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Mixed Convection Inside a Cavity Incorporating Cu-H_2O Nanofluid with Conducting Cylinders Placed at Optimum Position

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A computational study of laminar and steady heat transfer is carried out with copper (Cu)-water nanofluid inside a lid driven cavity. Different conducting obstacles are placed at the optimum position for which the maximum thermal transport occurs. The thermal performance of the Cu-H_2O nanofluid is found out at this optimum position with three different cylinder geometries (square, rectangular and circular), two Richardson numbers (0.01 and 1), and three volume concentrations of copper nanoparticles (0 %, 3 % and 5 %) in water. The Prandtl and Grashof numbers are considered as 6.2 and 10^4, respectively. The fluid is heated by placing a differential heater at the left wall. All the walls except the upper one are in a stationary condition. The top moving wall, stationary bottom wall and the remaining portion of the left wall, where there is no heater, are made insulated. The rectangular cylinder is placed at two different orientations (vertical and horizontal). The results show that the shape of the cylinder contributes to a compelling role in efficient heat transfer. For both Richardson numbers, the Nusselt number is maximum with the case where the square-shaped cylinder is placed at the top left corner. The Nusselt number increases with an increase in the percentage volume of nanoparticles and reduces with an increase in the Richardson number.

Keywords: Conjugate heat transfer, Nanofluid, Lid driven cavity, Fluent, Nanoparticle.

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1. INTRODUCTION

The flow inside a lid-driven cavity is of great importance as all the phenomena that can occur in incompressible flows like the formation of eddies, motion of chaotic particles, instabilities, transition, and turbulence can be studied by utilizing this flow model. Several studies related to fluid flow and heat transfer inside the cavity have been carried out numerically and experimentally by considering different parameters like aspect ratio of the cavity, geometrical shape, and size of obstacle inside it and varying boundary conditions. The eddy structures found in the shear driven-cavity flow gives an insight into the behavior of such structures in the manufacturing of fine polymeric composites. The conventional fluids like water, mineral oil, ethylene glycol have a very low thermal conductivity which results in very low heat transfer. Hence, nanofluid is developed by suspending nanoparticles to conventional fluids to upsurge the conductivity of the base fluid. The different locations of the heat source inside the cavity were observed by Panigrahi et al. (2019) [1]. They mentioned that the location of the heater is a very important parameter in the heat transfer in a confined cavity. Bora et. al. (2019) [2] observed the thermal performance of silver nanofluid by efficient thermal mixing incorporating the cylinder inside the cavity. Daungthongsuk et al. (2007) [3] explained the reason for enhancement in heat transfer by suspending nanoparticles to base fluid. Kumar et al. (2018) [4] observed the heat transfer enhancement by varying the location of a conducting cylinder inside the cavity. The location of the cylinder for which maximum heat transfer is obtained was found out. The investigation carried out by Billah et al. (2011) [5] with a heated hollow circular cylinder explains that the cylinder diameter has a strong influence on the flow field, temperature distribution, and on the solid-fluid thermal conductivity at the convective regime. The study conducted by Khanafer et al. (2013) [6] in a lid driven cavity with a circular body inside concluded that for dominantly mixed convection, the average Nusselt number increase with an increase in the radius of the cylinder for various R_i. The results of Alinia et al. (2011) [7] showed the enhancement of the heat transfer in the cavity and causes significant changes to the flow pattern. Oztop et al. (2008) [8] performed calculations for Rayleigh number (R_a), position and height of the heater and found that heat transfer increases with the increasing height of the heater. Mina Shahi et al. (2010) [9] showed in a square cavity partially heated from below that Nusselt number increases with an increase in the value of nanoparticle concentration (ϕ). Muthtamilselvan et al. (2010) [10] studied the effect of aspect ratio and volume concentration influencing the Nusselt number and flow patterns in the cavity. Cheng (2011) [11] showed the effect of flow pattern and heat transfer inside the cavity by both Richardson number and the direction of the temperature gradient. The investigation conducted by Fereidoon et al. (2013) [12] stated that the Nusselt number increases with increase in ϕ for a constant R_e.

