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Entropy generation of turbulent double-diffusive natural convection in a rectangle cavity

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ABSTRACT

Turbulent double-diffusive natural convection is of fundamental interest and practical importance. In the present work we investigate systematically the effects of thermal Rayleigh number (Ra), ratio of buoyancy forces (N) and aspect ratio (A) on entropy generation of turbulent double-diffusive natural convection in a rectangle cavity. Several conclusions are obtained: (1) The total entropy generation number (S_{total}) increases with Ra, and the relative total entropy generation rates are nearly insensitive to Ra when $Ra \leq 10^9$; (2) Since $N > 1$, S_{total} increases quickly and linearly with N and the relative total entropy generation rate due to diffusive irreversibility becomes the dominant irreversibility; and (3) S_{total} increases nearly linearly with A. The relative total entropy generation rate due to diffusive and thermal irreversibilities both are monotonic decreasing functions against A while that due to viscous irreversibility is a monotonic increasing function with A. More important, through the present work we observe a new phenomenon named as "spatial self-copy" in such convectional flow. The "spatial self-copy" phenomenon implies that large-scale regular patterns may emerge through small-scale irregular and stochastic distributions. But it is still an open question required further investigation to reveal the physical meanings hidden behind it.

1. Introduction

Turbulent double-diffusive natural convection, i.e. flows generated by buoyancy due to simultaneous temperature and concentration gradients are ubiquitous in natural as well as technical systems. In nature such flows are frequently encountered in oceans, lakes, solar pounds, shallow coastal waters and the atmosphere. In industry examples include chemical processes, crystal growth, energy storage, material processing such as solidification, food processing, etc. But surprisingly, to date the open literature on turbulent double-diffusive natural convection is still sparse. Van Der Eyden et al. [1] numerically and experimentally investigated turbulent double-diffusive natural convection of a mixture in a trapezoidal enclosure. They announced that the numerical results obtained by $k-\epsilon$ model agreed well with the experimental data. Later, Papanicolaou and Belessiotis [2] reported the unsteady behavior of double-diffusive natural convection in an asymmetric trapezoidal enclosure with the thermal Rayleigh number Ra up to 10^{10}. They found that the ratio between the thermal and the concentration (or solutal) buoyancy forces N is a key parameter to determine the characteristics of convection patterns. A $k-\epsilon$ model for treating turbulent double-diffusive flows in porous media was proposed by de Lemos and Tofaneli but without any numerical validation [3]. Recently, they [4] validated their mathematical framework by simulating double-diffusive turbulent natural convection in a porous square cavity with opposing temperature and concentration gradients and the thermal Grashof number up to 2.25×10^{10}. In their work, the finite difference schemes were used to discretize the governing equations.

The references mentioned above all are based on the first-law of thermodynamics and avoid complicated analyses for optimum design. Recently the entropy generation analysis methodology [5] which based on the second-law of thermodynamics, is used to optimize heat and mass transfer performance [6–8]. Although until now the entropy generation analysis has been extended widely for reactive flows [9–11], the available literature on entropy generation analysis in double-diffusive convection is very few yet. To the best knowledge of the present authors, there are only three publications

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Nomenclature

N	ratio of buoyant forces
C	Smagorinsky constant
D_e	effective thermal diffusivity
$\vec{u}$	fluid velocity vector
$\vec{e}_k$	discrete velocity
F_k	source term in Eq. (7)
$\vec{g}$	gravity
g_k, f_j, h_j	distribution function for velocity and scalar fields
$g_k^{eq}, f_j^{eq}, h_j^{eq}$	equilibrium distribution function for velocity and scalar fields
H	height of the cavity
$\vec{v}$	equilibrium velocity vector
p	pressure
Nu	Nusselt number
Ec	Eckert number
Pr	Prandtl number
Be	Bejan number
Ra	thermal Rayleigh number
Sh	Sherwood number
S_{total}	total entropy generation number
S_v	entropy generation number
T	dimensionless temperature
W	width of the cavity
$\vec{x}$	phase space

