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Research Article

Effect of Thermophoresis on Heat Diffusion in Isobutane/Copper-Oxide Nanofluid under Pool Boiling Condition: Numerical Investigation

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Understanding thermophoresis in nanorefrigerants stands challenging for a long period despite the phenomenon is attributed for the motion dynamics of particles in nanofluids. Influence of thermophoretic mobility of copper-oxide nanoparticles on the heat transfer behavior of isobutane (R600a) refrigerant is reported in this work. Pool boiling of the isobutane/copper-oxide nanofluid is numerically simulated in computational fluid dynamics utilizing both single and two-phase approaches. Mobility of particles in the saturated refrigerant is studied, and the time scales associated with (Brownian and momentum) diffusions are numerically solved. The temperature contour of the liquid pool is validated with the experimental data, and the properties of the nanorefrigerant such as thermal conductivity, viscosity, and specific heat are estimated in ANSYS Fluent. 5% increase in thermal conductivity and marginal reduction in specific heat of the nanorefrigerant for 0.01% volume fraction of copper-oxide nanoparticles is witnessed. Mobility of particles due to temperature gradient is found higher near the heater; however, thermophoretic velocity is predicted to be lower because of the narrow temperature gradient. Numerical results showed that the time scale for momentum diffusion is shorter (in the order of e+03) than Brownian diffusion, and hence the momentum diffusion is found to be the predominant mode of heat transfer in nanorefrigerant.

1. Introduction

Compact thermal systems attract number of industrial applications for being its cost-effective and augmented performance characteristic nature. Developing such compact systems originally demands cooling fluids with improved heat transfer properties. Recent developments towards enhancing the heat transfer in thermal systems evidenced that nanofluids usage can be promising [1–3]. Nanofluids are colloidal suspensions of nanoscale particles in base fluids. Addition of conductive nanoparticles in base fluid improves its thermal conductivity, and thus the nanofluids are found to improve the cooling performance in electronic devices, vehicle engines, nuclear reactors, and laser diodes [4, 5]. The particles are typically extracted from oxides, metals, and carbon forms [6] while the common base fluids include water, ethylene glycol, and oil. The term nanofluid was proposed by Choi [7] to describe this combination. Upon stable dispersion, the nanoparticles due to its effective surface area, thermal conductivity, specific heat, and random motions could improve the thermal properties of base fluids. Prolonged suspension of particles in base liquids can be materialized in one way using surfactants, which could alter the adhesion behavior of particles, causing agglomeration-free suspension. Surfactants such as SDBS, SDS, and PVP are tested and found to establish stable suspension of

particles in base liquid [8]. Beyond the optimum level, the surfactants gain less diffusion velocities and fail to increase the bubble departure frequency which adversely deteriorates the heat transport [9].

In pool boiling, fluid motion is possible due to natural convection current, and bubble motion is caused by the influence of buoyancy. The urge for pool boiling study arises since rapid phase change mechanisms and time bound cyclic processes are inevitable in numerous industrial applications, one being the HVAC&R (heating ventilation air-conditioning and refrigeration) systems. HVAC&R systems utilize refrigerants, a special class of fluids that undergo phase change in evaporator and condenser regions upon transferring large heat loads. Nanoparticles are demonstrated for their potential in improving the refrigeration system performance [10–12]. Nevertheless, attention is needed in elucidating the heat transport mechanism in nanoparticles suspended refrigerants under boiling conditions. To understand the cyclic phase change mechanisms under saturated conditions, research on pool boiling of refrigerants is proven to be versatile.

