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Heatline visualization of natural convection in a thick walled open cavity filled with a nanofluid

Nadezhda S. Bondareva [a], Mikhail A. Sheremet [a,b], Hakan F. Oztop [c,d,*], Nidal Abu-Hamdeh [d]

[a] Laboratory on Convective Heat and Mass Transfer, Tomsk State University, 634050 Tomsk, Russia
[b] Department of Nuclear and Thermal Power Plants, Tomsk Polytechnic University, 634050 Tomsk, Russia
[c] Department of Mechanical Engineering, Technology Faculty, Fırat University, Elazig, Turkey
[d] Department of Mechanical Engineering, King Abdulaziz University, Jeddah, Saudi Arabia

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ABSTRACT

Natural convection of an alumina-water nanofluid in a partially open rectangular cavity with a left heat-conducting solid wall of finite thickness and conductivity has been studied numerically. Governing equations formulated in dimensionless stream function and vorticity variables on the basis of a single-phase nanofluid model with corresponding boundary conditions have been solved by finite difference method. Analysis of the influence of Rayleigh number ($Ra = 10^3$–10^6), thermal conductivity ratio ($1 \leqslant K \leqslant 20$), solid wall thickness ($0.1 \leqslant \delta \leqslant 0.3$) and nanoparticles volume fraction ($0 \leqslant \phi \leqslant 0.05$) on streamlines, heatlines and isotherms as well as average Nusselt number at solid-fluid interface and fluid flow rate has been carried out. It has been revealed that for the considered models for an effective thermal conductivity ratio and dynamic viscosity an increase in the nanoparticles volume fraction leads to the heat transfer reduction and decrease of the fluid flow rate.

1. Introduction

Obtaining of heat transport way due to mixed, forced or natural convection in thermal systems for engineering applications is extremely important to obtain the energy efficiency. It is very important for both convection and conduction problems and conjugate heat transfer applications such as cooling of electronical equipments, building design, furnaces or boilers and heat exchangers.

Costa [1] is the Pioneer of application of heatline and massline methods to visualize the two-dimensional heat and mass transfer. He applied this technique to anisotropic media. He indicated that the primitive conserved variables and the streamfunction, heatfunction and massfunction fields can be evaluated by using the same procedures and code routines, primarily designed to evaluated the fields of primitive conserved variables. Rahman et al. [2] investigated the time dependent heat and mass transfer in a ventilated enclosure with two ventilation ports as inlet and outlet for different configurations. They used finite element method to solve governing equations. It was found that to reach highest heat and mass transfer rates for $Gr = 10^7$, the outlet port should be located near the top of the left vertical wall. Basak et al. [3] used heatline approach in entrapped fluid to visualize thermal transport. They examined efficient heat recovery for the entrapped fluid in the system. They observed that the heatlines are smooth and perfectly normal to the isotherms indicating the dominance of conduction for two triangles. Deng and Tang [4] solved a computational problem to make visualization of mass and heat transport for conjugate natural convection via heatline approach. In their case, the functions/lines are unified for both fluid and solid regions, and the diffusion coefficients of the function equations are invariant. It was reported that visualization results by streamlines and heatlines directly exhibit the nature of fluid flow and heat transfer in macroscopical level, and hence, provides a more vigorous means to discuss the convective heat transfer accordingly. Basak et al. [5] discussed the role of Bejan's heatline technique on natural convection heat transfer in a differentially heated cavity under different heating and cooling conditions. In their another work, this approach was applied to natural convection in rhombic cavities by Kavya et al. [6]. It is observed that the Nusselt number decreases with area for all values of inclination angle, irrespective of Rayleigh and Prandtl numbers. In both works, it is found that using of heatline approach is an effective tool so see the heat transport ways. Singh et al. [7] worked on a problem of heatlines and thermal management analysis for natural convection in an inclined porous

* Corresponding author at: Department of Mechanical Engineering, Technology Faculty, Fırat University, Elazig, Turkey.
E-mail address: hfoztop1@gmail.com (H.F. Oztop).

