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Mixed Convection Enhancement in a 3D Lid-Driven Cavity Containing a Rotating Cylinder by Applying an Artificial Roughness

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Abstract**—**A numerical investigation of unsteady mixed convection heat transfer in a 3D moving top wall enclosure, which has a central rotating cylinder and uses either artificial roughness on the bottom hot plate or smooth bottom hot plate to study the heat transfer enhancement, is completed for fixed circular cylinder, and anticlockwise and clockwise rotational speeds, $-1 \leq \Omega \leq 1$, at Reynolds number of 5000. The top lid-driven wall was cooled, while the other remaining walls that completed obstructed cubic were kept insulated and motionless. A standard k-ε model of Unsteady Reynolds-Averaged Navier-Stokes (URANS) method is involved to deal with turbulent flow. It has been clearly noted that artificial roughness can strongly control the thermal fields and fluid flow patterns. Ultimately, the heat transfer rate has been dramatically increased by involving artificial roughness on the heated bottom wall in the presence of rotating cylinder.

Keywords**—**Artificial roughness, Lid-driven cavity, Mixed convection heat transfer, Rotating cylinder, URANS method.

I. Introduction

ENHANCING the heat transfer rate can reduce a thermal load and improve a system efficiency. Heat transfer enhancement of convective fluid flow in a cavity has a great importance and interest in several engineering and industrial applications, for instance, heat exchangers, solar air collectors, microelectronics to nuclear chemical reactors, electronic equipment's cooling, air conditioning systems and various cooling devices [1]-[13], etc. Heat transfer coefficient between the heated wall/plate and the working fluid can be increased by using artificial roughness wall instead of the traditional or smooth wall. Viscous sub-layer can be broken by involving artificial roughness wall that leads to decrease thermal resistance and raise the number of turbulent regimes [14].

A V-down ribs shape of artificial roughness within a rectangular duct was experimentally completed by Deo et al. [15] to investigate the heat transfer augmentation at Reynolds numbers in the range of 4000 to 12,000 and different roughness parameters, such as relative roughness pitch, relative roughness heights. It was noticed that increasing the relative roughness height leads to reduce the Nusselt number. When relative roughness pitch is 6 or 12, it can have a positive effect on heat transfer increment. The highest Nusselt number enhancement was 3.34. Artificially roughened with V-rips was analysed experimentally by Maithani and Saini [16] to increase the convection heat transfer rate of solar air channel by involving varying values of artificial roughness parameters. For example, constant relative roughness height value of 0.043, angles of attack, 30 – 75° and relative roughness pitches, 6 – 12. Reynolds number in the range of 4000 to 18,000 was utilized. A maximum growing in Nusselt number was 3.6 times bigger than that of the smooth duct. Multiple V-rips roughness within solar heater duct was accomplished by Hans et al. [17] to study and evaluate the effect of roughness elements at Reynolds number values of 2000 – 20,000 on the convection heat transfer enhancement. Essentially, a remarkable positive influence of Nusselt number can be occurred due to changing of roughness parameters values, practically when the relative roughness width value is 8. Kumar et al. [18] experimentally investigated the influence of multi V-shaped rips on the heated plate of a rectangular channel to examine the heat transfer coefficient enhancement due to changing in roughness elements values such as roughness height and pitch. 6.32 times of Nusselt number had been improved compared to the smooth duct Nusselt number.

It can be obviously noticed from the literature review and to the best of the authors' knowledge that generally, artificial roughness has incredible positive impacts on convection heat transfer enhancement and has not been used enough. Ultimately, no work has been found for the application of artificial roughness on mixed convection heat transfer of lid-driven cavity. However, the current work attempts to fill this gap by adding artificial roughness to the heated bottom wall of the lid-driven enclosure. Artificial roughness was designed and compared with the smooth bottom wall case of the domain in this research to enhance the heat transfer rate. URANS method was used to deal with the turbulent flow for Reynolds number, 5000. Clockwise and anticlockwise rotational central cylinder directions with speeds range $-1 \leq \Omega \leq 1$ were investigated besides the motionless circular cylinder case.