A very few past works focused on the variation in the shape and location of the cylinder. Earlier research showed that the optimum location of the obstacle inside the lid driven cavity is either top left or top bottom corner of the cavity. Based on this consideration the objective of present study is to analyze the heat transport performance of nanofluid by varying the geometry of the solid obstacles, percentage volume of C_u nanoparticles, and R_i.

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2. METHODOLOGY

The square-shaped cavity of width L is filled with Cu-water nanofluid, and it is assumed that the nanoparticles are uniformly dispersed. The diameter of the nanoparticles is considered as less than 100 nm such that nanofluid behaves like the single-phase fluid. The thermo-physical properties of nanoparticles and the base fluid (H_2O) are taken from Sharma et. al (2018) [13].

Two dimensional and steady continuity, momentum, and energy equations are discretized and solved with finite volume-based solver Fluent [14]. The governing equations are made non-dimensional with the length scale as the width of the cavity (L), the velocity of the lid (U_o) and the temperature difference between hot and cold lid ($\Delta T = T_h - T_c$). The solid obstacles with 3 different geometrical shapes i.e., a square, circular, and rectangular, are located at the different locations inside the cavity. Two different orientations are considered for the rectangular obstacles i.e., vertical and horizontal. The isothermal top moving wall is moving with a constant horizontal velocity U_o. The two adjacent right and the bottom walls are kept insulated and stationary. The heater of finite length is located at the center of the left wall (half the length of the wall) and heated isothermally. The remaining part is kept at the insulated condition. Fig. 1 shows the schematic of the domain with the rectangular solid obstacles at the center with different boundary conditions. The top and bottom wall of the cavity is kept thermally insulated. The effective thermophysical properties of the nanofluid have been provided as referred from Sharma et. al (2018) [13].

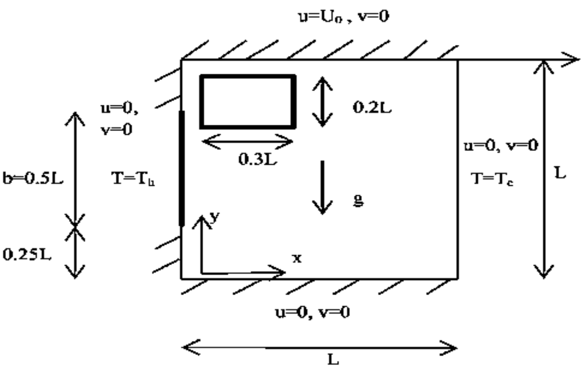

Fig. 1 – Schematic of the domain with the different boundary condition

The grid convergence study is carried out by considering different grid counts and observing variation in average Nusselt number on the left cold wall. The total number of mesh is varied from 3300 to 17600. Average Nusselt number is considered as the parameter to analyse the convergence of heat transfer inside the cavity. The obtained result converges for grid count more than 12600. It is necessary to validate the numerical models adopted in this work. The average Nusselt number is computed at the cold wall of cavity and the results are validated against the study of De Vahl Devis (1983) [15]. The present numerical model is tested for Rayleigh number variation from 10^4 to 10^6 and a good agreement is achieved as shown in Table 1.

Table 1 – Comparison of average Nusselt number with past work

I_a	(I_u) [15]	Present study	Error %
1×10^4	2.242	2.27	1.42
1×10^5	4.523	4.62	2.16
1×10^6	8.928	9.06	1.51

3. RESULTS AND DISCUSSION

The thermal performance of the nanofluid is analyzed by varying R_i, ϕ, shape, and position of the conducting obstacle. Three different shapes of the obstacle i.e., rectangular, square and circular are placed at different corners in the cavity. The Grashof and Prandtl numbers for the whole study are kept at 10^4 and 6.2, respectively.