In the recent past, extensive studies on thermophysical properties of nanofluids include thermal conductivity, viscosity, specific heat, and density; yet, limited studies on latent heat and surface tension are reported in the literature. In a common way, nanofluids heat transfer is characterized either by its coefficient or by the variations in its thermophysical properties [13–15]. Studies pertaining to the mechanism of heat transport in nanofluids proposed remarkable outcomes behind the augmentation such as (i) intensified interactions and collision among particles, fluid, and the wall surface; (ii) migration and rotation of nanoparticles in the base fluid; (iii) diffusion of nanoparticles due to concentration gradient; (iv) mobility of particles due to temperature gradient; and (v) decrease in bubble sizes due to particles interactions. Apart from major studies on thermophysical properties, limited works to understand the influence of particles motion dynamics on heat transport in base liquids are found in literature. Understanding the concept of particle dynamics in base liquid is equally important to its thermal transport phenomenon. Yu and Xie [16] established that the rotation and migration of nanoparticles have significant role in nanofluids heat transfer. Kostic [17] reported that the combined effect of attractive (Van der Waal's force) and electric repulsion forces determines the stability of particles suspension in liquids. In the same fashion, forces such as drag force, Brownian force, Basset force, Staffmann force, Magnus force, buoyancy force, and thermophoretic force are reported as interaction forces between fluid and particles [18]. Thermophoretic force in fluids, the effect of molecular movements from warmer to colder region due to temperature gradient, has been extended to nanoparticles studies in the literature [19, 20].

The literature survey reveals that the studies on thermophoretic phenomena pertaining to migration characteristics of nanoparticles and heat transfer in refrigerants are limited. In the present work, the influence of thermophoretic mobility of copper-oxide (CuO) nanoparticles on the heat transport in isobutane refrigerant is numerically investigated utilizing the equations of ANSYS Fluent code (as per standard documentation).

2. Problem Definition

2.1. Computational Approach. Numerical prediction of heat transfer in fluids can be made following either single-phase or two-phase approach. Two-phase approach treats the solid particles and liquid medium as two different components while the single-phase approach considers both liquid and solid particles under thermal equilibrium. At present, the nucleate pool boiling of nanorefrigerant is numerically simulated using both the approaches: dispersion model (single-phase approach) and Eulerian model (two-phase approach). The temperature profiles resulted from these approaches are compared and cross verified with the experimental data.

2.2. Governing Equations. The following governing equations Equations (1), (2) and (3) are solved to simulate the nucleate pool boiling of the nanorefrigerant using single-phase approach.

Conservation of mass is as follows:

$$\nabla.\left(\rho_{nf}\vec{V}\right) = 0. \tag{1}$$

Conservation of momentum is as follows:

$$\nabla.\left(\rho_{nf}\vec{V}\vec{V}\right) = -\nabla P + \mu_{nf}\nabla^2\vec{V} - \rho_{nf}\nabla.(\bar{v}\bar{v}) - (\rho\beta)_{nf}(T - T_0)g. \tag{2}$$

Conservation of energy is as follows:

$$\nabla.\left(\left(\rho C_p\right)_{nf}\vec{\bar{V}}\bar{T}\right) = \nabla.\left(k_{nf}\nabla\bar{T}\right) - \nabla.\left(\left(\rho C_p\right)_{nf}\bar{\bar{V}}\bar{\bar{T}}\right). \tag{3}$$

The following governing equations Equations (4), (5) and (6) are solved to simulate the nucleate pool boiling of the nanorefrigerant using two-phase approach.

Conservation of mass is as follows:

$$\nabla.\left(\varnothing_q\rho_q\vec{V}_q\right) = 0. \tag{4}$$

Conservation of momentum is as follows:

$$\nabla.\left(\varnothing_q\rho_q\vec{V}_q\vec{V}_q\right) = -\varnothing_q\nabla P + \varnothing_q\mu_q\nabla^2\vec{V} + \varnothing_q\nabla.\left(\sum_{k=1}^{n}\varnothing_k\rho_k\overline{v_k v_k}\right) + \varnothing_q\rho_q\vec{g} + \sum_{k=1}^{n}\overrightarrow{R_{pq}}. \tag{5}$$

Conservation of energy is as follows:

$$\nabla.\left(\varnothing_q\rho_q\vec{V}_q H_q\right) = -\nabla.\left(k\nabla.T_q\right) - \tau_q : \nabla\vec{V}_q + \sum_{p=1}^{n}Q_{pq}. \tag{6}$$

The phase interaction force involved in Eq. (5) is estimated using Schiller-Naumann correlation, and the heat transfer coefficient from Eq. (6) is calculated using the Ranz-Marshall model.

