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Theoretical and numerical study of enhanced heat transfer in partitioned thermal convection

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ABSTRACT

It was recently discovered that a partitioned Rayleigh-Bénard convection (PRBC) by vertical adiabatic boards leaving a narrow horizontal channel (HC) open between partition boards and the cooling/heating plates, may remarkably enhance the overall heat transfer (Bao et al., 2015). This phenomenon is thoroughly investigated by both numerical and analytic study. Numerically, we perform a series of two-dimensional (2-D) direct numerical simulations (DNS) of PRBC for the same set of Rayleigh and Prandtl numbers ($Ra = 1 \times 10^8$, $Pr = 0.7$ and 5.3) and two aspect ratios ($\Gamma = 1$ and 5). The DNS confirm that when the number of partition boards n is large enough, the flow in PRBC becomes coherent and laminar, and the wall jet in HC forms a thinner thermal boundary layer and hence enhances the heat flux from/to conducting plates. A thermosiphoning mode (*TS-mode*) is used to characterize this laminar forced convection state, which yields an analytic description of the relation between geometrical parameters and the heat transfer coefficient, including two asymptotes for small and large board-to-plate spacing d, where the Nusselt number (Nu) varies with d as d^3 and d^{-1}, respectively. The analytical model then predicts an optimal partition spacing maximizing the heat transport, in good agreement with the DNS. More interestingly, the model yields an optimal width of the vertical channel (VC) between two partition boards, in the range $0.01 \leqslant s/H \leqslant 1.00$ for $\Gamma = 1$, as also validated by DNS. For large VC width, we develop a convection-adaptive (CA) model describing the interplay between turbulent bulk flow in VC and the *TS-mode*, which yields a prediction of Nu in close agreement with DNS for a wide range of n ($n = 0$–35 for $\Gamma = 5$). Therefore, we have developed an analytic understanding of the PRBC enhanced heat transfer, which provides useful relations for engineering design in industrial applications.

1. Introduction

Convective heat transfer plays an important role in a wide variety of engineering systems involving electronic heat exchangers [2–4], and thermal management [5]. High performance chips and electronic miniaturization tend to install an ever increasing number of heat generating devices in a limited space; then, the heat release becomes an important bottleneck. In contrast to forced convection driven by propellers, natural convection results from the buoyancy force induced by gravity. From the industrial point of view, buoyancy-driven convection has the advantage of being self-sustainable and free of energy input. Therefore, it is of intense interest to investigate efficient ways to enhance heat transfer in natural thermal convection systems, and to develop advanced passive heat transfer strategies.

Conventional ways to enhance heat transfer in a thermal cell can be divided into three types: (a) increasing turbulent intensity near the cell boundary using roughness, grooved wall, and the like [6–8]; (b) changing the geometry of the cell [9,10]; (c) changing the properties of the fluid, e.g. varying the Prandtl number [11,12], adding polymer additives [13,14], and making multi-phase flow [15]. Partitioning the thermal cell with walls mounted on the cell wall, normally have marginal effects on heat transfer [16,17]; sometimes it even reduces the heat transfer [18]. Hence, a partitioned cell is usually considered to be an useless option for heat transfer enhancement.

Contrary to stirring turbulent flow as a way to enhance heat transfer, some studies revealed that, by making thinner thermal boundary layers, well-organized motions may also significantly increase the heat transfer [10]. The results of Guo et al. suggested that provoking turbulence no longer enhanced heat transfer when

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Nomenclature

ℓ	effective length for *TS-mode* (m)
C_p	specific heat at constant pressure (J/kg °C)
Gr	Grashof number, $\frac{g\beta(T_h-T_c)H^3}{\nu^2}$
Nu	Nusselt number, hL/k
Pe	Peclét number, $\frac{Ud}{\kappa}$
Pr	Prandtl number, ν/κ
Re	Reynolds number, Ud/ν
B	impact factor
d	spacing between the partition boards and the upper/lower conducting plates (m)
g	gravitational acceleration (m/s^2)
H	height of the closure (m)
h	heat transfer coefficient (w/°C)
k	thermal conductivity (w/m °C)
L	length of the closure (m)
l	length of the channel formed by the partition boards and the upper/lower conducting plate (m)
n	number of partition boards
P	mean pressure (kg/ms^2)
p	pressure (kg/ms^2)
q	heat transfer rate (w)
q'	heat transfer rate per unit length (w/m)
q''	heat flux (w/m^2)
s	width of the vertical channel (m)
T	temperature (°C)
U, V	mean velocity components in the (x, y) system of coordinates
u, v	velocity components in the (x, y) system of coordinates