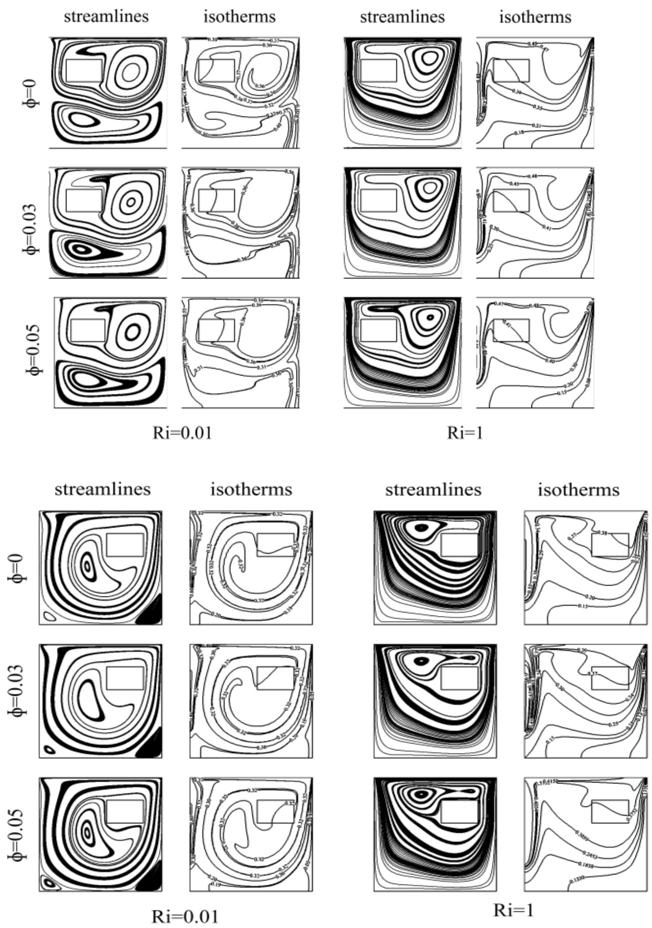

Fig. 2 – Streamlines and isotherms for horizontal rectangular obstacle placed at left and right sides

Fig. 2 shows the streamlines and the isotherms for the horizontal rectangular obstacle placed at top right and top left corners of the cavity which is found as the optimized location for an obstacle for heat transfer enhancement. When the obstacle is placed on the left side, the restriction in the vertical flow field produced and lower velocity cause the flow to separate at $R_i = 0.01$. The low R_i signifies the dominance of inertial flow or forced convection in the domain which also gives rise to strong vorticity inside the cavity. As the Φ increases, no significant changes are seen in both streamlines and isotherms for all R_i range. This can be understood by the fact that the thermal properties like K and C_p does not affect the fluid flow directly, but the flow is continuous for $R_i = 1$ as there is no restriction to flow field in the left side. When the obstacle is placed at the right side two eddies at the two bottom corners and one near the top wall can be seen for lower and higher R_i, respectively. The isotherms near the heated and cold wall are relatively denser in the case of higher R_i. For lower R_i, the maximum N_u is obtained for the horizontal obstacle placed on the left side due to forced convection. At $R_i = 0.01$, the bigger eddy circulating in the anticlockwise direction and closer to the bottom wall is ensuring additional heat transfer to the cold wall. At the top due to the presence of the obstacle flow is accelerated between the wall and obstacle and heat is transferred mainly to the upper part of the cold wall. As a result, the cold wall is differentially heated. At $R_i = 1$, only the upper half of the cold wall is receiving more amount of heat which can be inferred from the isotherm.

