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Entropy generation for mixed convection in a square cavity containing a rotating circular cylinder using a local radial basis function method

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ABSTRACT

The entropy generation for steady mixed convection due to a concentric isothermal rotating circular cylinder within a square enclosure is numerically investigated using a local radial basis function interpolation method. The top and bottom walls of the enclosure are adiabatic while the left and right walls have lower constant temperature, and the rotating concentric circular cylinder with high constant temperature hence induces the mixed convection. Air is considered as the working fluid and Prandtl number is fixed at 0.71. With the restriction of Taylor instability for viscous fluid flow, the Reynolds number should be below 60 and ranges from 1 to 50 for present work. Numerical results are obtained for various irreversibility distribution ratios ($10^{-3} \leqslant \Phi \leqslant 10^{-1}$) and Richardson numbers ($0.1 \leqslant \mathrm{Ri} \leqslant 20$). The variation of total entropy generation and average Bejan number with different parameters are discussed and analyzed in detail. The numerical results indicate that the total entropy generation increases with the irreversibility distribution ratio, Reynolds number and Richardson number generally. The average Bejan number decreases with the irreversibility distribution ratio and Richardson number generally while it almost keeps constant for $\mathrm{Ri} \leqslant 1$ and it decreases with Reynolds number remarkably for $\mathrm{Ri} \geqslant 10$ since the sufficient increase of entropy generation due to fluid friction corresponding to the obvious change of flow patterns. The maximum value of local entropy generation due to heat transfer and fluid friction is found around the wall of the rotating cylinder.

1. Introduction

Mixed convection flow occurs when both forced and free convection significantly and concurrently contribute to the heat transfer. The relative contribution of each mechanism depends on the flow regime and the magnitude of the thermal driving force for heat transfer. As a convectional thermodynamics system, mixed convection heat transfer in square enclosure with a rotating cylinder has recently been an important topic due to wide applications especially in some building service situations, when a pipe carrying a hot water passes through an enclosure formed by structural components of the building, rotating-tube heat exchangers, and the drilling of oil wells [1]. In addition, applications for this case of combined natural convection and rotation may be extended to rotary machine design, transpiration cooling, and rotary machines placed in confined regions such as silencers. Ghaddar et al. [2] studied the fluid flow and heat transfer from a rotating cylinder with constant heat flux in an isothermal rectangular enclosure using spectral element method. The rotation of the obstacle enhanced the heat transfer at low Rayleigh number while weakened the heat transfer at high Rayleigh number. The effect of rotating cylinder on heat transfer within a differentially heated square cavity has been experimentally studied by Kimura et al. [3]. It was shown that the rotating cylinder suppressed the heat transfer rate of the enclosure in the low rotating speed. However, obvious heat transfer enhancement could be concluded in the high rotating speed. Lewis [4] and Fu et al. [5] investigated the steady flow induced by rotating cylinder within an enclosure. Otherwise, Selimefendigil [6–8] comprehensively studied the forced convection of different fluids at different flow regions with a rotating cylinder, and compared the Nu under different control parameter to investigate the pronounced enhancement of heat transfer. Shih [9] presented the periodic fluid flow and heat transfer of different shape and size obstacles within an enclosure, and concluded that the performance of the system seemed to be independent on shapes of the object at high Reynolds number.

Entropy generation is traditional and very useful in describing the energy losses of the thermodynamics system due to the fluid

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Nomenclature

Be	local Bejan number
D	diameter of circular cylinder
g	acceleration of gravity
L	length of the square enclosure
p	pressure
P	dimensionless pressure
R	radius of the circular cylinder
Ra	Rayleigh number
Re	Reynolds number
Ri	Richardson number
Pr	Prandtl number
S'	entropy generation
S	dimensionless entropy generation
T	temperature
T_0	bulk temperature
u, *v*	velocity components in x, y directions
U, *V*	dimensionless velocity components in x, y directions
x, *y*	Cartesian coordinates
X, *Y*	dimensionless Cartesian coordinates

Greek symbols

α	thermal diffusivity
β	thermal expansion coefficient
τ	pseudo time
κ	conductivity
μ	viscosity
ν	kinematic viscosity
ρ	density
θ	dimensionless temperature
ω	rotational speed
Φ	irreversibility distribution ratio