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Nomenclature

AR	aspect ratio
c_p	specific heat at constant pressure
$\mathbf{g}$	gravitational acceleration vector
H	height of the cavity
h	thickness of the solid wall
$H_1(\phi), H_2(\phi), H_3(\phi), H_4(\phi)$	special functions
K	thermal conductivity ratio
k	thermal conductivity
L	length of the cavity
Nu	local Nusselt number
$\overline{Nu}$	average Nusselt number
$\bar{p}$	dimensional pressure
Pr	Prandtl number
Ra	Rayleigh number
T	dimensional nanofluid temperature
T_c	low constant temperature
T_h	high constant temperature
T_w	temperature inside the solid wall
u, v	dimensionless velocity components
$\bar{u}$, $\bar{v}$	dimensional velocity components
x, y	dimensionless Cartesian coordinates
$\bar{x}$, $\bar{y}$	dimensional Cartesian coordinates

Greek symbols

α	thermal diffusivity
β	thermal expansion coefficient
δ	dimensionless thickness of the solid wall
θ	dimensionless temperature
μ	dynamic viscosity
Π	dimensionless heat function
ρ	density
ρC_p	heat capacitance
$\rho\beta$	buoyancy coefficient
ϕ	nanoparticles volume fraction
ψ	dimensionless stream function
ω	dimensionless vorticity

Subscripts

c	cold
f	fluid
h	hot
nf	nanofluid
p	(nano) particle
w	wall

square closed spaces. They observed that the larger inclination angle may be optimal for the energy efficient processes involving inclined enclosures due to larger heat flow circulations with enhanced thermal mixing. Bondareva et al. [8] numerically analyzed MHD natural convection in an inclined wavy open porous cavity filled with a nanofluid with a local heater using the heatline methodology. It was found that heatlines and streamlines allow to present in detail the fluid flow and heat transfer.

In some of engineering problem of heat transfer, both conduction and convection heat transfer is solved which is called conjugate heat transfer problem. For these kinds of problem, heatline visualization technique can be a very good tool. In this context, flow visualization and heat transport way are presented by using the streamline, heatline and massline for conjugate heat and mass transfer in a closed space with inserted conductive body (see Zhao et al. [9]). They obtained Nusselt and Sherwood numbers for different parameters. As an expected result, streamlines would only be valid in fluid regions, while heatlines and masslines can penetrate the solid inserted body. Alsabery et al. [10] used heatline visualization technique for conjugate natural convection in a square cavity filled with nanofluid with sinusoidal temperature variations. In their case, the bottom side of the cavity has a solid wall with finite thickness. They showed that thickness of the wall is an important parameter for heat and fluid flow and the heat transfer rate is significantly enhanced by incrementing the solid wall thickness. Mobedi [11] solved a problem on natural convection in a thick walled cavity and he plotted heat transport way via heatline technique and found that although the horizontal walls do not directly reduce temperature difference between the vertical walls of cavity. Mobedi and Oztop [12] made a visualization of heat transport using dimensionless heatfunction for natural convection and conduction in a closed space with thick solid ceiling by using finite difference method. They observed that wall thickness comparatively has less effect on heat transfer rate through the cavity. Lima and Ganzarolli [13] used heatline approach to make visualization of heat transport in a square enclosure with an internal conducting solid body with a finite volume method. They indicated that as solid body becomes larger, flow interference caused by the solid hinders the heat transfer in the closed space approximates to the pure conduction limit.

Open cavities can be seen in many engineering applications such as electronic cooling, solar collectors or different passive systems [14–23]. Polat and Bilgen [14] used finite volume technique to simulate the heat and fluid flow in an inclination shallow cavity at different inclination angle. Polat and Bilgen [15] made a solution on conjugate heat transfer in inclined open shallow cavities by using finite volume technique. They observed that Nusselt number is an increasing function of the aspect ratio up to a critical Rayleigh number. Also, thermal conductivity ratio of the thick wall material plays important role on heat and fluid flow. Singh and Singh [16] made a computational solution on conjugate free convection in top side open cavity. They included radiation effect in their solution. They observed that surface radiation changes the basic flow physics and enhances the radiative heat transfer as a result of which heat transfer by convection decreases. About the nanofluids flow over open cavity to see the mixed convection and entropy generation is studied by Mehrez et al. [17]. They tested the different types of nanofluids and observed that the heat transfer and the entropy generation increase with the increase of *Re* number, *Ri* number and volume fraction of nanoparticles, and vary with the aspect ratio. Double-diffusive natural convection in an open top square cavity is investigated numerically by Arbin et al. [18]. They used heatline approach for different values of Marangoni number, the solutal Marangoni number, the Lewis number, the heater size, Grashof number, Prandtl number, Biot number and aspect ratio 1. They found that the heat and mass transfer mechanisms are affected by the heater segment length. Heatline approach was used for other engineering applications and gave successful results as jet flow by Mukherjee et al. [19], wavy walled cavities by Hussain et al. [20] and water near 4 °C in thick walled porous cavity by Varol et al. [21].

At the same time a development of nanofluidics technique allows to use these specific liquids in different processes and devices for an intensification or attenuation of the phenomenon. There are many interesting papers published on this useful topic [24–38].