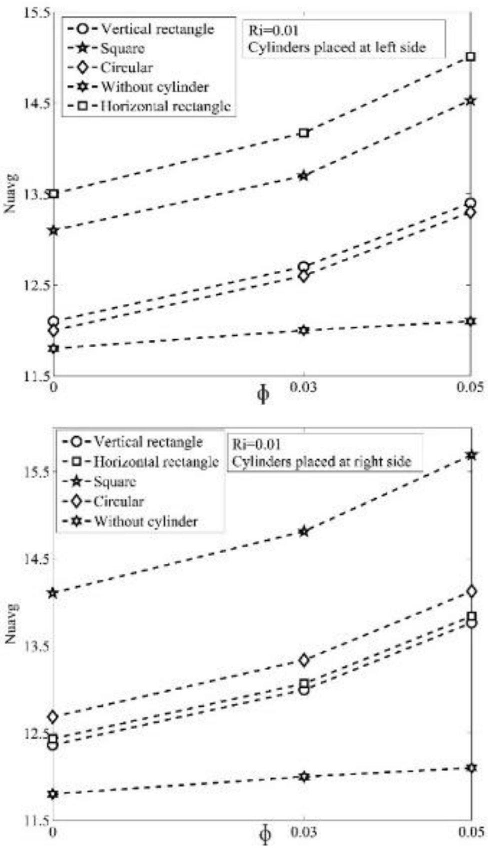

Fig. 3 – Streamlines and isotherms for circular obstacles placed on the left and right sides

Similarly, the flow physics can be explained for vertical and horizontal rectangular, circular and square cylinders. For $R_i = 0.01$, when the vertical rectangular obstacle is placed near the left boundary, four eddies are formed with two very close to the obstacle and other two at the two bottom corners but only three eddies can be seen when the obstacle is kept at right side because in case of later one circulation is uniform. For $R_i = 1$ irrespective of the location of the vertical obstacle, only one eddy is formed. For $R_i = 0.01$ three eddies are formed in case of a circular obstacle at both the locations. For $R_i = 1$ only one eddy is formed in both the cases because natural convection is more predominant and also due to uniformity in the flow field. For $R_i = 0.01$, when the circular obstacle is placed at the left side minimum N_u is obtained due to the presence of relatively bigger eddies at the center which restricts the heat flow. If the square obstacle is placed at top left corner of the cavity, the formation of a primary clockwise direction eddy can be seen at lower right corner and left corner of the square obstacle at $R_i = 0.01$ and $R_i = 1$, respectively. For the location of square obstacle at top right corner, the primary eddy shifts to left side of the cavity. A significant change in the flow field is seen by changing the location of the square obstacle. The isotherms are similar for all the location at specific R_i. The formation of two secondary corner eddies is seen when the square obstacle shifts to the top left corner. To determine the effectiveness of nanofluid in heat transport, Nusselt number (N_u) is one of the most important parameters.

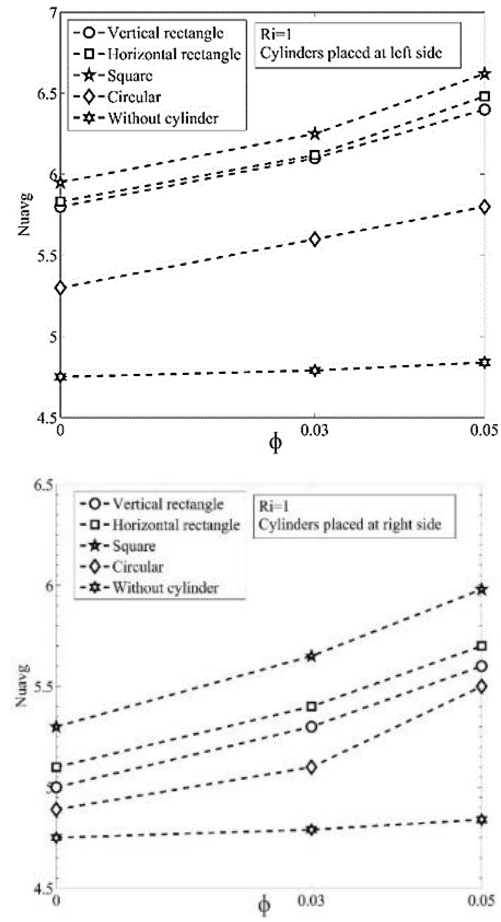

Fig. 4 – Average Nusselt number of the cold wall at $R_i = 1$ when cylinder is placed at left and right side of the cavity