Subscripts

avg	average
c	cool
f, f	fluid friction
h	hot
h, t	heat transfer
l	local
ref	reference parameter
tot	total

friction, heat transfer and chemical reaction. For simple flow system without chemical reaction, heat transfer and fluid friction dominate the entropy generation. Therefore, entropy generation has recently been the topic of fields such as heat exchangers, turbomachinery, electric cooling, porous media and combustion [10]. Many numerical studies have been conducted on entropy generation of the natural convective fluid flow and heat transfer problems. Ilis [11] discussed the effect of unit area with different aspect ratio on entropy generation in a rectangular cavity and showed that the high Rayleigh number of the system generated high entropy generation due to fluid friction. Entropy generation for various shapes of enclosure has been widely studied [12–16]. Selimefendigil [17] discussed the effect of Rayleigh number, Hartmann number and different shaped obstacles within the square enclosure filled with nanofluids on entropy generation and heat transfer. Other researchers changed the thermal condition of cavity walls and analyzed the effect on total entropy generation. Kaluri [18] investigated entropy generation of three differentially and discretely heated square cavities, which indicated that the adequate and uniform temperature distribution caused the minimization of entropy generation. In other words, multiple heat sources on cavity walls would be the energy efficient strategy. Basak [19] performed five different cavity wall conditions with the temperature variation and obtained that the high thermal mixing was the efficient strategy. In order to gain the optimal thermal strategy of inclined square cavity, the entropy generation analysis with different thermal boundaries were carried out [20]. In addition, Soleimani [21] studied the natural convection in a partially heated cavity by local radial basis function-differential quadrature (RBF-DQ) method and discussed the effect of different Rayleigh number on heatlines, streamlines, and entropy generation. The computational result demonstrated that the local RBF-DQ method was an attractive approach in terms of accuracy, capability and flexibility.

The above studies show that we have better and solid understanding of entropy generation on natural convection, however, due to the effect of forced convective fluid flow and heat transfer, mixed convection is of course more complicated and attractive than natural convection in the thermodynamics system. Therefore, many researchers' attention has focused on the entropy generation analysis between two rotating cylinder [22–25], they explored and discussed the various parameter effect on entropy generation for mixed convection in detail. Moreover, the optimal strategy of entropy generation for mixed convection between vertical parallel plates has been vastly discussed. Mokheimer [26] found that the optimum values of the buoyancy parameter (Gr/Re) caused the minimum entropy generation for mixed convection, and it was available to design of heat transfer equipment such as electronic package and stacked packaging of laminar-convection-cooled printed circuit. Chen [27] investigated the minimum entropy generation of fully developed mixed convection and concluded that the minimum value was near the centerline of the channel. In addition, Chen analyzed the entropy generation and mixed convection of nanofluids filled with the same mathematical model [28]. Selimefendigil [29] studied the entropy generation of lid-driven square enclosure filled with nanofluids under the influence of magnetic field. Yang [30] considered that the local entropy generation due to heat transfer and fluid friction was strongly influenced by the buoyancy induced flow reversal phenomenon. For a constant Reynolds number, the results indicated that the total entropy generation due to fluid friction increased sharply for $Gr/Re > 100$, while total entropy generation due to heat transfer was not sensitive. MHD mixed convection and entropy generation of nanofluids filled with differentially heated triangular enclosure with a rotating adiabatic circular cylinder was studied, and the results was concluded that the total entropy generation increased with the increase of rotational speed of cylinder [31].

Until recently, much attention has been devoted to investigate the entropy generation for mixed convection as stated before. But for a typical mixed convection due to a rotating cylinder within square enclosure, there is no open research about it at present to the authors' best knowledge. To understanding this basic and interesting problem better, this paper reports on the entropy generation analysis for mixed convection using a local radial basis function method (LRBF). We preliminarily focus on the influence of different control parameters on entropy generation and utilization of the LRBF. It is assumed that the fluid property is steady and the Prandtl number of fluid is fixed at 0.71. The influence of various Reynolds number and Richardson number on local and total

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