2.3. Solution Steps. The nanoparticle velocity within the suspension depends on parameters such as viscosity of the refrigerant, temperature distribution, and particle-liquid effective thermal conductivity. Thermophoresis is a phenomenon by which the nanoparticles in the base fluid will be thrusted from hotter to the colder region due to the temperature gradient exists in the fluid. Thermophoretic velocity of nanoparticles accounts all the three aforesaid parameters, and it can be estimated through the thermophoretic mobility of nanoparticles [21] as given in Equation (7):

$$\vartheta_T = -D_T * \nabla T, \tag{7}$$

where D_T is the thermophoretic mobility (m^2/s.K) of particles given by Equation (8):

$$D_T = \alpha * \frac{\beta_T}{\mu_{ref}} \frac{k_{\text{ref}}}{(2 * k_{\text{ref}} + k_{CuO})}. \tag{8}$$

The total energy of the suspended nanoparticles is proportionate to its velocity, and in further, the energetic particles can enhance the heat transport in the refrigerant by carrying the heat energy near the heater surface to the colder region, under temperature gradient exist in the fluid. The mobility of nanoparticles in the refrigerant is estimated for the range of heater surface temperatures between 290 K and 303 K. The result for the surface temperature of 300 K is reported, in this work.

3. Methods

Nucleate pool boiling of the isobutane/CuO nanorefrigerant is numerically simulated with the input boundary conditions as given in Table 1. The steady-state temperature results from the simulation are crossverified with the data, collected through the experiments. The schematic of the experimental set-up is shown in Figure 1. Figure 2(a) shows the computational domain for the present study while Figure 2(b) shows the properties measurement lines. The temperature-dependent thermophysical properties of pure and nano-based isobutane are listed in Table 2. The polynomials presented in Table 2 are obtained using the saturation properties for isobutane [22] and the thermophysical properties of CuO nanoparticles [23]. Thermophoretic mobility of particles at the heater surface temperature of 300 K is simulated, and its effect on heat transfer rate in the nanoparticle suspended refrigerant is analyzed through Brownian and momentum diffusion coefficients.

3.1. Solver Details. The numerical problem of the study is solved using the equations of ANSYS Fluent code, as per the standard documentation. In line with the experimental condition, no mass transfer is allowed across the boundary of the boiling chamber in the simulation work. The procedure of the experiments and method of data reduction are explained in the previous work [24]. Henceforth, the continuity, momentum (x and y), and energy equations across the cells (part of ANSYS Fluent) are solved using 2-D steady implicit pressure based solver. Gauss-Seidel iterative procedure is used to obtain the results. Pressure-correction in the numerical procedure is done using the SIMPLE (Semi-Implicit Method for Pressure Linked Equation) algorithm. A 2-D geometry of the boiling chamber in the experimental setup is modeled (diameter = 0.076 m; height = 0.380 m) and meshed with structured quadrilateral cells of 7500 numbers with 7700 nodes to estimate the properties of the nanorefrigerant, numerically. Grid independent checks have been carried out with temperature estimation using 6500 and 8000 cells. The deviations in the results were found to be less than 1.5% and hence chosen to stick with 7500 cells for the study. The initialization is done with zero velocity for the refrigerant in the boiling chamber, and initial temperatures of heater surface as well as the refrigerant are set to 290 K. The key assumptions made during the numerical study are as follows: (i) fluid is under steady state condition, and (ii) pressure is constant. The steady-state simulation was iterated such that the residuals converged to 10^{-6}, and the results are reported.

Table 1: Boundary conditions and parameters for numerical simulation.

Walls of the chamber	Adiabatic, no mass transfer
Heater surface	Constant temperature
Base fluid and particles	R600a and CuO
Nanoparticle concentration	0.01%
Particle diameter	45 nm
Chamber pressure	2.76 bar
Heater surface temperature	300 K
Initial fluid temperature	290 K
Initial fluid velocity	0

4. Results and Discussion

4.1. Temperature Results from Simulations. The temperature profile is obtained for the nanorefrigerant pool from simulation and crossverified with the experimental data at the specified location. Figure 3(a) shows the temperature profile of the nanorefrigerant pool obtained using dispersion model and Figure 3(b) shows the same profile, obtained using Eulerian approach. As witnessed from figures, the temperature profile of the pool for an input surface temperature of 30°C under single phase and two phase simulations remains similar. In the dispersion model, turbulence effect is included through perturbation (temperature and velocity field), due to relative motion of particles with the base fluid [25]. Despite its simplicity, the single phase approach closely captured the pool temperature profile as obtained with two-phase simulations, which might be due to the small fraction of nanoparticles considered as reported in previous studies [26, 27].