II. Numerical Model

A. Physical Model

The three-dimensional sketch of a top wall lid-driven obstructed enclosure that contains a thermally insulated

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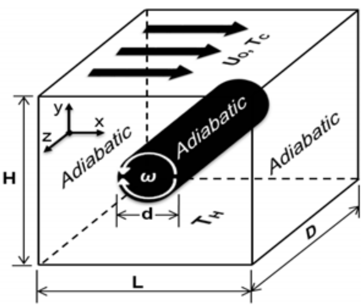
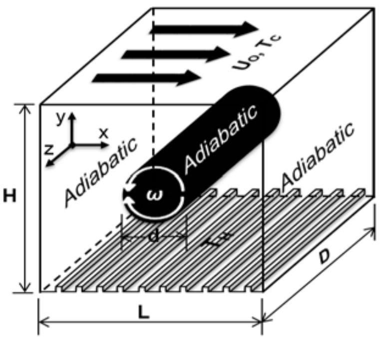
rotating cylinder with diameter, d = 0.2D and has either an artificially roughened heated bottom wall or smooth heated bottom wall is shown in Fig. 1. The roughness parameters, which are used in this paper, are calculated by rip height (e) 10 mm, rip pitch (p) 90 mm, relative roughness height, (e/D_h) is 0.01, and relative roughness pitch (p/e) is 9. Two different bottom wall condition cases are studied in this paper which are case1 (S), that refers to the smooth bottom wall condition, case2 (R-s), that points out to the square roughness rips on the bottom wall case.



(a)



(b)

Fig. 1 Two schematic diagrams of lid-driven cavities contain rotating cylinder (a) S and (b) R-s

B. Boundary Conditions

The boundary conditions for the present models are shown as follows; the top wall is a cold moving wall at uniform velocity ($T = T_C$, U = U0, V = 0, W = 0), whereas the sidewalls, rear wall, and front wall of the geometry are defined as adiabatic and motionless plates (U = V = W = 0). The central horizontal cylinder is adiabatic and rotating object at uniform rotational speeds and different rotational directions ($\omega = (\Omega \times 2U_0) / d$, d = 0.2L). Finally, the bottom walls of all different cases (S, R-s and R-c) are stationary and hot walls ($T = T_H$, U = V = W = 0).

C. Numerical Procedure

Pure water fluid has been involved as working fluid inside the lid-driven enclosure in terms of studying the mixed convection heat transfer enhancement by applying artificial roughness on the heated bottom wall of the domain and compared it to the smooth heated bottom wall condition. The governing equations of heat and mass transfer, and the pressure-velocity coupling equations were solved by involving the finite volume method and SIMPLEC algorithm of the commercial CFD code ANSYS©FLUENT (version R16.2) [19]. The convection and time evolution terms are completed by engaging QUICK and implicit second order scheme. The standard k-ε turbulence model is used for the URANS equations. The convergence criterion of this simulation is chosen as 10^{-5} to obtain high results accuracy.

D. Code Validations

A study of a 2D central rotating cylinder, which was erected horizontally within the lid-driven enclosure, was performed by Chatterjee et al. [20]. This research was chosen to validate the present work in terms of achieving the requirements of running new simulations. The validation is completed at the rotational speed in the range of $1 \leq \Omega \leq 5$, Richardson number of 1, Grashof number of 10^4, and Prandtl number of 6.95. A good agreement has been achieved as illustrated in Fig. 2.

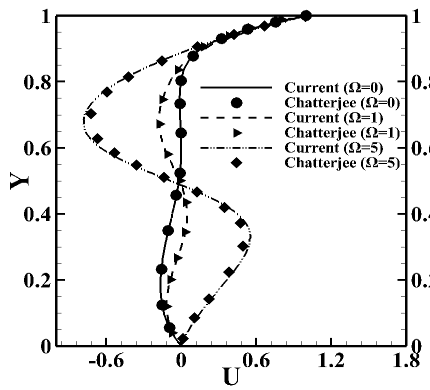


Fig. 2 Current work comparison of the dimensionless velocity profiles with Chatterjee, et al. [20]

III. Results and Discussion

Comparing the case of the artificial roughness located on the heated bottom wall (R-s) with the case of the heated smooth bottom wall (S) at Reynolds number, Re = 5000 and rotational cylinder speeds in the range of $-1 \leq \Omega \leq 1$ is presented here. Fig. 3 illustrates the isotherms and streamlines slides within the domain at z-axis of 0.05. Broadly, it can be demonstrated that artificial rips can significantly affect the fluid flow and heat transfer distributions, particularly, when the cylinder is rotating.

When the rotational speed, Ω, is set equal to zero, it can be seen from both figures of isotherms and streamlines that the fluid flow and heat distribution of two different bottom wall conditions have roughly the same behaviours; in the other words, one clockwise vortex is covering whole domain and the effects of the roughness condition could be neglected. This phenomenon could happen because of low fluid flow circulation speed at the bottom wall, unlike when the rotational cylinder speed equal to -1 or 1, that can help to increase the artificial rips influences on the turbulent flow.

