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On the onset of horizontal convection

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ABSTRACT

The convective flow driven by a differential heating along a horizontal boundary, commonly referred to as horizontal convection, is investigated. In particular, the inception of the convection cell following impulsive application of heating, i.e. the onset of horizontal convection, is studied experimentally in a rectangular box filled with water. Piecewise boundary conditions of uniform/constant heat flux and temperature are imposed along the box length at its bottom wall. The convective heat transfer coefficient on the heated half of the base is evaluated using the heated thin foil sensor modified to account for the unsteady term of the energy balance. The experiments are carried out over a range of Rayleigh numbers (based on heat flux input, box length and initial fluid properties) from 1.6×10^{11} to 1.3×10^{12} and for a Prandtl number (based on the initial water temperature) of approximately 6. Flow visualizations with the shadowgraph technique are also performed to complement heat transfer measurements. Thermocouple data are acquired inside the domain for validation purposes. A scaling for the characteristic time of the transient is proposed and verified. In the range of the investigated Rayleigh and Prandtl numbers, three subsequent phases in the onset process are identified: pure heat conduction through the fluid layer, Rayleigh-Bènard convection with transition of the boundary layer; onset and time evolution of longitudinal rolls. The presence of longitudinal rolls is justified via an analogy with Görtler vortices theory and results show a Nusselt number enhancement on the heated side of the order of 200% with respect to that on the cold one.

1. Introduction

A fluid exposed to a variable heating condition along a horizontal boundary, such as a variation of temperature and/or heat flux, develops a circulation pattern of natural convective motion, which is referred to as horizontal convection [1]. Horizontal convection occurs in flows of paramount importance, such as the meridional overturning circulation in oceans [2]; there, differential boundary conditions are provided on the superficial layer by the non-uniform solar radiation input, which is on average more intense at the Equator than at the poles. Horizontal convection plays a relevant role also in the dynamics of the Earth mantle [3], as well as in several industrial processes, such as glass/metal melting [4].

The dynamic features of this phenomenon are very different from the classic Rayleigh-Bénard structure [5], where the fluid is heated from below and cooled from above [6]. In contrast to the Rayleigh-Bénard configuration, where a vertical heat flow across opposite boundaries promotes a local overturning motion of the fluid and there is a net heat transport between the boundaries, in horizontal convection only one of the boundaries is responsible of the flow overturning [7], and no net heating occurs across any horizontal plane at equilibrium. This particular feature makes the horizontal convection a peculiar and intriguing problem. Nevertheless, horizontal convection has received less attention than the classic Rayleigh-Bénard problem, and still many questions remain at issue [7].

Both in the laboratory and numerical simulations, horizontal convection is typically reproduced in a parallelepiped enclosed domain. Pioneering studies were carried out in 1965 by Rossby [1], who imposed a linear temperature distribution along the base of a water tank. Under these circumstances, the flow is driven along the horizontal boundary, moving from the colder zone towards the hotter one to compensate for the vertical convective motion of the

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Nomenclature

Symbols

A	area
AR	aspect ratio (D/L)
Bi	Biot number
c	specific heat capacity
D	depth of the domain
f	IR camera sampling frequency rate
Fo	Fourier number
g	gravity acceleration
G	Görtler number
h	convective heat transfer coefficient
I	current through the printed circuit board
k	thermal conductivity coefficient
L	length of the domain
Nu	Nusselt number
Pr	Prandtl number
q''	heat flux
Q	heat (input/output) rate to the system
R	radius of curvature
Ra	Rayleigh number
s	thickness
t	time
T	temperature
u	horizontal velocity
V	electric voltage across the printed circuit board
W	width of the domain
x	streamwise direction
y	crosswise direction
z	vertical direction
α	fluid thermal diffusivity coefficient
β	fluid volumetric thermal expansion coefficient
δ	boundary layer thickness
ε	emissivity coefficient
κ	wave number of the longitudinal rolls
λ	wavelength
ν	fluid kinematic viscosity coefficient
ρ	mass density
σ	Stefan–Boltzmann's constant
τ	characteristic time

Subscripts

amb	referred to the ambient
c	referred to the cold side
$circ$	referred to the printed circuit board
Cu	referred to the copper plate
f	final
F	referred to the heat flux
g	referred to global variable
h	referred to the heated side
in	referred to the inner side
k	referred to heat conduction
n	referred to natural convection
out	referred to the outer side
r	referred to radiation
R	referred to the streamwise rolls
RB	referred to Rayleigh-Bénard
T	thermal
w	wall
α	referred to diffusion
δ	referred to the boundary layer
0	referred to initial conditions

Superscripts

$-$	spatially averaged

rising plume nearby the side wall close to the hotter zone. In fact, once the flow reaches this side wall, it rises as a vertical plume adjacent to the wall. The convective cell is then closed by an upper horizontal flow region (involving a large portion of the cell) and a diffuse sinking region nearby the sidewall opposite to the upwelling plume. At higher Rayleigh number, the flow exhibits a highly asymmetric behavior, specifically with a stronger rising plume with respect to the sinking one.

More recently, Mullarney et al. [8] studied a different boundary condition where, on one side of the base of the domain, a uniform constant heat flux is applied, while on the remaining part a fixed temperature condition is imposed. For its relative simplicity of experimental implementation, a uniform heating can be easily achieved in the portion of fixed heat flux conditions, while the fixed temperature region may be provided by efficiently cooling it.

The main parameters governing the horizontal convection phenomena depend on the working fluid, the domain geometry and the boundary conditions.

The Prandtl number, which together with the volumetric thermal expansion coefficient characterizes the working fluid, is defined as

$$Pr = \frac{\nu}{\alpha}, \tag{1}$$

where α and ν are the fluid thermal diffusivity and kinematic viscosity coefficients, respectively.

The most relevant geometrical parameter of the parallelepiped domain is its aspect ratio,

$$AR = \frac{D}{L}, \tag{2}$$

where D and L are the depth and the length of the domain, respectively. The depth is aligned with gravity.

Finally, the influence of the boundary conditions is captured by the Rayleigh number Ra since the features of the horizontal convection are strongly dependent on Ra. At low Rayleigh numbers, the flow motion is mainly driven by diffusion, and is stable in time. Above a critical Rayleigh number of the order of 10^8, the flow starts to become unsteady, as it can be observed in the vicinity of the rising plume, and for $Ra > 10^{10}$ the flow develops three dimensional features ([8,9,10]). The Rayleigh number, which is the ratio between buoyancy driven heat convection and heat diffusion, is defined according to the boundary conditions of the system. Classically, Ra is defined as

$$Ra = \frac{g\beta\Delta T L^3}{\alpha\nu} \tag{3}$$

i.e. referred to an imposed temperature difference ΔT. In the case of horizontal convection with the heat flux boundary conditions imposed by Ref. [8], which are reproduced in the present work, the Rayleigh number is more properly defined as