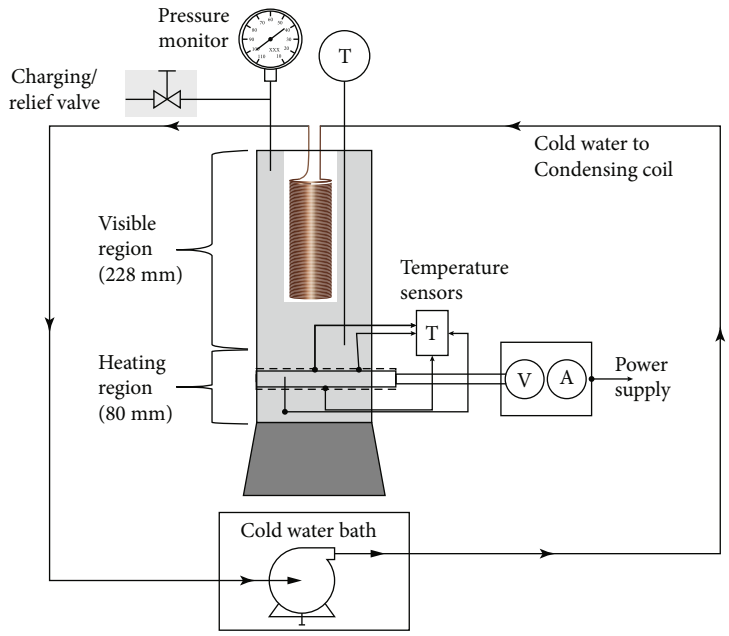

Figure 1: Schematic of the experimental setup.

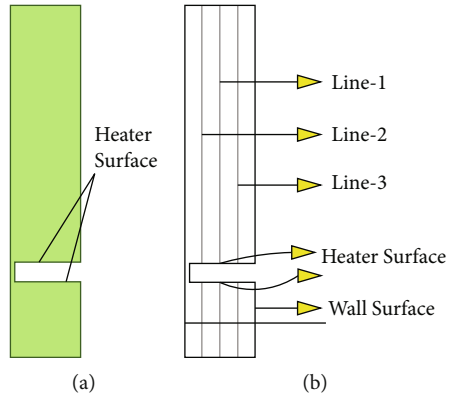

Figure 2: (a) Meshed computational domain. (b) Properties measurement lines.

Table 2: Polynomial interpolation for pure and nanoisobutane properties.

Property	Polynomial interpolation
Density of isobutane (ρ_r)	$11.4225 * 10^4 - 106.2647 * T + 34.9785 * 10^{-2} * T^2 - 38.8 * 10^{-5} * T^3$
Specific heat of Isobutane ($C_{p,r}$)	$3.1201 - 11.2362 * 10^{-3} * T + 29.9347 * 10^{-6} * T^2$
Thermal conductivity of isobutane (k_r)	$0.2567 - 76.5861 * 10^{-5} * T + 68.48 * 10^{-8} * T^2$
Viscosity of isobutane (μ_r)	$1.244 * 10^{-3} - 56.401 * 10^{-7} * T + 66 * 10^{-10} * T^2$
Density of CuO nanoparticles (ρ_p)	$\left[3.753 * 10^{-4} + 2.797 * 10^{-7} * T\right]^{-1}$
Thermal conductivity and specific heat of CuO nanoparticles	32.9 W/m.K and 532.6 J/kg.K, respectively
Density of nanorefrigerant (ρ)	$C_v\rho_p + (1 - C_v)\rho_r$
Specific heat of nanorefrigerant (C_p)	$\left[C_v\rho_p C_{p,p} + (1 - C_v)\rho_r C_{p,r}\right]/\rho$
Thermal conductivity of nanorefrigerant (k)	$k_r\,(1 + 4.5503C_v)$
Viscosity of nanorefrigerant (μ)	$\mu_r/(1 - C_v)^{0.25}$