Greek symbols

β	volume expansion coefficient (1/°C)
δ	normalized boundary layer thickness (m)
η	efficiency of heat transfer
Γ	aspect ratio of the RB cell
ρ	density (kg/m^3)
θ	dimensionless temperature
ξ	ratio of temperature difference, T_{io}/T_{HC}
κ	thermal diffusivity (m^2/s)
μ	viscosity (kg/ms)
ν	kinematic viscosity (m^2/s)
ϕ	aspect ratio of the horizontal channel, d/l
τ	shear stress (kg/ms^2)

Subscripts

a	adiabatic boundary
C	cooled plate
d	based on the board-to-plate spacing
H	heated plate
HC	value between the heated and the cooled plates
hc	horizontal channel
in	parameters at the entrance
io	the difference between the entrance and the exit
jc	joint convection mode
out	parameters at the exit
r	characteristic parameters or the normal Rayleigh-Bénard convection
th	thermal boundary layer
ts	thermosiphoning mode
vc	vertical channel
w	insulated boundary

Superscripts

$*$	normalized parameters

the head loss by turbulent energy dissipation was important [19]. This indicates that laminar convection with less power loss may be a potential way to obtain high heat transfer in passive heat exchangers. It should be noted that strong confinement may also cause a reduction of the Nusselt number, as first reported by Wagner et al. in numerical study of the aspect-ratio dependency of Rayleigh-Bénard convection for $Pr = 0.79$ [20]. Small aspect-ratio, for example $\Gamma < 1/4$ at $Ra \approx 10^6$, may lead to sudden drop in Nu and Re, due to the appearance of the vertically stacked rolls. Effect of severe confinement on heat transfer was lately confirmed by the numerical [10] and the experimental studies [21]. These results suggest that as the aspect-ratio decreases, Nu increases significantly above the value at $\Gamma = 1$, and for each Ra a maximum Nu at a certain Γ, and below which a remarkable drop of Nu appears—a severe confinement in a Rayleigh-Bénard convection system inevitably leads to a reduction of heat transfer.

The Rayleigh-Bénard convection (RBC) is a simplified single-phase passive heat transfer model, for which the mechanism of enhanced heat transfer can be carefully studied. A prototype of RB convection, heated from below and cooled from above, ubiquitously takes place in nature [22,23]. Being driven by buoyancy, the fluids of lower density rise up from the heated bottom layer, and those of higher density descend from the cooled top layer. The global upward heat transfer is therefore achieved by the inside large scale circulation. The heat flux carried by the fluid is typically many times of that by thermal diffusion, defined as the Nusselt number (Nu). Then, investigating how Nu depends on imposed temperature difference across the cell and other physical conditions become the most important theoretical task.

The RB convection is usually characterized by three control parameters—the Rayleigh number $Ra = \beta g \Delta T H^3/(\nu\kappa)$, the Prandtl number $Pr = \nu/\kappa$ and the aspect ratio $\Gamma = L/H$, where ΔT is the temperature difference across the cell of height H, L is the length of the heat transfer zone, g is the acceleration of gravity, and β, κ and ν are the thermal expansion coefficient, the thermal diffusivity, and kinematic viscosity of the convective fluid, respectively. In a simple RB cell, $Nu = hL/k$, where h is the heat transfer coefficient, and k is the heat conductivity coefficient. During the past decades, the Ra and Pr dependence of Nu has been the object of intensive studies, both experimentally and numerically.

A recent study shows that a partitioned Rayleigh-Bénard convection (PRBC) by vertical adiabatic walls leaving a narrow horizontal channel (HC) open between partition boards and the cooling/heating plates, enhances the overall heat transfer by a factor of 2.3, compared to that without any partitions [1]. Since such heat flux enhancement by a passive setting might lead to industrial applications, there is an urgent need for understanding the underlying physics of the heat flux enhancement, in particular regarding the dependence of enhanced heat flux on the characteristic geometrical parameters of the system. This work is motivated by the idea that the global heat flux should be linked to the flow state determined by the geometrical configuration of the PRBC.

Some enhanced heat transport in natural convection (without pumping power) may be explained by the present study of the partitioned RB system. The application areas may include solar energy, nuclear safety, and the cooling of electrical and electronic components. In process industries, heat exchangers are often used for transferring heat from one fluid to another through a separating