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# Numerical Investigation of Heat Transfer of Water/Nano-Encapsulated Phase Change Materials in a Cavity Including a Rotating Cylinder

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**ABSTRACT:** In the present paper, heat transfer in a cavity containing a mixture of water/ phase change materials surrounded by nanoparticles is investigated. The left and right walls are fixed at hot and cold temperatures, respectively, and horizontal walls are assumed to be adiabatic. There is a circular rotating cylinder in the center of the hole that can rotate clockwise or counterclockwise. The problem is considered two-dimensional and fundamental governing equations such as continuity, momentum, and energy are solved in a coupled manner utilizing the finite element method. To check the accuracy of the numerical results, a comparison with the outputs of others is provided, which indicates a very good agreement between the results. The parameters studied in this study are the dimensionless radius of the cylinder ($R$), Rayleigh number ($Ra$), the dimensionless melting temperature of the phase change material ($\theta_{fu}$), Stephan number ($Ste$), and the dimensionless angular velocity of the rotating cylinder ($\Omega$). By increasing the dimensional radius of the cylinder and assuming the clockwise rotation of $\Omega$ =-300 from $R$ =0.1 to $R$ =0.4, the heat transfer rate increases by 23.37%. On the other hand, if the cylinder is not rotated and with =0.4, the heat transfer rate will decrease by about 59.7% compared to the cavity without the cylinder. This indicates the importance of the rotation of the cylinder inside the cavity in increasing the heat transfer rate.

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## 1- Introduction

Supplying energy in the coming years and increasing the need for energy due to non-renewable and expensive fossil fuels, it is important and vital to replace these types of fuels with renewable energies. Today, with the methods that are on the agenda of many researchers, renewable energy can be harnessed, released, and stored. Mixed natural convection heat transfer, which includes both natural and forced heat transfer, is a target of interest in many industrial, engineering, and scientific fields including fan-cooled electrical equipment, heat exchangers in low-viscosity media, solar panels exposed to wind, flow oceans, atmospheric currents, etc. The use of phase change materials is one of the new methods in storage as well as improving thermal performance. Because these materials keep their temperature and the environment constant by taking heat during the phase change process and absorbing and releasing a lot of heat, which increases the speed of heat transfer in the use of these materials in the future. Ghalambaz et al. [1] simulated the effects of hybrid nanoparticles on the melting process of nanofluid-surrounded phase change material in a cavity. The heat moved from the horizontal wall at the bottom of the cavity to the cold horizontal wall at the top of the cavity and the vertical walls were insulated. Simulation results showed that increasing the volume fraction values of nanoparticles, viscosity, and conductivity parameters resulted in significant changes in the solid-liquid common surface for high values of Fourier number. Mobadersani et al. [2] investigated the effect of adding nanoparticles on the thermal performance of an oscillating heat pipe in the presence of a uniform magnetic field. This work showed that with the increase of the Hartmann number, the momentum of the fluid elements decreases, and therefore the heat transfer rate decreases. According to the review of previous works, the analysis and study of nanofluid flow of phase change materials and base fluid considering both natural and forced mechanisms inside a cavity containing a rotating cylinder has not been done. Due to the increasing importance of using phase change materials and, also nanoparticles in the cooling of industrial tools, in this article, a numerical analysis of these types of flows has been done.

## 2- Mathematical Formulation

In this paper, natural and forced convection heat transfer of two-dimensional laminar flow inside a square cavity filled with Nano-Encapsulated Phase Change Material (NEPCM) particles is investigated. The thermophysical properties of the base fluid, the core, and the shell of the NEPCM particles are

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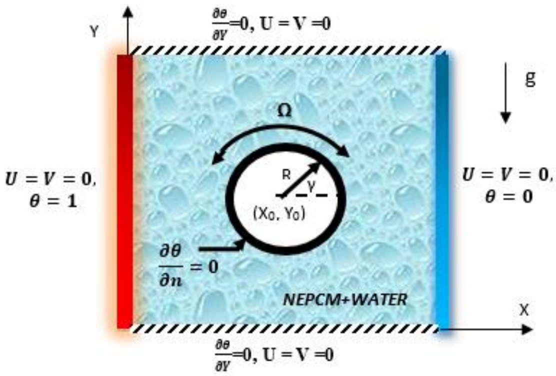


