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# Numerical and experimental visualization of reverse flow in an inclined isothermal tube

Thierry Maré *, Ionut Voicu, Jacques Miriel

*Laboratoire de Génie Civil et de Génie Mécanique (LGCM), INSA de Rennes, IUT Saint Malo, 35043 Rennes, France*

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**Abstract**

Combined forced and free convection in the entrance region of tubes occurs in many engineering installations such as heat exchangers, nuclear reactors, solar collectors, etc. The secondary flow induced by the buoyancy force and its effects on the hydrodynamic and thermal fields have therefore been investigated both experimentally and numerically. The present study considers the three dimensional developing laminar flow of water with constant viscosity and conductivity in an isothermal pipe inclined of 60° from horizontal. At first, the elliptical partial differential equations modelling mixed convection, have been numerically solved using a control volume based finite difference solver for $Re = 90$, $Pr = 7$ and $Gr = 3.3 \times 10^5$. The axial evolution of the velocity and fluid temperature profiles has shown that the upstream diffusion has an important effect near the inlet of the heating region. The shape and size of the region with negative velocities are detailed. Secondly, an experimental set up is described. The techniques used are based on PIV technology employing micrometer Nylon particles placed in a laser light-sheet and results are recorded by using a CDD camera. Analysed pictures have confirmed the existence of the reverse flow region in accordance with numerical results as obtained for an inclination of 60°.


*Keywords:* Laminar flow; Aiding buoyancy; Reverse flow; Upstream diffusion; Numerical and experimental study; Elliptical formulation; PIV technique

## 1. Introduction

Thermal transfer is present in many engineering installations and especially in heat exchangers and nuclear reactors where combined forced and free convection exists.

A large amount of numerical studies have considered isothermal as well as heated tubes in mixed convection. Hallman [1], Jackson et al. [2] and Wang et al. [3] have obtained significant results in the case of horizontal or vertical tubes. Zghal et al. [4] identified the regimes of reverse flow for a vertical pipe with uniform heat flux at the fluid–solid interface, and Su and Chung [5] found that mixed convection flow in a vertical pipe with constant heat flux can become unstable. However, the effects of the tube's inclination on the velocity and temperature distributions were only studied by Orfi et al. [6,7] who have shown the existence of multiple solutions for different combinations of $Pr$, $Re$, $Gr$ and tube inclination, but as they used parabolic resolution and were, consequently, unable to predict reverse flow.

Experimental studies, considered as reference studies [8,9] describe flow in a uniformly heated tube. The results have been obtained for temperatures and axial

* Corresponding author. Address: IUT, Saint Malo, la croix Désilles, 35400 Saint Malo, France. Tel.: +33 02 99 21 9505; fax: +33 02 99 21 9541.
*E-mail address:* thierry.mare@univ-rennes1.fr (T. Maré).

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**Nomenclature**

| | |
|---|---|
| $a$ | thermal diffusivity ($m^2 s^{-1}$) |
| $V$ | velocity ($m\ s^{-1}$) |
| $g$ | acceleration of gravity ($m\ s^{-2}$) |
| $k$ | thermal conductivity ($W\ m^{-1} K^{-1}$) |
| $L1$ | length of adiabatic region (m) |
| $L2$ | length of isothermal region (m) |
| $P$ | pressure (Pa) |
| $q$ | heat flux ($W\ m^{-2}$) |
| $R$ | radial coordinate |
| $T$ | temperature (K) |
| $D$ | tube diameter (m) |
| $Z$ | axial coordinate (m) |
| $z = Z/D$ | adimensional length |
| $Gr = \frac{g\beta\rho^2 D^3 (T - T_w)}{\mu^2}$ | Grashof number |
| $Pr = \frac{\mu Cp}{k}$ | Prandtl number |
| $Re = \frac{\rho V D}{\mu}$ | Reynolds number |

*Greek letters*

| | |
|---|---|
| $\beta$ | thermal expansion coefficient ($K^{-1}$) |
| $\mu$ | viscosity ($N\ s\ m^{-2}$) |
| $\alpha$ | tube inclination |
| $\rho$ | density ($kg\ m^{-3}$) |
| $\Phi$ | circumferential coordinate |

*Indices*

| | |
|---|---|
| o | inlet conditions |
| $x$, $y$ | Cartesian coordinates (m) |
| $R$, $Z$, $\Phi$ | radial, axial, circumferential |
| w | wall value |

velocity measurements in different points in several planes. The method has given some interesting results but did not allow a global and continuous vision of the flow structure. Moreover, for the case of low flow, the presence of sensors can produce some disturbances within the flow itself.

An other flow visualization technique is based on fluorescent particles seeding in the fluid that is then lighted up with a diffuse light source. Using such technique, Lavine et al. [10] and Bernier and Baliga [11] have studied flow reversal in the case of opposing mixed convection flow in vertical pipes and most recently, Benhamou et al. [12] have visualized the flow structure in oscillating pipes.

The purpose of this paper is to study the axial velocity distribution in an isothermal tube, both numerically and experimentally. We are particularly interested to establish the existence of the reverse flow. Results as obtained for a particular case with a Reynolds number of 90, a Grashof number of $0.33 \times 10^6$, a Prandtl number of 7 and a tube inclination of 60° are presented and discussed.

## 2. Numerical study

### 2.1. Mathematical formulation and numerical scheme

We are interested in developing flow for a liquid in an isothermal tube with an inclination of 60° with respect to the horizontal plane. The fluid enters the tube with a parabolic velocity profile and a uniform temperature. The flow is directed upwards and the wall temperature is higher than the fluid entry temperature. The schematic representation of the system studied is presented in Fig. 1. The theoretical study is based on the following hypotheses:

- The tube has cylindrical shape with an inside diameter $D$ and is long enough so the flow is fully developed at the exit section of the tube.
- The heated part of the tube is preceded by an adiabatic zone of length $L1 = 10D$ in order to predict axial diffusion.
- Isothermal length $L2$ is $72D$.
- The fluid is considered Newtonian and incompressible with constant physical properties except for the density in the buoyancy terms where the Boussinesq's assumption is applied

$$\rho = \rho_o[1 - \beta(T - T_o)] \quad (1)$$

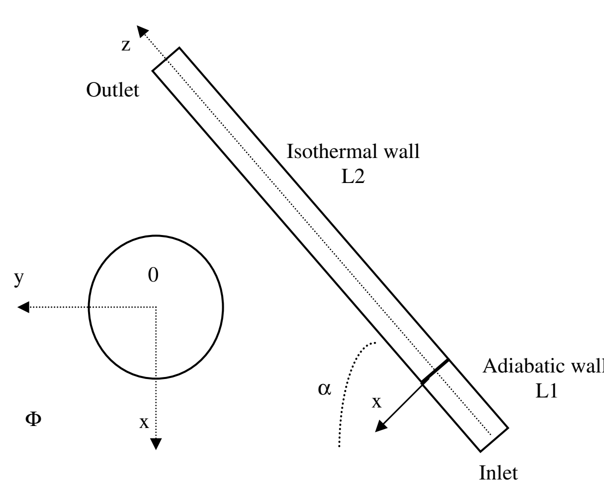


Fig. 1. Schematic representation of system under study.