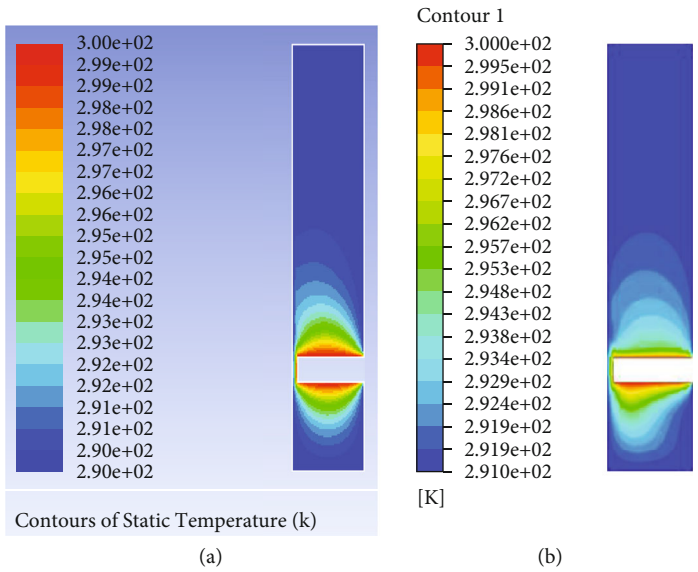

Figure 3: Temperature profile: (a) single-phase approach and (b) two-phase approach.

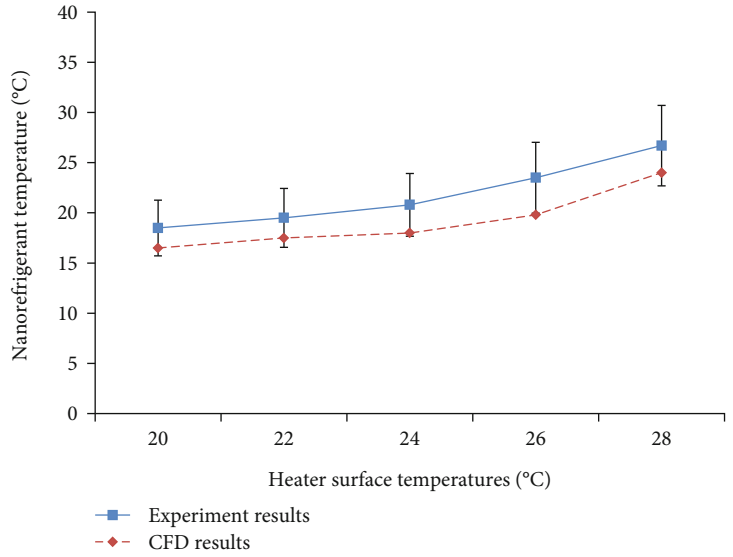

Figure 4: Comparison of CFD results with experiment values.

Figure 4 shows the variation of pool temperature obtained through simulations and experiments with different surface temperatures. As found from the graph, the CFD simulation result for the pool temperature is matched with the experimental values. The CFD results deviated from the experimental data around 10% at lower surface temperatures while the deviation is 15% at higher surface temperatures (25°C-28°C). Possible reasons for the deviations could be as follows: (a) steady state assumptions in simulation study might not match with the dynamics of the experimental conditions and (b) constant pressure assumption made in the numerical simulation.

4.2. Thermophysical Properties. Thermophysical properties such as thermal conductivity, viscosity, and specific heat capacity of the saturated isobutane and isobutane/CuO suspension for the given boundary conditions are numerically simulated. The properties are measured along the three different lines as given in Figure 2(b), and the variations are found to be negligible among these lines. The results of the simulated properties are reported from Figures 5–7, for the surface temperature of 300 K.