**Fig. 1. Geometry and the boundary conditions of the problem**

**Table 1. Thermophysical properties of the host fluid, core, and shell**

| | Host fluid | Nonadecane | Polyurethane | Solid |
|---|---|---|---|---|
| **μ** ( kgm$^{-1}$s$^{-1}$) | 8.9×10$^{-4}$ | - | - | - |
| **β** (K$^{-1}$) | 21×10$^{-5}$ | - | 17.28×10$^{-5}$ | - |
| K (Wm$^{-1}$k$^{-1}$) | 0.613 | - | - | - |
| $c_p$ (kJkg$^{-1}$K$^{-1}$) | 4179 | 2037 | 1317.7 | 475 |
| **ρ** (kgm$^{-1}$) | 997 | 721 | 786 | 7850 |

presented in Table 1. According to Fig. 1, there is an adiabatic rotating cylinder at the center of the cavity. It is necessary to explain that negative and positive rotational speeds mean clockwise and counterclockwise movement of the cylinder, respectively.

The basic dimensionless equations governing the problem include continuity, momentum, and energy equations as below:

$$\frac{\partial U}{\partial X}+\frac{\partial V}{\partial Y}=0 \tag{1}$$

$$\left(\frac{\rho_{nf}}{\rho_{bf}}\right)\left(U\frac{\partial U}{\partial X}+V\frac{\partial U}{\partial V}\right)=-\frac{\partial P}{\partial X}+\Pr\left(1+N\nu\phi\right)\left(\frac{\partial^2 U}{\partial X^2}+\frac{\partial^2 U}{\partial Y^2}\right) \tag{2}$$

$$\left(\frac{\rho_{nf}}{\rho_{bf}}\right)\left(U\frac{\partial V}{\partial X}+V\frac{\partial V}{\partial V}\right)=-\frac{\partial P}{\partial Y}+\Pr\left(1+N\nu\phi\right)\left(\frac{\partial^2 V}{\partial X^2}+\frac{\partial^2 V}{\partial Y^2}\right)+Ra.\Pr\left(\frac{\beta_{nf}}{\beta_{bf}}\right)\left(\frac{\rho_{nf}}{\rho_{bf}}\right)\theta_{nf} \tag{3}$$

$$Cr\left(U\frac{\partial\theta_{nf}}{\partial x}+V\frac{\partial\theta_{nf}}{\partial Y}\right)=\left(1+Nc\phi\right)\left(\frac{\partial^2\theta_{nf}}{\partial x^2}+\frac{\partial^2\theta_{nf}}{\partial Y^2}\right) \tag{4}$$

The thermophysical properties of the NEPCM/water mixture are calculated using the given relations [3]. The following relationship is performed to calculate the specific thermal capacity of the mixture

$$C_{p,nf}=\frac{\left(1+\phi\right)\left(\rho C_p\right)_{bf}+\phi\left(\rho C_p\right)_p}{\rho_{nf}} \tag{5}$$

Since the phase change materials as the core of nanoparticles can melt and absorb heat, so the heat capacity properties of the particles should also include the latent heat of the phase change materials:

$$Cr=\frac{\left(\rho C_p\right)_{nf}+\phi\left(\rho C_p\right)_p}{\left(\rho C_p\right)_{bf}}=\left(1-\phi\right)+\phi\lambda+\frac{\phi}{\delta Ste}f \tag{6}$$

In the provided relationships, dimensionless numbers are defined as follows:

$$\lambda=\frac{\rho_{co}\rho_{sh}\left(C_{p,co}+lC_{p,sh}\right)}{\left(\rho C_p\right)_{bf}\left(\rho_{sh}+l\rho_{co}\right)}\quad \delta=\frac{T_{Mr}}{\Delta T}\quad Ra=\frac{g\,\rho_{bf}\,\beta_{bf}\,\Delta TL^3}{\alpha_{bf}\,\mu_{bf}}$$
$$Ste=\frac{\left(\rho C_p\right)_{bf}\Delta T\left(\rho_{sh}+l\rho_{co}\right)}{\alpha_{bf}\left(h_{sf}\,\rho_{co}\rho_{sh}\right)}\qquad \Pr=\frac{\mu_{bf}}{\rho_{bf}\,\alpha_{bf}} \tag{7}$$

In the present work, the heat transfer rate is the most expected parameter. Therefore, the heat transfer rate on the hot wall is calculated locally as well as averagely as follows:

$$Nu_{local}=-\left(1+Nc\phi\right)\left(\frac{\partial\theta_{nf}}{\partial X}\right)_{X=0}\qquad Nu_{avg}=\int_0^1 Nu_{local}dY \tag{8}$$

## 3- Solution and Validation Method

The numerical solution of the above equations was carried out by the Galerkin method using Comsol Multiphysics 5.6 software. Non-structured triangular Mesh in the solution domain is also generated by this software. In order to confirm and check the accuracy of the results of the present numerical code, the phase change process of NEPCM particles in a square chamber without a rotating cylinder was compared with the results provided by Ghalambaz et al. [3]. This comparison is presented in Fig. 2 which shows very good agreement.

