subscripts

a	annulus
o	inlet
t	tube

problem can be avoided by visualisation techniques such as those used by Lavine et al. [10], Bernier et al. [11] and Benhamou et al. [12] who inject fluorescent particles into the flow before illuminating them with a diffuse light source. The first two of these studies were interested in flow reversal for mixed convection in a vertical tube and the latter studied isothermal flow in an oscillating tube. The visualisation of large parts of the hydrodynamic field for flow in a heated or cooled vertical tube does not appear to have been tackled.

The problem of heat transfer in a double pipe vertical heat exchanger has been treated numerically by the present authors for steady state, simultaneously developing, laminar flow with variable fluid properties using an elliptic model which takes into account conduction in the solid walls as well as dissipation. In a first paper [13] results were calculated for upward parallel flow, fixed inlet conditions, a Richardson number equal to one for the annular space and three different values in the cylinder. The results showed that flow reversal occurs in the warm fluid for $Ri \geqslant 1$ and that neither the T nor the H conditions apply at the cylindrical wall separating the two fluids. In a second paper [14] the effects of flow direction were investigated. It was shown that the fluid velocities as well as he wall and fluid bulk temperatures depend on the flow direction and Richardson number. Furthermore, the fully developed Nusselt number in the inner pipe lies between the corresponding forced convection values for the H and T conditions while the one in the annulus is smaller than both these two forced convection values.

In the present study, the particle image velocimetry (PIV) technique is used to analyse the developing velocity field for laminar mixed convection of water in a vertical double tube heat exchanger. Particular attention is paid to the region where flow reversal is predicted by the previously mentioned model [13,14]. The corresponding numerically predicted and experimentally determined velocity fields are compared for two thermal conditions, namely for heating and cooling of the flow in the inner tube.

2. Description of the problem and the experimental setup

The schematic representation of the heat exchanger under study which consists of two coaxial vertical ducts

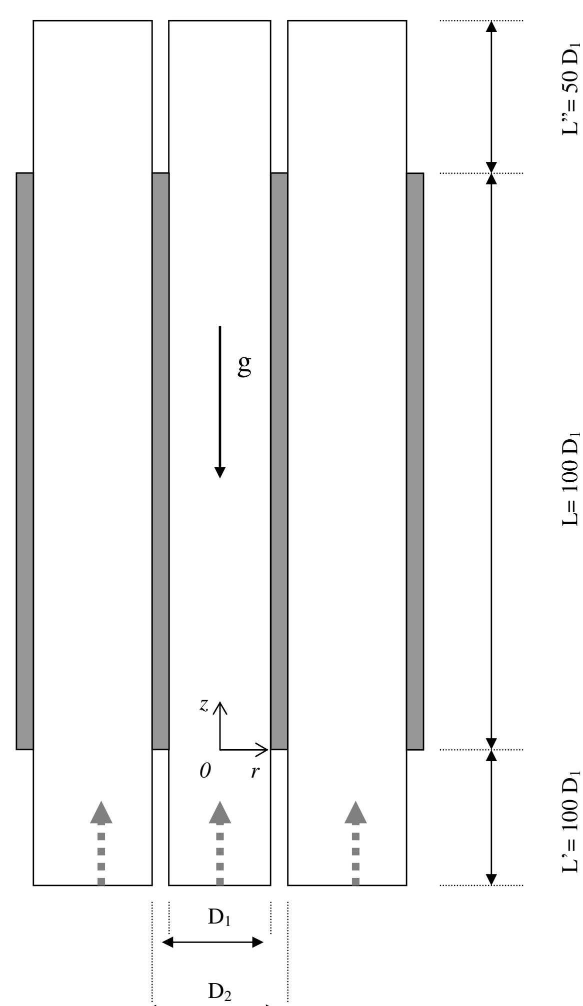

Fig. 1. Schematic representation of the heat exchanger.