Figure 5 shows the thermal conductivity contour of the pure and that of the nanorefrigerant. General increase in temperature increases molecular movement in liquids which obstructs the heat transport through the molecules, and hence the conductivity reduces. Figure 5(b) shows the thermal conductivity profile for the nanorefrigerant whose trend is found to be similar with the previous studies on nano based refrigerants [28]. Thermal conductivity is observed to be lower at the proximity of heater surface and found to be higher farther from the heating zone. Furthermore, its

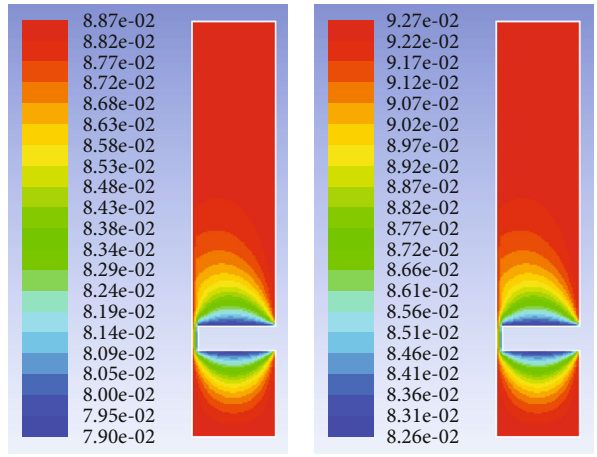

Figure 5: Thermal conductivity ($W.m^{-1}.K^{-1}$): (a) pure isobutane and (b) isobutane+CuO nanoparticles.

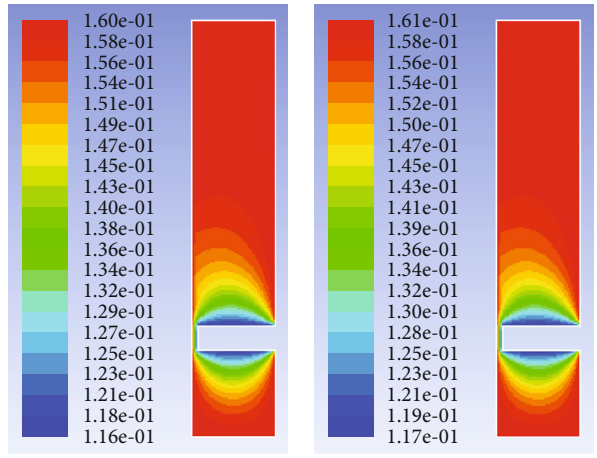

Figure 6: Viscosity (Pa·s): (a) Pure isobutane and (b) isobutane+CuO nanoparticles.

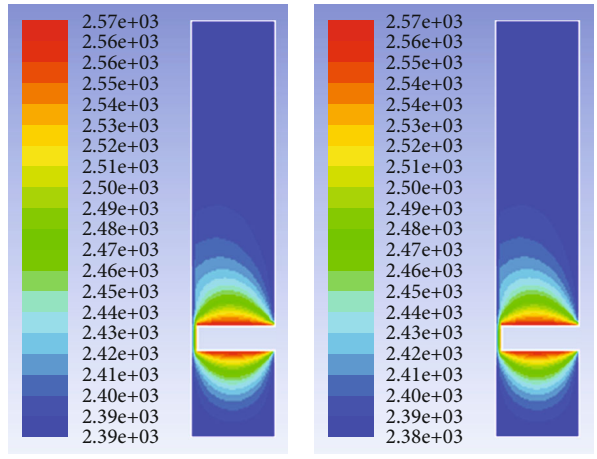

Figure 7: Specific heat ($J.kg^{-1}.K^{-1}$): (a) pure R600a and (b) R600a + CuO nanoparticles.

value is significantly enhanced from the conductivity value of pure refrigerant. The maximum enhancement is found to be 4.6%, for 0.01% volume fraction of CuO nanoparticles. The high temperature and its gradient at the proximity of the heater surface are assumed to have strong influence on the thermal conductivity of the liquid refrigerant.