## 4- Results and Discussion

In this study, the effects of clockwise and anti-clockwise rotations of an insulated rotating cylinder in the center of the geometry on the heat transfer rate and melting process of

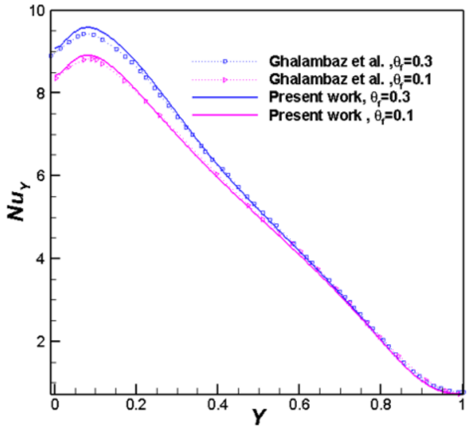


**Fig. 2. Comparison of the local Nusselt number on the hot wall by implementing the present code with those of Ghalambaz et al. [3] versus different dimensionless fusion temperatures.**

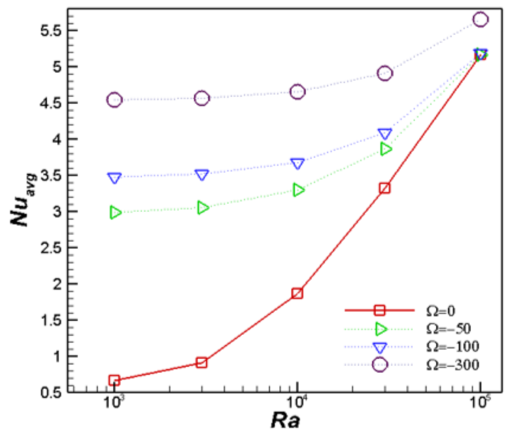


**Fig. 4. The average Nusselt number at $R$ =0.3 according to different Rayleigh numbers for clockwise rotations**

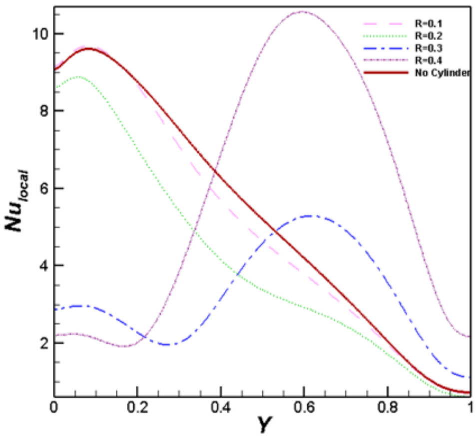


**Fig. 3. The local Nusselt number on the hot wall versus the rotating cylinder radius assuming $\Omega$ =300**

NEPCMs within a square cavity are presented.

Fig. 3 shows that increasing the cylinder radius leads to the enhancement of the local Nusselt at the middle of the hot wall and a maximum local heat transfer rate at the upper section of the hot wall is observed. This is due to the reduction of the flow area in the vicinity of the hot wall which causes the intensification of the fluid elements convection at the upper section of the hot wall. Furthermore, at these positions the forced and natural convections act aligned which amplifies the heat transfer rate more.

Fig. 4 presents the changes in the average Nusselt number in terms of the Rayleigh number for the clockwise angular velocities. It can be observed that the rotating cylinder insertion inside the cavity causes a significant enhancement in the average Nusselt number compared to the fixed cylinder case in lower $Ra$ numbers. Because the buoyancy force is small in lower $Ra$ numbers and by increasing the clockwise rotation of the cylinder, the momentum is transferred to the elements of the fluid which intensifies the natural convection flow, and thus, the average Nusselt number increases.

## 5- Conclusions

By increasing the dimensionless radius of the cylinder and assuming $\Omega$=-300 from $R$ =0.1 to $R$ =0.4, the heat transfer rate increases by 23.37%, but the presence of the counterclockwise rotating cylinder inside the cavity is not favorable in terms of heat transfer.

Increasing the Rayleigh number when the cylinder rotates clockwise increases the average Nusselt at any angular velocity. When the cylinder rotates counter-clockwise, the mean Nusselt first decreases until it reaches a minimum point and then begins to increase.

In clockwise rotation, if the latent heat is ignored ( $Ste \to \infty$ ), the heat transfer rate decreases by 10.56% compared to $\theta_{fu}$=0.4.

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