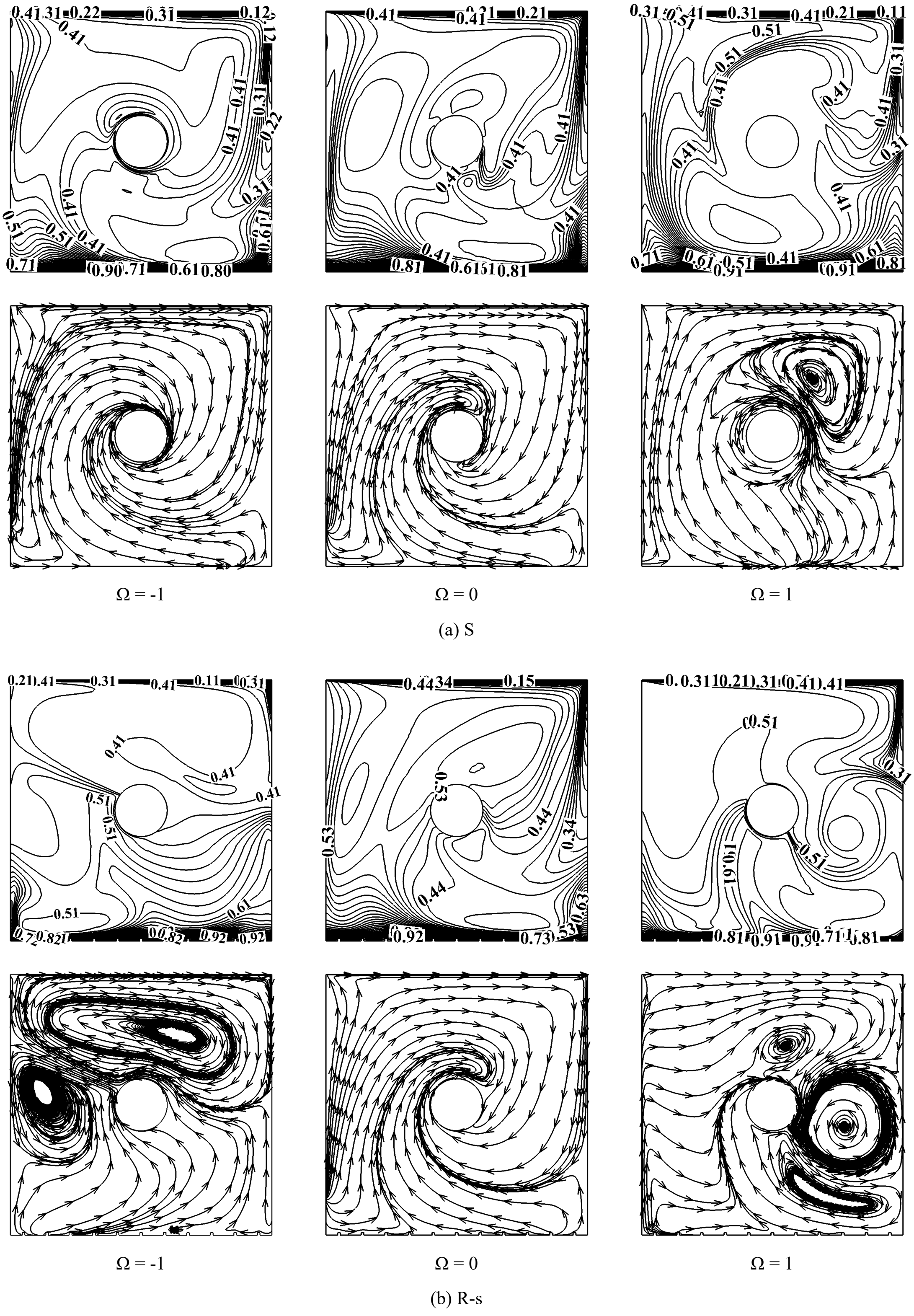
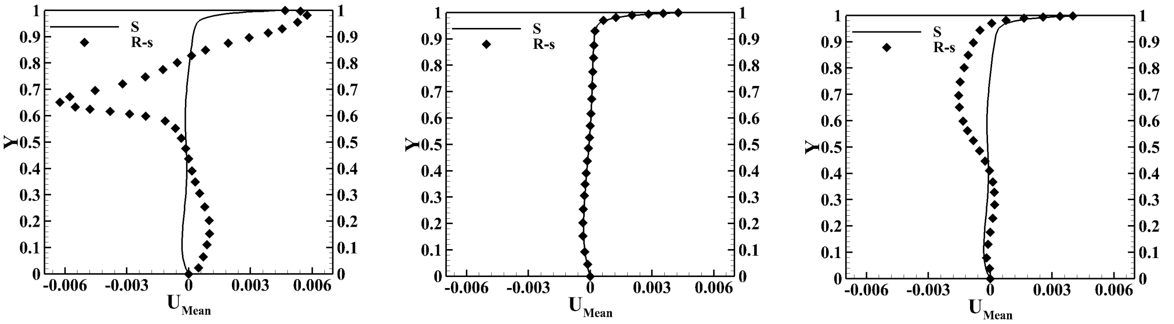