The viscosity of the nanorefrigerant is found to be increased with a maximum value of 2.5%. The higher the liquid layer temperature, the lower will be the shear resistance of the liquid between their layers, and hence a low viscosity can be observed close to the heater surface region. As it can be seen from Figure 6, the viscosity of pure as well as nanorefrigerant closer to the heater surface seems to be the lowest and also, the values of nanorefrigerant in this regime remain close to the pure refrigerant value, respectively. This could be attributed to the fact that particles availability near to the heater zone is less probable. It is hence reasonable to presume that the nanoparticles at such low volume fraction will be in the suspension away from the wall (heater surface). Simulated results for the specific heat of the pure and nanorefrigerant are shown in Figure 7. The addition of low volume fraction of CuO nanoparticles could not influence the specific heat capacity of the refrigerant as observed in the figure. However, it results a small reduction in the specific heat capacity of the refrigerant. The highly conductive nanoparticles could enhance the conductivity of the refrigerant and henceforth believed to acquire less energy for its temperature rise. This trend of reduction in specific heat capacity of the refrigerant is analogous to the trend of increase in its thermal conductivity. The combined effect of enhancement in thermal conductivity and reduction in the specific heat of the refrigerant favors a swift phase change of the refrigerant. This desirable effect can improve the heat transfer rate, especially in the evaporator region of a refrigeration system.

4.3. Thermophoresis Results. In the boiling chamber, there exists a temperature gradient in the liquid pool as shown in Figure 3. It can be explained that the internal energy of liquids is proportional to its temperature and hence, the molecules near to the heater possess higher internal energy while the molecules exist away from the heater region have less energy. Such liquid molecules with greater momentum will swiftly interact with the molecules come from the cold region. This effect would develop a net force in the liquid called thermophoretic force. Thermophoretic force is proportional to the temperature gradient of the fluid, and it is directed towards the decrease in temperature. In case of any particles suspended in the base fluid, this force will mobilize the particles within the fluid and causes the Brownian motion of the particles. Brownian motion of particles tends to enhance the convection heat transport in the refrigerant since it ensures continuous movement and further collisions among them [23]. The particles' motion behavior in base fluid can be analyzed through its diffusivity characteristics. Diffusion of particles in base fluid due to a unit temperature increase is called thermophoretic mobility of particles. Figure 8 shows the thermophoretic mobility of CuO nanoparticles in the refrigerant.

Based on the numerical simulation results, the following explanation is presented to understand the thermophoretic mobility of nanoparticles. In general, the fluid molecules of large internal energy that are found to be present near the heater surface impart more kinetic energy to the nanoparticles. Sequentially, the nanoparticles will diffuse towards the colder region and thereby take part in carrying the heat from the high temperature region towards the cold.

Additionally, the particles' diffusion (thermophoretic mobility) is found to be higher close to the heater surface, and it diminishes far away from the heater zone. As the nanoparticle travel towards the cold region, where the liquid molecules are considered to be having less kinetic energy, the particles share its energy with the molecules. Under equilibrium, the nanoparticles would be existing in the suspension. The understanding is similar to the one proposed by Michaelides [29], who reported that thermophoresis would result in more particles concentration in the colder region. Michaelides [30] also proposed that particles could not be accumulated due to the repulsion force between them. Henceforth, the simulation results of thermophoretic mobility of nanoparticles reveal that the nanoparticles diffuse towards cold region (due to thermophoretic force), and it is expected to be in the suspension without any accumulations at cold region (due to reduced mean free path length and hence, strong repulsion force).

4.4. Heat Transfer in Nanorefrigerant. Motion of nanoparticles in base liquids intensifies the interactions between the particles and the liquid molecules which in further augments the heat transfer rate in base liquids. The interactions can happen in any of the four possible modes: (i) collision between particles, (ii) surface interaction of the Brownian particles with the base fluid, (iii) thermal diffusion of the particles in the fluid, and (iv) collision between base fluid molecules [31]. In the present work, numerical analysis is carried out on particle-particle collisions and particle-fluid molecule interactions that are mainly categorized to contribute particles motion dynamics. The particle-particle collisions could increase the thermal conductivity of the fluid through solid to solid heat transport [32]. Additionally, the nanoparticle-fluid molecule interactions at their surface levels mainly because of the Brownian motion would enhance the nanoconvection [33]. The coefficients of Brownian diffusion and momentum diffusion describe the ability of particles to move between two successive collisions, within the fluid, and these coefficients are utilized to capture the above mentioned effects in nanorefrigerant using the equations given in Table 3.

