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Investigation of free convection in a vertical water channel

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ABSTRACT

Natural convection in an asymmetrically heated, vertical channel was studied both experimentally and computationally. The experiments were performed in water for an aspect ratio of the vertical channel (ratio between spacing and height) equal to 0.1. The schlieren technique was used to obtain the local heat transfer coefficient; this work seemingly represents the first attempt to apply this optical method to measure the local heat transfer coefficient using water as convective fluid. Numerical simulations demonstrated that thermal and fluid flow fields can be regarded as two-dimensional inside the channel and that the heated wall of the channel is practically isothermal. The good agreement between experimental and numerical distributions of the heat transfer coefficient encourages the use of the schlieren technique for the study of free-convection heat transfer in water flows.

1. Introduction

Natural convection in open-ended vertical channels is encountered in many practical applications and has been extensively investigated in the past by many authors (e.g., [1–5]). Literature papers, however, are typically restricted to natural convection with air as convective fluid while experiments performed in water are relatively rare. Sparrow and co-workers [6–8] investigated the natural convection heat transfer in water vertical channels with one or two walls heated, taking into account the effects of the channel aspect ratio and channel inclination. A standard heating-foils/thermocouples technique was used to deduce the average heat transfer coefficient from the readings of the electrical power dissipated and the thermocouple array deployed into the wall material and in the fluid. More recent investigations of the water free convection in vertical channels are presented in [9,10] for asymmetric and symmetric heating conditions, respectively; again, heat transfer characteristics were provided on an average basis.

This paper presents measurements of the local heat transfer coefficient along the heated wall of a vertical channel using water as working fluid. The channel is formed by an electrically heated plate bounded by two unheated walls to form two identical, one-side heated, vertical channels open at the top and bottom to permit the natural circulation of the convective fluid (water). A schlieren technique has been employed to reconstruct the distribution of the heat transfer coefficient. This optical technique has been extensively used for the measurement of heat transfer coefficients in air (e.g., [11–14]), whereas its use in water was restricted in the past to qualitative observations like flow visualization (see, e.g., [15]).

2. The experiment

2.1. The test section

The schematic view of the test section utilized in the experiments is shown in Fig. 1a. It basically consisted in two adjacent, identical, asymmetrically heated, vertical channels placed inside a tank filled with water. The heated wall of the channels was made of two thin sheets of chrome-plated copper with an electric foil heater sandwiched between them. The two copper sheets were sealed with a waterproof cement to prevent any contact between the heater and the fluid. When electrical power was delivered to the resistance, owing to the high thermal conductivity of copper, the heated plate attained a uniform surface temperature at steady state. The dimensions of the heated plate were the following: height $H = 87$ mm, length $L = 48$ mm, overall thickness $t = 8$ mm. The heated plate was bounded by two 5 mm-thick shrouding walls, smooth and unheated, made of bakelite.

The spacing S between each unheated wall and the heated plate, set equal on both sides, was 8.7 mm, thus corresponding to a channel aspect ratio S/H equal to 0.1. The symmetrical arrangement of the heated plate/shrouding walls assembly allows the optical measurements to be repeated on both sides and, owing to the symmetry, averaged at the same elevation, thus reducing the experimental error. The heated plate/shrouding walls assembly

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Nomenclature

f_2	focal length of the schlieren head (m)
H	channel height (m)
h	local convective heat transfer coefficient (W/m^2 K)
k	fluid thermal conductivity (W/m K)
L	plate length (m)
n	refractive index of water
n_{air}	refractive index of ambient air
n_0	refractive index of water at a standard condition
S	channel spacing (m)
T	temperature (°C) or (K)
t	heated plate thickness (m)
x, y, z	spatial Cartesian coordinates (m)

Greek symbols

α, α'	light ray angular deflection (rad)
Δ	light ray displacement (m)

Subscripts

f	refers to (inlet) fluid conditions
w	refers to conditions at the wall
y	refers to the y direction

