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Early-stage dynamics in the onset of free-convective reversal flow in an open-ended channel asymmetrically heated

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ABSTRACT

An experimental study from PIV in an open-ended vertical channel is carried out in order to describe the fluid dynamics during the early stage regime of free convection inside a vertical channel asymmetrically heated at 445 W/m^2 and 1550 W/m^2 uniform heat fluxes. The analysis allowed to detect a complex topological behavior in the internal flow leading to numerous instabilities whose topological features are described. Vortex formation and shedding, vortex splitting, separation and beating of the boundary layer from one wall to another are identified, leading to an imbalance in the outlet pressure field which is certainly at the origin of a large-scale reversal flow.

1. Introduction

This experimental work is part of a series of studies conducted by the French Research Group GDR AMETh (*Analyse – Maîtrise des écoulements et Echanges Thermiques*) on natural convection in open-ended channels. The main objective of these studies is to allow a better prediction of the thermal and dynamic behavior of free-convective flows in open-ended channels by developing reliable numerical simulation tools [1]. The validation step of these tools requires the establishment of experimental setups for providing the necessary thermal and dynamic data [2]. The present work aims at providing such data by experimentally investigating the flow dynamics in a vertical channel heated asymmetrically.

The heated vertical open-ended channel is representative of several problems of practical interest such as the chimney, the solar panel or the Trombe wall [3–5]. Natural convection in open-ended vertical channels has been widely studied, both experimentally and numerically, since the pioneering work of Elenbaas [6]. For many years, experimental studies carried out on natural convection in vertical open-ended channels were mainly concerned with thermal measurements (flow and wall temperature) both for uniform heat flux (UHF) and for uniform wall temperature (UWT) problems [5–9]. The natural convection flow dynamics in parallel-plate channels has also been investigated by means of flow visualization techniques [2,7,10], Laser Doppler Velocimetry [10–15] and more recently by Particle Image Velocimetry [16]. Sparrow et al. [17] performed flow visualizations in an asymmetrically heated water channel. They observed a flow reversal close to the unheated wall. Ospir et al. [2] investigated the influence of the channel aspect ratio and the Rayleigh number on the flow structure, also in the case of asymmetric heating. A recent work by Dupont et al. [10] has focused the need to generalize the conditions of existence of the reverse flow by quantifying its global characteristics and extend the range of tested parameters, namely the Rayleigh number and the aspect ratio.

In parallel, several numerical studies have been carried out [1,18,19] in an attempt to predict the heat transfer and flow field characteristics in open channels. However, despite these efforts, the prediction remains an open problem. At the level of knowledge and current thinking, it seems clear that numerical simulations of free convection in open domain require further developments before being usable for design. This can only be possible by the contribution of new experiments necessary to understand physical phenomena that drive the flow behavior, to generate reference measurements, to validate numerical simulations in order to find out reliable ways to enhance heat transfer.

This is why we chose to focus the study presented in this paper only on the very first moments of the implementation of this channel flow, with the assumption that the flow reversal phenomena, poorly understood to date, find their explanation in the

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Nomenclature

Symbols

A	heated length, m
b	channel wall spacing, m
g	acceleration of gravity, m/s^2
Gr	Grashof number based on wall heat flux and channel wall spacing $(=g\beta\phi_w b^4/k\nu^2)$
k	thermal conductivity, W/m.K
L	recirculation length, m
Pr	Prandtl number
Ra	Rayleigh number based on heat flux and channel wall spacing $(=Gr.Pr)$
Ra^*	$(=Ra/R_f)$ modified Rayleigh number
R_f	aspect ratio $(=b/A)$
t	time, s
v	vertical velocity component, m/s
x	horizontal coordinate, m
y	vertical coordinate, m

Greek letters

β	volume expansion coefficient, 1/K
ρ	density, kg/m^3
ν	kinematic viscosity, m^2/s
φ	heat flux, W/m^2

Indices/exponents

f	fluid
p	particle
w	wall
∞	ambient

history of their appearance. To the authors' knowledge, it is the first time that such a study focuses on the early stages in the development of reversal flows in open-ended channels.

