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Experiments on natural convection in water-cooled ribbed channels with different aspect ratios

Giovanni Tanda

DIME, Università degli Studi di Genova, via Montallegro 1, 16145 Genova, Italy

A R T I C L E I N F O

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Natural convection heat transfer in vertical ribbed channels, using water as working fluid, has been experimentally studied. The investigation encompassed a large range of the channel aspect ratio, defined as the ratio between channel spacing and channel height, while the wall-to-fluid temperature difference was kept fixed. The measurement of local heat transfer coefficient was facilitated by a non-intrusive diagnostic tool, the schlieren technique, whose use for the quantitative study of liquid flows is rarely documented in the literature. Results provided an insight into the nature of free convection heat transfer from ribbed channels, whose geometry is significant in such several engineering devices as electronic equipment. It was found that a general reduction of heat transfer performance, relative to that of a flat vertical surface or a smooth vertical channel, was induced by the presence of ribs, within the range of the parameters investigated. Local and heat transfer characteristics were sensitive to changes in interplate spacing for small channel aspect ratios. Experimental data, recast in dimensionless form, were in excellent agreement with those obtained by this author in a previous research performed for air-cooled channels, using the same experimental technique, the same geometric parameters of the ribbed surface, and a similar Rayleigh number.

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1. Introduction

Natural convective flows in vertical ribbed channels are encountered in many engineering applications such as electronic circuit board cooling, solar collectors, building heat transfer, and nuclear reactor safety. Existing literature for both experimental and numerical investigations of this phenomenon deals mostly with the use of air as convective fluid [1–7]. Even though air cooling is well understood, it is limited in the heat removal rate by the relatively low heat transfer coefficient. Within the framework of electronic equipment cooling, the direct immersion of electronic components into liquids (for instance dielectric fluids) provides significantly higher heat transfer coefficients than air cooling [8]. Liquid immersion cooling of packed electronics has been extensively studied since the 90s (see, for instance, Refs. [9–11]) mainly with computational tools, while literature is relatively scarce on experimental heat transfer in complex geometries with a liquid as coolant.

Park and Bergles [12] were among the first to experimentally investigate the natural convection heat transfer characteristics of discrete heaters mounted on a vertical plate under liquid (water and Freon R-113) cooling conditions; their study highlighted the effects on heat transfer of the discrete heater size (width and height) and of the location of multiple heaters (staggered or inline). Joshi et al. [13] reported flow visualization and temperature measurements in water of steady and transient natural convection from an unheated vertical surface with eight heated protrusions. Experiments showed that the vertical sides of each protrusion are typically more efficient than horizontal surfaces and that thermal efficiency is highest for the lowest component and decreases for the components located at increasing heights. More recently, Abidi-Saad et al. [14] have experimentally studied the fluid dynamics and heat transfer for the transient water free convection in a vertical channel, asymmetrically heated at uniform heat flux, with a couple of adiabatic ribs symmetrically located on each wall. Ribs were installed at three different elevations in the channel. Only the top location of ribs was found to provide a significant heat transfer enhancement, with respect to the smooth wall, at moderate Rayleigh numbers.

Aforementioned studies considered either heat dissipating components mounted on an adiabatic substrate or smooth, vertical, heated surfaces with adiabatic ribs. The present experiment considers the heating of both the rib and the substrate surfaces. In particular, the main objective of this work is to present local and average heat transfer characteristics of vertical channels

E-mail address: giovanni.tanda@unige.it

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Nomenclature

e	square rib height (m)
f_2	focal length of the schlieren head (m)
g	acceleration of gravity (m s^{-2})
h	local convective heat transfer coefficient (W m^{-2} K^{-1})
$\bar{h}$	average convective heat transfer coefficient (W m^{-2} K^{-1})
H	channel height (m)
k	fluid thermal conductivity (W m^{-1} K^{-1})
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
Nu	Nusselt number, Eq. (3) or Eq. (7)
Nu_{ch}	channel Nusselt number, Eq. (8)
P	rib pitch (m)
Pr	Prandtl number
Ra	Rayleigh number, Eq. (4) or Eq. (5)
Ra_{ch}	channel Rayleigh number, Eq. (6)
S	interplate spacing (m)
t	heated plate thickness (m)
T	temperature (°C, K)
x, y, z	spatial Cartesian coordinates (m)

