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Parabolic flight results of electrohydrodynamic heat transfer enhancement in a square duct

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ABSTRACT

In the present work, we investigate the effect of the electrical and gravitational force fields on weakly forced convection (Reynolds numbers range from 500 to 5600) in a square duct heated from the bottom side. On the top side, we placed an array of sharp point electrodes. Microgravity conditions were obtained during a parabolic flight campaign. At the application of a sufficiently-high DC electric field, a plume-like motion is induced in the fluid by the mechanism of ion injection and heat transfer is dramatically augmented. The working fluid is the dielectric liquid HFE-7100. Local temperatures on the heated wall were measured by liquid crystal thermography and by electrical resistance thermometers. By means of the temperature field, we were able to characterize the behaviour of the ionic jets and their interaction with the crossflow. We also investigated the effects of the Reynolds number, the gravity level, and the major electrical parameters on the average heat transfer coefficients. When no electric field is applied, heat transfer coefficients are influenced by the gravity level, particularly at the low flow rates. On the other hand, in the electrohydrodynamic regimes, heat transfer rates are not only enhanced, but also no longer gravity-dependent, showing that the resulting convection is dominated by the electric field intensity, conveniently controllable by the applied high voltage. Relatively small pressure drop increases caused by the induced flow were also measured. Profitable implementation of electrohydrodynamics in the design of compact heat exchangers and heat sinks such as cold plates is foreseen; possible benefits are pumping power reduction, size and weight reduction, and heat exchange capability augmentation.

1. Introduction

This work represents the final element of a wider research program carried out at the LOTHAR laboratory of the University of Pisa and supported by the European Space Agency (ESA), aimed at investigating the electrohydrodynamic (EHD) phenomenon and its effects on heat transfer, both on ground and in microgravity conditions. Past experimental campaigns conducted on ground have shown that, at the application of a sufficiently-high DC electric field, heat transfer coefficients are drastically augmented [1–4]. As it will be described in the next section, the major physical phenomenon acting into the fluid, responsible for the mentioned increase of the heat transfer rate, is ion injection. Profitable application of the EHD-technique in the design of compact heat sinks for thermal control in space is also described in Ref. [5]. Given the significant effects of the EHD-phenomenon on the heat transfer rate, even at low flow rates ($Re = 500$) and high heat fluxes, when favourable conditions for the onset of mixed convection are present (Richardson number $Ri = 0.16$), as confirmed by the flow regime map in Ref. [6], it is useful to investigate the influence of gravity level and, consequently, the combined effects of the buoyancy forces and the EHD-mechanism. For this reason, an experimental campaign was carried out, in order to verify if the enhanced heat transfer rate is preserved also in mixed convection regimes and in microgravity conditions, which were obtained during an ESA parabolic flight campaign. An array of electrohydrodynamic jets is used to improve forced convection heat transfer of a dielectric liquid, in a square duct heated from the bottom side. Weakly forced convection regimes were investigated: $500 < Re < 5600$. Local temperatures on the heated wall were measured both by thermochromics liquid crystals (TLCs) and electrical resistance thermometers (RTDs). The former ones provide a complete map of the temperature field, useful to investigate the interaction between neighbouring ionic jets at different levels of crossflow intensity and provide experimental data to characterize the heat transfer coefficients relative to each jet of the array. The effects of the Reynolds