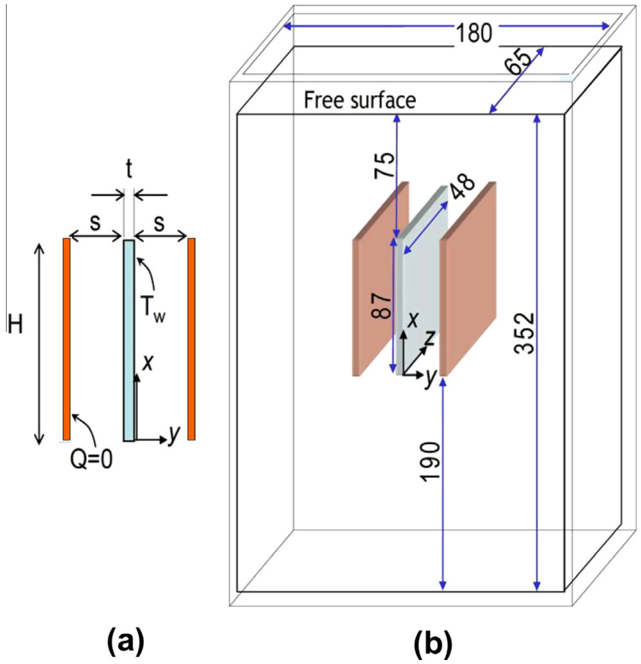

Fig. 1. Schematic drawing of (a) the test section (frontal view) and of (b) the water tank (3D view). Dimensions, in (mm), not to scale.

was suspended, by using a supporting frame and thin nylon wires, inside a chamber with inner dimensions 180 × 65 × 390 mm (width × length × height). The water chamber and the coordinate system adopted for the vertical channels are schematically reported in Fig. 1b. The chamber was filled with distilled water up to a 352 mm level from the tank inner floor and was open at the top side to provide ambient pressure conditions at the water/air interface. The exit of the channels was situated 75 mm below the water surface and the entrance at 190 mm above the tank inner floor. The vertical sides of the chamber normal to the light beam were made of 6 mm-thick, high quality glasses so as to permit the schlieren measurements. The remaining sides and the bottom of the tank were made of 10 mm-thick chrome-plated copper, finned on the ambient air side to facilitate the dissipation of the input power to the laboratory ambient air.

The heated plate and the water tank were instrumented with 0.5-mm-dia sheathed thermocouples, calibrated to ±0.05 K. Six thermocouples were embedded in the wall of the heated plate at different locations through 0.5-mm-dia holes drilled into the material as close to the exposed surfaces as possible. The wall temperature T_w was obtained by averaging the readings of the six thermocouples deployed in the plate material. The fluid temperature T_f was measured by a thermocouple located at the inlet section of one of the two identical channels; an additional thermocouple, able to travel vertically within the tank and outside the channels, was used to check the presence of undesirable water temperature stratification.

2.2. The optical arrangement

A Z-type schlieren arrangement, schematically shown in Fig. 2, was used for the visualization of thermal field and to infer the local heat transfer coefficient at the heated wall/fluid interface. The optical principles are here briefly summarized. A non-coherent light beam from a vertical slit source, collimated by the concave mirror M$_1$, passes through the test section. Here, the heated plate and the two unheated vertical walls are deployed with the length L aligned to the travelling light beam (i.e. along the z-coordinate of Figs. 1b and 2). A second concave mirror M$_2$, is then used to project a real image of the slit source in the focal plane and a real image of the test section onto a screen or camera.

The occurrence of thermal gradients in the test section leads to inhomogeneities of the water refractive index; as a consequence the light rays undergo angular deflections. Fig. 2 shows a light ray deflected, within the test section, by an angle α_y, whose extent is related to thermal gradients, along the y direction, in the water. As the light ray emerges into the surrounding air, the deflection angle is modified, according to Snell's law, and it becomes $\alpha'_y = \alpha_y(n_0/n_{air})$, where n_0 (=1.335) and n_{air} (=1.0003) are the refractive indices of water and air at ambient conditions (18–26 °C, atmospheric pressure), respectively.

Regions of the optical field characterized by the same light deflection in the y–z plane can be identified by shifting an opaque vertical filament in the focal plane of mirror M$_2$, as shown in Fig. 3 (focal filament method). When a deflected light ray is stopped by the focal filament, the image of the corresponding region of fluid will appear dark on the screen, while the remaining field will be bright. A typical example of a photograph taken by the schlieren apparatus using the focal filament method is reported in Fig. 4. The amount of the angular deflection of a disturbed ray can be deduced by measuring, in the focal plane of mirror M$_2$, the distance Δ_y between the middle of the undisturbed image of the slit source and the centerline of the filament, i.e. the distance Δ_y between filament positions 1 and 2 displayed in Fig. 3. This distance corresponds to the displacement impressed to the filament, directly measured by a micrometer, and it is related to the local angular deflection α'_y by the simple formula $\Delta_y = f_2\alpha'_y$ where f_2 is the focal length of the mirror M$_2$ (also called the *schlieren head*). It is worth noting that Δ_y represents the light ray displacement, in the focal

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