Greek symbols

Δx, Δy	grid spacing in x and y direction
Δt	time step
$\phi_{\alpha\beta}$	strain rate tensor
ν_e	effective kinematic viscosity
μ	effective dynamic viscosity
τ_D	relaxation time for concentration
τ_Θ	relaxation time for temperature
ρ	density
α_e	effective thermal diffusivity
ω_k, χ_k	the weights for equilibrium distribution function
Δ	filter width
φ	irreversibility distribution ratio

Subscripts and superscripts

D	thermal
μ	viscous
j,k	discrete velocity direction
0	initial index
-	filter operator or average
t	turbulent
α,β	spatial index
Ω,T	global, total

on this topic. Magherbi et al. [12] investigated entropy generation of double diffusion in an inclined cavity. They found that the angle of inclination had a significant effect on entropy generation in convective heat and mass transfer. The total entropy generation increased with the thermal Grashof number and the buoyancy ratio for moderate Lewis numbers. Later, they revealed the influence of Dufour effect on entropy generation in double-diffusive convection [13]. In their work, the total entropy generation was evaluated as a function of the buoyancy ratio, the Dufour parameter and the thermal Grashof number. Recently, Hidouri and Brahim [14] investigated the influence of Soret and Dufour effects on entropy generation in transient double-diffusive convection of a binary gas mixture for the special case of opposing buoyancy forces with equal intensity. It was found that for moderate thermal Grashof number, Soret and Dufour parameters induced a slight increase of entropy generation, but for relatively higher thermal Grashof number, oscillatory behavior of entropy generation was obtained.

As is seen, all of the studies in the above cited literature, there is no investigation that is conducted to analyze entropy generation in turbulent double-diffusive natural convection, which inspires the present work. The LES (large eddy simulationLES) based LB (lattice BoltzmannLB) method is employed to solve the turbulent convectional flow and part of the entropy generation equation, following the line proposed in our previous work [15,16]. The effects of thermal Rayleigh number, ratio of buoyancy forces and aspect ratio on entropy generation of turbulent double-diffusive natural convection in a rectangle cavity are investigated systematically. More important, an interesting phenomenon, named as "spatial self-copy", is observed through the present study. It brings forward an open question on turbulent natural convectional flow and requires further investigation to explain it.

2. Governing equations

The configuration of the two-dimensional computational domain is illustrated in Fig. 1. The aspect ratio $A = H/W$, where H is the height of the cavity and W is the width. In the present study we set $W = 1$.

With the aid of the normalizing characteristic quantities, i.e. length with H, velocity with $(\alpha/H)Ra^{0.5}$, pressure with $\rho(\alpha/H)^2Ra$, temperature with $(T - T_0)/\Delta T$, concentration with $(Y - Y_0)/\Delta Y$ and time with $H^2/\alpha Ra^{0.5}$, the corresponding dimensionless governing equations read [3,17]

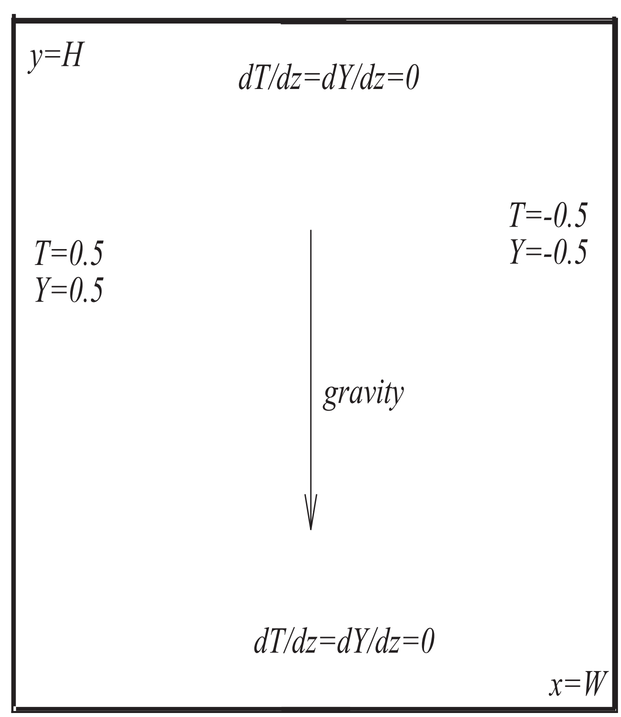

Fig. 1. Configuration of the computational domain and boundary conditions.