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Nomenclature

c	fluid specific heat $[J \cdot kg^{-1} \cdot K^{-1}]$
D_h	hydraulic diameter $[m]$
D_j	jet diameter $[m]$
$\mathbf{E}$	electric field vector $[V \cdot m^{-1}]$
Ec^*	modified Eckert number
f	Darcy-Weisbach friction factor
g'	gravity level (ratio between the actual value of the vertical acceleration and the gravity level on ground)
Q_v	volume flow rate $[m^3 \cdot s^{-1}]$
Gr	Grashof number
Gr_h	Grashof number based on the wall heat flux
Gr_ε	dielectrophoretic Grashof number
Gr_σ	electrophoretic Grashof number
h	inter-electrode spacing (point-to-plane distance) $[m]$
HV	applied voltage [V]
I	electrical current [A]
I_{HV}	electrical current passing through the fluid [A]
L	heated strip length $[m]$
L_h	hydrodynamic entry length $[m]$
L_{th}	thermal entry length $[m]$
l	heated strip width $[m]$
Nu	local Nusselt number
Nu_0	Nusselt number for $Ec^* = 0$
$<Nu>_s$	spatial-averaged Nusselt number
$<Nu>_{s,t}$	time and spatial-averaged Nusselt number
p	pitch (distance between two consecutive emitters) $[m]$
Pr	Prandtl number
r^*	radius of curvature of the emitting electrode $[m]$
L_c	characteristic length $[m]$
Ri	Richardson number
Ri_h	Richardson number based on the wall heat flux
Re	Reynolds number
Re_{cr}	critical Reynolds number
s	heated strip thickness $[m]$
S	square duct side $[m]$
t	time $[s]$
T	fluid temperature [K, °C]
u	mean fluid velocity $[m \cdot s^{-1}]$
u_0	inlet fluid velocity $[m \cdot s^{-1}]$
$\boldsymbol{u}$	velocity vector $[m \cdot s^{-1}]$
ω	vorticity vector $[s^{-1}]$
x	longitudinal distance from the test section inlet $[m]$

Greek letters

α	convective heat transfer coefficient $[W \cdot m^{-2} \cdot K^{-1}]$
β	fluid thermal expansion coefficient $[K^{-1}]$
β_ε	temperature coefficient of electrical permittivity $[K^{-1}]$
β_σ	temperature coefficient of electrical conductivity $[K^{-1}]$
ε	electrical permittivity $[F \cdot m^{-1}]$
λ	fluid thermal conductivity $[W \cdot m^{-1} \cdot K^{-1}]$
μ	dynamic viscosity $[Pa \cdot s]$
ν	kinematic viscosity $[m^2 \cdot s]$
Π_h	wall heat flow $[W]$
Π_e	electrically-generated heat within the fluid $[W]$
ρ	fluid mass density $[kg \cdot m^{-3}]$
ρ_e	space-charge density $[C \cdot m^{-3}]$
τ	time constant $[s]$
τ_v	time at which the fluid exits the hydrodynamic entry length $[s]$
τ_{th}	time at which the fluid exits the thermal entry length $[s]$
T	characteristic transient time $[s]$
Ω	ionic mobility $[m^2 \cdot V^{-1} \cdot s^{-1}]$

Hebrew symbols

$\aleph$	ratio between free-charge densities generated by thermal gradients and by ion injection

Subscripts

A	axial position of the first electrical resistance thermometer along the duct
B	axial position of the second electrical resistance thermometer along the duct
C	axial position of the third electrical resistance thermometer along the duct
in	inlet
inj	due to ion injection
out	outlet
th	thermal
w	wall
x,y,z	Cartesian coordinate

Superscripts

t	turbulent
*	denotes the scaling factor of the physical quantity at which it is applied

number, heat input from the impingement surface (Π_h), electrical current transiting through the fluid (I_{HV}) and applied DC voltage (HV) were also investigated.

2. EHD effects

Various hypotheses concerning the nature of the phenomena involved in heat transfer under electric fields have been formulated, including the increase of molecular heat conduction (i.e., λ). However, studies of dielectric fluids subject to a wide range of electric field strengths have left no doubt that heat transfer enhancement is due to fluid destabilization and subsequent transition to convective motion [7]. The most relevant processes capable of generating convection in a single-phase fluid under a strong DC electric field, due to the different space-charge generation mechanisms into the fluid, can be summarized as follows: electro-thermal convection, field-enhanced dissociation, and ion injection [8]. Electrohydrodynamic effects associated with the temperature field are referred to as electro-thermal convection. As we can see from the vorticity transport equation reported below (Eq. (1)), thermal gradients generate vorticity both through dielectrophoresis, due to the dependence on temperature of the fluid electrical permittivity, and through electrophoresis, being the space-charge density temperature-dependent, too.

$$\frac{\partial\omega}{\partial t} + \boldsymbol{u} \cdot \nabla\omega = \omega \cdot \nabla\boldsymbol{u} + \nu\nabla^2\omega + \left(\beta\boldsymbol{g} + \frac{\beta_\varepsilon \varepsilon \nabla \boldsymbol{E}^2}{2\rho}\right) \times \nabla T + \frac{\nabla\rho_e \times \boldsymbol{E}}{\rho} \tag{1}$$

Besides, in a quiescent fluid, the charge conservation equation gives: