Thermal and Flow Visualization of a Square Heat Source in a Nanofluid Material with a Cubic-Interpolated Pseudo-particle

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ABSTRACT: Using thermal sources with nanoparticles can change the thermal and velocity distribution and the streamline around solid objects in mechanical devices. In the current study, square-shaped thermal structures are used in the cavity, while the fluid in the domain is fully contaminated with nanoparticles to enhance the heat- and mass-transfer distribution within the system. The connection of thermal elements is installed with equal distance in the domain, and then the nanoparticle is added in the container to improve the heat-transfer rate. The nanofluid is simulated using Cubic-Interpolated Pseudo-particle (CIP) model in the domain with different concentrations. The study shows that the sequence of hot wall structure can disturb the flow as well as thermal distribution. However, a very small streamline can be generated during heat transfer. As a result of thermal structure in the domain, the zero velocity zone in the domain can move to other parts of the cavity. This disturbance can change the heating mechanism in the system, which results in a better rate of heat-transfer characteristics in the system and process engineering. Also, the CIP computing method shows great ability in the modeling of sharp walls/structures with thermal sources.

1. INTRODUCTION

There has been notable growth in the demand for energy in different fields, including industrial, commercial, and domestic domains, due to speedy industrialization in the past decades. To keep down the consumption of energy worldwide, researchers are constantly designing highly efficient energy-transfer devices and technologies in process engineering. The most applied device of any thermal system is found to be heat exchangers in process engineering and thermal processing. The heat exchangers are widely used for industrial purposes when heating/cooling during the process is required. For domestic purposes, heat exchangers are used as heaters; therefore, people use heat exchangers to warm the environment and as a tool for air conditioning. Examples of applying these systems for air conditioning and controlling heat in commercial domains include such as recreational complexes, supermarkets, and stadiums.1

The use of heat exchangers for industrial purposes includes steel and power transmission, pharmaceutical and medical devices, water purification, energy-transfer industries, and, more importantly, chemical engineering. By increasing the heat rate and specifically the convective heat, the heat exchangers become more efficient. Therefore, the increased heat-transfer rate leads to saving more energy in the systems and avoiding its waste due to higher efficiency.3,4 Heat exchangers, which are used in industries, are tubular types. According to the placement of pipes, the movement of fluid, and the direction of the fluid inside the heat exchangers, they can be designed and constructed in different forms.1 The tubular heat exchangers are designed modularly with low maintenance. Nevertheless, initial research studies done by Ganapathy,5 Nag,6 and Bejan7 revealed that most of the processes that use heat exchangers for industrial purposes include fluid flow interaction around the tube shape geometry or surface of cylindrical devices.8,9 Among the various tubular heat exchangers, the technology of cross-flow heat exchanger due to efficient fluid interaction in the liquid mixture and high rate of heat transfer is commonly applied in process engineering.10 For the special dissipation of fluid from the wall, the vortexes that are created on the cylinders are different; therefore, the cross-flow heat exchangers function differently. Through convection structure, thermal distribution in different processes is much more functional compared to the conduction mechanism. The design of heat exchangers, the movement of the fluid, and the arrangement of pipes inside the heat exchangers can impact the efficiency of the heat exchanger as well as the heating system, but other parameters including thermophysical and hydrothermal characteristics can also affect the efficiency of heat exchangers.11–13 Therefore, it is much more worth applying the mentioned method rather than the active method.14 Generally, adding nanoparticles inside the base...
fluid in the heat exchanger can change the thermodynamic characteristics of the heat exchangers, which leads to changing the efficiency. Utilizing dispersed liquids on nanoparticles as a promising alternative for different uses of heat transfer has been suggested owing to the observed increase in thermal conductivity and heat-transfer coefficients.\textsuperscript{14−16} Notwithstanding its existing benefits, stability is its significant element.\textsuperscript{17,18} Different industries and academic domains analyze different parameters of the particles to study its effect on the general efficiency of the fluid flow as well as the efficiency of the heat exchangers. For instance, the shape and size of the nanoparticles are analyzed, and the effect of the mentioned parameters on efficiency, temperature, and pH values of the system was studied. Researchers can study the thermophysical and hydrothermal parameters of nanofluids applicable to heat-transfer equipment.\textsuperscript{19−21} Additionally, experimental studies about the impact of nanoparticles have been examined in previous studies. There are also many numerical and experimental studies about using nanomaterials in industrial applications and academic research studies.\textsuperscript{22,23} It has been reported that the addition of nanoparticles can enhance the heat-transfer efficiency in heat exchangers and phase change materials by increasing the thermal conductivity of the fluid.\textsuperscript{23−26}

Recently, numerical methods have emerged for predicting fluid flow and thermal distribution in different devices.\textsuperscript{27,28} Among all numerical methods, finite difference and finite volume are very popular, but new numerical methods have also been developed for visualization of heat and flow distribution in heat-transfer and fluid flow systems. Cubic-Interpolated Pseudo-particle (CIP) numerical model was also introduced to the academia and industries to predict or visualize the thermal characteristics and fluid flow calculations in mechanical devices and process engineering in different technologies. The ability to couple nanomaterials into the fluid flow computing nodes can also be another potential of this numerical modeling.

In the current study, we used the Cubic-Interpolated Pseudo-particle model to predict thermal distribution in the domain. Moreover, nanoparticles are added in the primary fluid to change the heat-transfer rate. Cubic-Interpolated Pseudo-particle model is used to illustrate the streamline of fluid near the heating source structures. We also examined the effect of the number of heating sources on thermal distribution. Additionally, the ability of the CIP method in simulating sharp walls with thermal sources was examined. This method was assessed to show that adding thermal walls as a heating source and nanomaterials in the domain is a possible task for this numerical calculation. The impact of heating source with a specific distance between them is fully examined in this study. More specifically, fluid flow streamlines, velocity, and thermal distributions are considered to thoroughly analyze the influence of these sources on flow and thermal characteristics.

2. RESULTS AND DISCUSSION

To investigate the impact of thermal structures and disturbance flow points in the square-shaped structure, we used square-shaped heating sources on the right side of the domain in the very beginning. Figure 1 shows that by adding the thermal structure on the right side of the cavity, streamlines of velocity and flow change a little bit due to the addition of the thermal structure. However, because the thermal structure is not very large, the change is not very significant. It also shows us the speed streamlines, and according to which the structure of the fluid flow velocity in the middle of the domain is fixed. When the structure is in the middle of the domain, the velocity equals zero, and by moving toward the sides, the velocity of the fluid increases. By adding the thermal structure in the domain, thermal distribution makes a huge difference, and as shown, the side of the thermal fluid, the temperature is very high.

As shown in Figure 2, thermal fluid is very high near the sides, and the thermal structure leads to an increase in the temperature of the liquid mixture in the square shape domain. By moving steadily from the heating structure, the temperature tends to decrease.

Figure 3 indicates the fluid flow in different parts of the domains. It also shows the thermal fluid in the middle of the cavity. As indicated, the velocity of the fluid in the horizontal line near the sides is steady. Also, by moving forward to the middle of the domain, the velocity is inverted. One source of heat/flow disturbance can only disturb the flow at the right-
hand side. In this case, the flow and thermal streamline can be fully formed in the square-shaped structure.

However, it is shown that the flow velocity in the vertical line and the middle of the domain increases and that near the sides changes steadily. Also, the temperature profile of fluid in the middle of the domain and near the thermal sides reaches its maximum amount. By moving from the thermal structure, the temperature decreases gradually and moves toward the colder sides. By increasing the number of thermal structures in the domain, the fluid flow can be disturbed. As shown in Figure 4, by adding thermal structures with specific distances from each other, the fluid flow changes significantly. It is perceived that the thermal distribution of the liquid mixture is the square-shaped structure. The thermal distribution near the last thermal structure on the left shows the most thermal gradient. Also, by moving from the thermal structure on the upper side of the domain, colder parts are revealed.

The heating source can potentially disturb the thermal and liquid mixture flow in the square-shaped system. As shown, the streamline of liquid velocity is fully squeezed by the solid structure on the top. In this case, the flow can not move to the top, and more stagnation fluid points appeared in the domain, particularly at the top part of the domain. However, the flow circulation strongly impacts the bottom level of the square-shaped domain.

Figure 5 shows the thermal contour plot in the domain. The thermal structures with specific distances from each other lead to the development of heat distribution in the domain. The structures also lead to changes in fluid flow that are shown. For instance, near the last thermal structure, which is beside the left side, the maximum velocity has been reached.

3. CONCLUSIONS

In this study, the Cubic-Interpolated Pseudo-particle model is used to visualize the flow characteristics (such as velocity in different directions) and thermal parameters, such as temperature throughout a square-shaped system. The different number of heating source structures are used to observe the liquid mixture flow and thermal streamline in the square-shaped system. Adding more thermal sources in the domain causes the expansion of the heating source throughout the domain. The is capable of illustrating the distribution of heat in the domain. Besides, adding nanofluid in the system can also change the thermal and fluid distributions. There is a great potential to change the thermal and velocity distributions in the cavity domain. This change can improve the overall mass and heat transfer and, eventually, thermal efficiency. The CIP method is able to simulate sharp walls with a heating source. Furthermore, the technology of coupling nanomaterials in this method is faster than those of other numerical and mathematical models. Utilizing the nanoparticle technology and creating heating structures inside the heating exchangers can significantly change the transferring heat in exchangers, and increase the heat efficiency in heat exchangers. By increasing heat efficiency, one can develop heating systems, air conditioning systems, and therefore more energy can be saved inside the heating systems. By saving the energy inside the heating exchangers, we can significantly affect the environment, especially air pollution. The flow and thermal disturbance points in the system can potentially improve thermal devices in different technologies in industrial sections, such as chemical industries. For future work, this type of pattern can be used in process engineering to optimally control the process, which has an economic impact on the process and consumption of energy. The optimization tools and analysis can be of great assistance to learn the process and explore the best selection of heating sources in thermal systems.
Calculation of velocity and thermal distribution in the cavity or square-shaped domain enables us to fully understand the flow behavior in a simple domain, particularly when the thermal source is coupled with fluid flow. This type of domain, due to having a simple shape, contains a cubic element computing structure that provides higher accuracy of the numerical method and better convergence criteria. In addition to flow distribution, this type of case study makes it easy to consider nanomaterial in the domain. For example, consideration of different nanomaterial concentrations, type of nanofluid, or adding heat source can be simple.

4. COMPUTATIONAL METHODS

CFD is used to visualize and calculate the thermal characteristics (such as temperature) and fluid flow parameters, such as velocity components in the x- and y-directions in the square-shaped domain. Besides, for the validation of the method, adding nanoparticles in the fluid is based on an earlier study. For this study, the structure of adding nanoparticles, type of nanoparticles, and the amount of material are similar to those in the previous study. As a novelty of this study, different wall structures with a heating source are implemented to test the ability of the CIP method and observe how walls can disturb the velocity and the thermal profiles in the domain.

Nano fluids have been used in different research studies for various research purposes. As an instance, Masuda et al. used nanofluids in their research study. The researchers of the mentioned study used nanofluids to develop heat transfer as well as the thermal conductivity of the fluids. The result of their investigation revealed that the heat transfer rises in the same ratio to the volume fraction. Another researcher also noticed the convective features of water with particles of Al₂O₃. Ho et al. applied nanofluids in their research study for various volume fractions of Cu and water of up to 2%.

The details of the written code for the simulation of the nanoparticle in the fluid are shown in Figure 6. The code includes applying thermal walls in the domain as well as the CIP method for solving the fluid movement and thermal distribution. After solving the fluid movement, the researchers used code processing to study the details of the fluid movement as well as the thermal distribution. We used the optimization of parameters to achieve the best result.

