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Analysis of entropy generation in double-diffusive natural convection of nanofluid

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ABSTRACT

In the present work, entropy generation analysis on double-diffusive natural convection of nanofluid in a rectangular enclosure is conducted to deepen our insights into the performance of solar thermal systems. The effects of thermal Rayleigh number, ratio of buoyancy forces, nanoparticle volume fraction and aspect ratio of enclosure are discussed in details. It is found that entropy generation will be enhanced more intensively in turbulent regimes. The total entropy generation will reach its minimum when the ratio of buoyancy forces is unity. The total entropy generation is a monotonic decreasing function of nanoparticle volume fraction. It is interesting that the irreversibility due to thermal diffusion, viscous dissipation and concentration diffusion will change about the same rate with nanoparticle volume fraction. The differences and similarities between nanofluid and pure base fluid are also analyzed. In some scenarios, the data based on the second law of thermodynamics are better than that based on the first law of thermodynamics to describe the difference between heat and mass transfer intensity. Moreover, we find a kind of self-organized phenomenon, which we firstly observed in double-diffusive natural convection of air, also exists in its nanofluid counterpart. Especially, even in fully turbulent regimes, there appear order structures in the picture of relative entropy generation. Such phenomenon can be used as an indicator to find order in complicated flow.

1. Introduction

To reckon with the serious challenge raised by intensive carbon dioxide emission from fossil fuel utilization, it is urgent to develop and spread green energy technologies to sustain the global development. Among the available feasible options in the near future, solar energy is a promising one as it can meet both environmental and safety requirements [1]. One crucial problem in solar thermal systems is to improve their efficiency as far as possible so they can have sufficient competition against other renewable energy technologies [2]. Thanks to its excellent enhancement feature on heat transfer, nanofluid has become being a promising working media in solar industry to conquer this difficulty [3]. In a latest review paper [3], the application of nanofluid in various solar thermal systems has been presented.

Double-diffusive natural convection is a popular phenomenon emerging in solar engineering equipments, such as solar collectors [4,5], solar stills [1] and solar distillers [6]. In such convection, heat and mass transfer will become more complicated than pure thermal natural convection as in which there is a competition between thermal buoyancy and compositional buoyancy. In order to deepen our understanding in this challenging area, a number of studies have been conducted. Rahman et al. [5] numerically investigated double-diffusive natural convection in a triangular solar collector. They discussed the influences of the thermal Rayleigh number and buoyancy ratio on the performance of the installation. Such results are helpful to improve the design of similar solar collectors. In Ref. [7], the authors tried to reveal the heat and mass transfer mechanism of double diffusion in a solar still device by numerical experiment. It was found that there was an optimized configuration for the investigated solar still. The double-diffusive natural convection in a solar distiller was reported in Ref. [6]. The effect of the ratio of buoyancy forces on flow pattern and heat transfer was presented in detail in their study. More recently, Saha et al. [8] focused on the influence of the Lewis number on unsteady double-diffusive convection in a triangular solar collector with corrugated wall. They observed that the variation of the Lewis number could change the isotherms and isoconcentration significantly.

Although the available literature on double-diffusive natural convection in solar thermal systems is numerous, the

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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 Fig. 8
$\vec{g}$	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

$\Delta x, \Delta y$	grid spacing in x and y direction
Δt	time step
$\phi_{\alpha\beta}$	strain rate tensor
v_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	nanoparticle volume fraction

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

corresponding research utilizing nanofluid is quite sparse. Recently, laminar double diffusion in a solar collector using water-CuO nanofluid was modeled in Ref. [4]. It was observed that the incident angle of the solar collector influenced the performance of heat and mass transfer of nanofluid significantly. Esfahani and Bordbar [9] investigated laminar double-diffusive natural convection heat transfer enhancement in a square enclosure filled with various nanofluids by numerical simulation. The influences of the nanoparticle volume fraction, Rayleigh and Lewis number on the Nusselt and Sherwood number were revealed. Later, Parvin et al. [10] numerically analyzed the flow and natural convection patterns of water-Al_2O_3 nanofluid in a partially heated enclosure. In their study, the nanoparticle volume fraction varies from 0 to 0.2 with the thermal Rayleigh number up to 10^6. Through their work, it is very clear that the distributions of isotherms and isoconcentration depend closely on the position of active walls of the cavity. Although in Refs. [9,10] the authors did not underline the relevant engineering background, their results are helpful to design some solar thermal installations, such as solar stills [3].

The above studies all are based on the first-law of thermodynamics. However, to further improve the performance of thermal systems, optimization based on the second-law of thermodynamics is necessary. During the past three decades, entropy generation analysis has become a powerful tool to optimize various complicated systems [11]. In Ref. [6], the entropy generation profile of double-diffusive natural convection in a solar distiller was plotted. The authors found that when the buoyancy ratio approached to unity the irreversibility due to friction would become more intensively. Mchirgui et al. [12] discussed the entropy generation of double diffusive convection within an inclined porous cavity. They revealed that entropy generation exhibited an oscillatory behavior for lower and higher medium permeability values in the enclosure. Entropy generation of salt solution in a tall rectangular cavity was numerically analyzed in Ref. [13]. It was observed that entropy generation due to fluid friction is greater than that due to diffusion and heat transfer. Chen and Du [14] studied the entropy generation in turbulent double-diffusive convection. A self-organized phenomenon was reported in the picture of entropy generation for the first time. It is an interesting unusual phenomenon and may open a new door for turbulence research. The effect of rotation on entropy generation in double diffusion was presented in Ref. [15]. It was found that only fast rotation had significant influence on entropy generation distribution and the irreversibility due concentration diffusion would become the main contributor to entropy generation if the buoyancy ratio was high enough. During the past two decades, the research based on entropy generation analysis for nanofluid in various applications also has emerged. Parvin et al. [16] analyzed the entropy generation rate of Cu-water naofluid in a solar collector. Their results provided a useful source of reference for enhancing the forced convection heat transfer performance while simultaneously reducing the entropy generation. The influences of tube roughness,

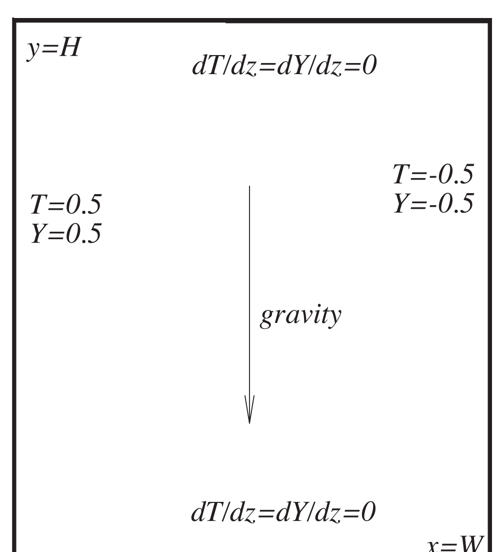

Fig. 1. Configuration of the investigated domain and boundary conditions.