Fig. 3 Isotherm and streamline contours comparison for different bottom wall conditions at Re = 5000



Ω = -1 Ω = 0 Ω = 1

Fig. 4 Mean velocity profiles for different bottom wall conditions at Re = 5000

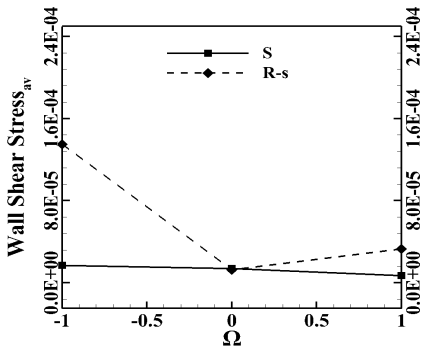


Fig. 5 Wall shear stresses on the bottom wall for different bottom wall conditions at Re = 5000

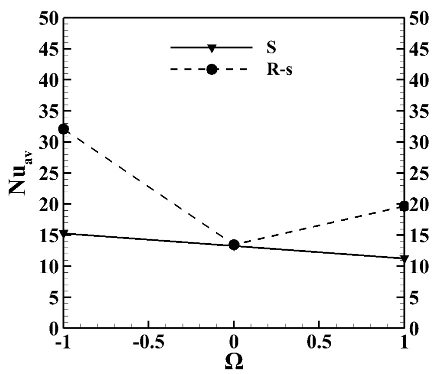


Fig. 6 Average Nusselt number on the bottom wall for different bottom wall conditions at Re = 5000

Mean velocity profiles located at the line drawn between the two points (0.25, 0.0, 0.5 and 0.25, 1.0, 0.5) are analysed in this paper for different heated bottom wall cases (R-s and S) as demonstrated in Fig. 4. The main aim here is to compare the impact of different bottom wall conditions, which are the roughened bottom wall with the smooth bottom wall case on the mean velocity profiles at Reynolds number, 5000, and various rotational speeds and directions of the cylinder. It can be noticed that artificial rips have miner effectiveness on the mean velocity when the cylinder is motionless, while major leverage can be observed when the cylinder moves in any direction. Whereas, at Ω = 1 or -1, it has been clearly observed differences in mean velocity profiles behaviours as results of involving roughness directly in fluid flow as mentioned earlier about the connection between roughness and rotating cylinder conditions.

Diverse cases of studying the wall shear stresses on the heated bottom wall have been completed in this section at different rotational speeds -1 ≤ Ω ≤ 1 of the horizontal cylinder inside the domain and Reynolds number, Re = 5000. Impacts of using different heated bottom wall conditions (S and R-s) on the bottom wall shear stress are presented in Fig. 5. Firstly, when rotational speed is equal to 0, it can be clearly seen that roughly the same values of the bottom wall shear stress have been figured out in both cases (S and R-s). Obvious differences between roughened bottom wall case and smooth wall case have been found when the rotational speed is -1 or 1. It is a consequence of bottom wall rips effects matching with rotational effects on the wall shear stress behaviours.

Increasing turbulence of fluid flow inside the cavity by either using rotational cylinder or involving artificial roughness is the way to break the insulating blanket near solid walls and enhance the convective heat transfer rate. As shown in Fig. 6, when Ω = 0, roughly the same Nusselt numbers have been found in both cases (S and R-s), unlike when the cylinder is rotating, which helps to increase the artificial rips influences on the heat transfer. Moreover, when the top wall and rotating cylinder movements are in the same direction, it shows better effects of artificial roughness on heat transfer enhancement than when the cylinder is rotating in anticlockwise direction.

IV. Conclusion

The 3D CFD analysis of an artificially roughened bottom wall of the cubic lid-driven enclosure that contains a central rotating cylinder has been carried out in this project in order to enhance the heat transfer rate. The effects of adding artificial roughness (R-s) on the hot bottom wall have been compared to the smooth bottom wall case (S), as well as the clockwise and anticlockwise rotational cylinder have been investigated. The main outcomings of the numerical simulations are: significant effects have been discovered on the fluid flow patterns, mean velocity profiles and wall shear stresses due to utilizing the roughened hot bottom wall of the cavity instead of the smooth hot bottom wall; the mixed convection increases with applying artificial roughness, especially when the rotating cylinder is not stationary; a good matching has been achieved between the roughness and the cylinder.

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