The discretization of equations and computing strategy is similar to that in the previous study, but the symbols are changed, meaning that the same equations are presented in the study, and the only difference refers to the changed geometrical structures. The equations relating to the nanofluids calculation in the format of dimensional analysis can be written as:

\[
\begin{align*}
\frac{\partial \Omega^*}{\partial \tau} + \frac{\partial}{\partial \alpha^*} \left( \Omega^* \frac{\partial \sigma^*}{\partial \beta^*} \right) &= \frac{\mu}{\beta^*} \frac{\partial \Omega^*}{\partial \alpha^*} + \frac{\partial \Omega^*}{\partial \beta^*} \\
+ \left( \alpha^* \beta^* (1 - \mu^*) \Omega^* \frac{\partial \beta^*}{\partial \beta^*} \right) \left( \frac{\partial \Omega^*}{\partial \alpha^*} \right) \\
\text{The energy equation} \quad \frac{\partial \Theta^*}{\partial \tau} + \frac{\partial}{\partial \alpha^*} \left( \Theta^* \frac{\partial \Theta^*}{\partial \beta^*} \right) &= \frac{\partial}{\partial \beta^*} \left( \alpha^* \Theta^* \frac{\partial \Theta^*}{\partial \beta^*} \right) \\
\text{The following equations are applied for the kinematics equation} \quad \Omega^* &= \left( \frac{\partial^2 \sigma^*}{\partial \alpha^* \beta^*} + \frac{\partial^2 \sigma^*}{\partial \beta^* \beta^*} \right) \\
\text{where the thermal diffusivity parameter in this work can be described as} \quad \alpha_{id} &= \frac{Q_{id}}{(\text{Den}^* \Theta^* c_p)_{id}} \\
\text{The effective velocity of a fluid is described as follows} \quad \text{Den}^*_{ef} &= (1 - \mu^*) \text{Den}^*_{f} + \mu^* \text{Den}^*_{s} \\
\text{The following equation is the heat capacitance for the system and the mixture liquid} \quad (\text{Den}^*_{m}) &= (1 - \mu^*) (\text{Den}^*_{m} c_p)_{f} + \mu^* (\text{Den}^*_{m} c_p)_{s}
\end{align*}
\]
The thermal conductivity in the square shape system is as follows

\[
Q_{nf} = \frac{Q_s + 2Q_f - 2\mu*(Q_f - Q_s)}{Q_s + 2Q_f + \mu*(Q_f - Q_s)}
\]  
(8)

The nondimensional parameters are represented below

\[
\nu* = \frac{\Omega*H^2}{\sqrt{g/\mu \Delta\text{Tem}*H^2}}
\]  
(9)

\[
aa*bb* = \frac{a*}{H}bb* = \frac{b*}{H}
\]  
(10)

More details on the equations and derivations can be found elsewhere.29

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### Notes

The authors declare no competing financial interest.

## NOMENCLATURE

- **g**: gravity in the square-shaped domain [m·s⁻²]
- **cₚ**: specific heat capacity [kJ·kg⁻¹·K⁻¹]
- **H**: height of square-shaped system [m]
- **t**: time in the system [s]
- **Tem**: temperature of mixture fluid [K]
- **u*, v**: computing velocity in different directions [m·s⁻¹]
- **a*, b***: Cartesian coordinates in the square-shaped system [-]
- **aa*, bb***: dimensionless for computing directions [-]

### Greek Symbols

- **α**: thermal diffusivity for liquid mixture [m²·s⁻¹]
- **μ***: fraction of nanomaterial as particles [-]
- **ν**: kinematic viscosity of liquid mixture [m²·s⁻¹]
- **Ω***: vorticity of the liquid mixture [s⁻¹]
- **ν***: vorticity of the liquid mixture in dimensionless format [-]
- **σ***: stream function in the domain [-]
- **Den***: density of liquid mixture [kg·m⁻³]

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