Fig. 3 shows the average N_u calculated at the cold wall for $R_i = 0.01$. N_u increases with an increase in ϕ and decreases with an increase in R_i. N_u for square obstacle placed at the left side is less as compared to the obstacle placed at the right side as the flow circulation is disturbed due to the presence of large-sized eddies at the center. The primary eddies are separated due to high inertia at low Richardson number. The lower eddies cause the flow circulation to be confined and prohibit the efficient mixing inside the cavity. Thus, the temperature difference between the cold wall and fluid reduces. Therefore, the significant reduction in the Nusselt number is seen for the obstacles to be placed at left corner as compared to the location at top right corner of the cavity. The average Nusselt number at the cold wall for all the obstacles at $R_i = 1$ are shown in Fig. 4. In each case, for $R_i = 1$, the maximum N_u is obtained when obstacle is placed at the left side as natural convection is predominant. Similar to the N_u value $R_i = 0.01$, the cases where the obstacles are placed at the right corner has higher N_u as compared when placed at left wall.

4. CONCLUSIONS

The numerical study of a heated shear driven square cavity with a nanofluid and locating four different shapes of conducting obstacles is carried out for $R_i = 0.01$ and 1. N_u increases with an increase in ϕ. When ϕ increases by 3 %, N_u increases by approximately 5 %. When ϕ increases by 5 % the increment in N_u is approximately 11 % which shows that thermal performance increases with the mixing of nanoparticles in the base fluid. In every case for $R_i = 1$, N_u obtained in case of an obstacle placed at the left side is more than the obstacle placed at the right side irrespective of the shape of the conducting obstacle. In every case for $R_i = 0.01$, N_u obtained in case of an obstacle placed at the right side is more than the obstacle placed at the left side irrespective of the shape of the conducting obstacle. For $R_i = 0.01$, when the obstacle is placed on the right side, maximum N_u is obtained in the case of the square-shaped obstacle. When the obstacle is placed at the left side N_u is maximum in horizontal rectangular obstacle case. For $R_i = 1$, maximum heat transfer is obtained in the case of a square obstacle placed on the left side. At a given ϕ, shape and position of the conducting obstacle avg, N_u decreases with increasing R_i. This is due to the predominance of free convection at $R_i = 1$ compared to $R_i = 0.01$.

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Змішана конвекція всередині порожнини, яка містить нанорідину Cu-H_2O, з провідними циліндрами, розміщеними в оптимальному положенні

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Обчислювальне дослідження ламінарного та стійкого теплообміну проводиться з нанорідиною мідь (Cu)-вода всередині порожнини з кришкою. Різні провідні перешкоди розміщено в оптимальному положенні, за якого має місце максимальний теплообмін. Теплові характеристики нанорідини Cu-H_2O визначаються в цьому оптимальному положенні з трьома різними геометріями циліндра (квадрат, прямокутник та коло), двома числами Річардсона (0,01 та 1) та трьома об'ємними концентраціями наночастинок міді у воді (0 %, 3 % і 5 %). Числа Прандтля та Грасгофа вважаються рівним 6,2 та 10^4 відповідно. Рідина нагрівається при розміщенні диференціального нагрівача біля лівої стінки. Усі стінки, крім верхньої, перебувають у стаціонарному стані. Верхню рухому стінку, нерухому нижню стінку та іншу частину лівої стінки, де немає обігрівача, зроблено утепленими. Прямокутний циліндр розміщують в двох різних орієнтаціях (вертикальній та горизонтальній). Результати показують, що форма циліндра робить свій внесок в ефективний теплообмін. Для обох чисел Річардсона число Нуссельта є максимальним у випадку, коли циліндр квадратної форми розміщений у верхньому лівому куті. Число Нуссельта збільшується зі збільшенням процентного об'єму наночастинок і зменшується зі збільшенням числа Річардсона.

Ключові слова: Спряжений теплообмін, Нанорідина, Порожнина з кришкою, Потік води, Наночастинка.