2. Experimental facilities

2.1. The channel geometry

Experimental investigations of the dynamics of the natural convection flow have been carried out in a vertical plane channel (height 376 mm; width 36 mm; depth 300 mm) heated asymmetrically [2]. The channel is located in a vertical tank filled with water the dimensions of which are presented in Fig. 1a. The choice of water as working fluid leads to a negligible effect of heat transfer by radiation to only consider free convection effects. The channel shown in Fig. 1b is composed of two vertical parallel plane walls separated by an adjustable distance (b). In the present study, the width b was fixed to 36 mm. One wall is composed of a heated central part (height A = 188 mm) and two unheated extensions (height $A/2$) respectively located at the bottom and top open-ends of the channel while the opposite wall remains entirely unheated throughout the duration of the experiments. The heating of the central half part of the heated wall is provided by a fabric heater which delivers a heat flux uniformly distributed throughout the heating zone. This thermal system consists of a vertical plane thermofoil heater, covered by a 3 mm-thick aluminum plate on the channel side, delivering an adjustable heat flux φ_w to water in the channel. It should be noticed that the channel is laterally bounded with two transparent PMMA vertical plates (10 mm thick) not represented in Fig. 1a,b in order to not overload the schemes. Experiments were performed in the plane of symmetry of the channel along its entire height.

To ensure an adiabatic behavior of the right cold wall [2], the temperature field in the 10 mm-thick PMMA cold plate has been

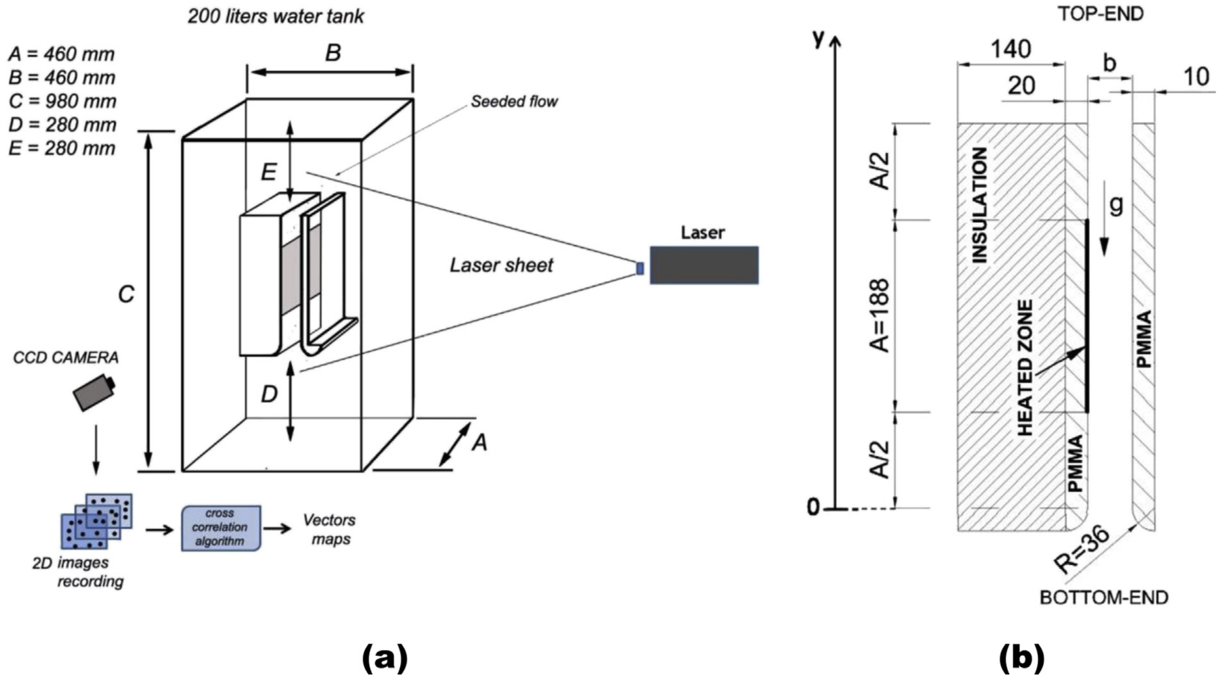

Fig. 1. (a) Experimental set-up. (b) Edge view of the vertical open channel. (Lateral bounded plates not represented).