Greek symbols

α, α'	light ray angular deflection (rad)
β	thermal expansion coefficient of the fluid (K^{-1})
Δ	light ray displacement (m)
ν	fluid kinematic viscosity (m^2 s^{-1})

Subscripts

f	refers to (inlet) fluid conditions
H	based on H as characteristic length
w	refers to conditions at the wall
x	based on x as characteristic length
y	refers to the y direction

formed by one heated rib-roughened surface and one unheated smooth surface, for a buoyancy-induced water flow. The schlieren optical technique was employed to provide a non-intrusive analysis of local heat transfer characteristics. While use of schlieren method was typically devoted in the past to the study of gaseous media, its potential for studying the heat transfer processes in liquids has not been adequately exploited, except for the very recent papers by Tanda et al. [15] and Jain et al. [16], where natural convection heat transfer from heated, smooth vertical walls was experimentally investigated for water and water with nanofluids, respectively. Water was chosen because the refractive index and its dependence on the thermodynamic properties are available in the literature, but in principle the diagnostic tool here employed can be adapted to any transparent liquid coolant, provided its optical properties are known or measured. Experimental results have been compared with literature relationships and experimental data obtained in air by the same technique and under similar conditions in terms of dimensionless groups.

2. The experiments

2.1. The test section

The test section used in the present research is schematically shown in Fig. 1. The thermally active component of the apparatus was a vertical plate (the *heated plate*) made of two thin sheets of chrome-plated copper with a 0.5-mm-thick electric foil heater sandwiched between them. The two copper sheets were sealed with a water-resistant cement to prevent any contact between the heater and the water. The dimensions of the heated plate were the following: height H = 87 mm, length L = 48 mm, overall thickness t = 8 mm. Each side of the heated plate exposed to the water flow was roughened with five transverse, square-cross-sectioned ribs, made integral with the baseplate to guarantee the absence of contact resistance. The square ribs had a height e of 2.42 mm and were regularly spaced at intervals of P = 17.4 mm, resulting in a rib pitch-to-height ratio P/e = 7.2. Two parallel vertical walls, smooth and unheated, formed with the heated plate two adjacent, identical, and asymmetrically heated, channels. The spacing S between each unheated wall and the heated plate, set equal on both sides, was varied from 4.35 to 34.8 mm, corresponding to a channel aspect ratio S/H ranging from 0.05 to 0.4 and to a blockage ratio e/S ranging from 0.556 to 0.0695.

Additional experiments were performed without the presence of the unheated walls, in order to reproduce the condition of an unconstrained ribbed surface ($S/H \approx \infty$). The symmetrical arrangement of the heated plate/shrouding wall assembly permitted the optical measurements to be performed on both sides and, owing to the symmetry, averaged at the same elevation, thus reducing the experimental error.

The heated and unheated walls were suspended, by using a supporting frame, inside a tank with inner dimensions 180 × 65 × 390 mm (width × length × height) filled with distilled water. The vertical sides of the tank normal to the light beam were made of 6-mm-thick, high quality glasses so as to permit the optical access to the test section. The remaining sides and the bottom of the tank were made of 10 mm-thick chrome-plated copper and finned on the ambient air side to facilitate the dissipation of the input power to the laboratory ambient air and to reduce, as much as possible, the thermal stratification in the fluid.

The heated plate and the water tank were instrumented with 0.5-mm-dia sheathed thermocouples, calibrated to ±0.05 K. Six thermocouples were brought into the heated plate from its sides through small diameter, blind holes, as shown in Fig. 1. These holes were drilled into the material for a depth (in the z direction) of about 12 mm (1/4 of the plate length L) in order to accommodate the thermocouple junctions sufficiently far from the plate sides. Thermocouples were placed in these holes and fixed in place using a waterproof adhesive. The location of thermocouples in the heated plate is illustrated in Fig. 1. Five thermocouples were aligned, at different elevation, along one of the two copper sheets forming the heated plate; a sixth thermocouple was located at midheight of the other copper sheet and brought in from the opposite side (the hole lodging this thermocouple is not visible in the photograph). Once electric power had been delivered to the heater, a uniform wall temperature boundary condition was expected, at the steady state, due to the high thermal conductivity of copper. This expectation was confirmed by the thermocouple measurements, since maximum differences among the thermocouple readings were within 0.15 K (i.e., within 10% of the mean imposed wall-to-fluid temperature difference). Even though the temperature close to the rib surface was not directly measured, the application of the conventional one-dimensional fin model for each rib led to

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