Figure 9 shows the contours of the mass and momentum diffusivities of CuO nanoparticles in the refrigerant at the heater surface temperature of 300 K. As evidenced from the figures, the momentum diffusion parameter (of order e-08) is larger than the Brownian diffusion parameter (of order e-11) for the present simulation conditions. This simulation results clarify that the heat transfer in nanorefrigerant is predominant with nanoconvection (particle surface–fluid interactions due to movement), among the two different modes considered. Similar results portraying the significance of

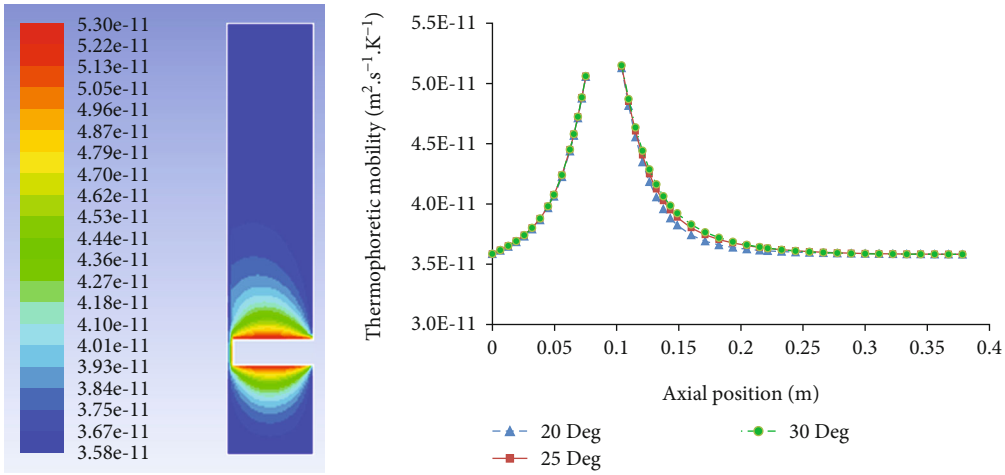

Figure 8: Thermophoretic mobility of nanoparticles in isobutane.

Table 3: Diffusion parameters.

Diffusion mechanism	Parameter	Formula
Brownian diffusion	Particle collision	$D = \frac{K_B T}{6\pi\mu r}$
Momentum diffusion	Kinematic viscosity of the refrigerant	$\vartheta = \left(\frac{\mu}{\rho}\right)_f$

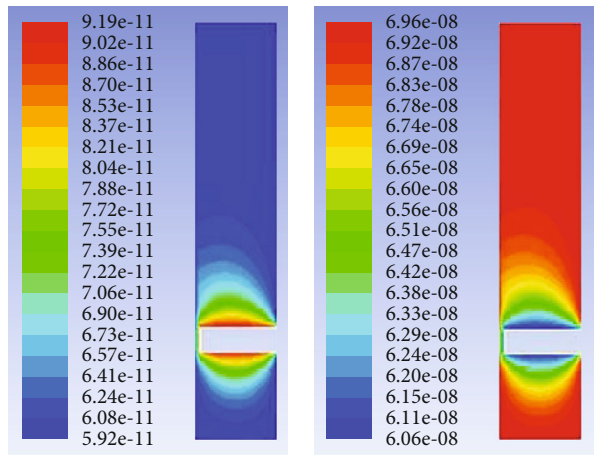

Figure 9: Diffusivity ($m^2.s^{-1}$): (a) Brownian motion and (b) momentum diffusion.

nanoparticles motion (rotation and migration) on thermal conductivity enhancement were reported through molecular dynamic simulation [34]. Also, an analogy in comparing the rate of particles motion with the rate of heat diffusion through their time scales is found in the literature [35]. Furthermore, the heat transfer time scales based on two different modes can be estimated using the diffusion coefficients. The average time taken for heat transfer to travel a distance equal to a particle size (45 nm) in the refrigerant is found to be $8.17 * e - 03$ s through nanoconvection, whereas the same phenomenon takes place in 4.70 s through particle-particle collisions. As witnessed from Figure 9(a), the Brownian diffusion is high near the heater region and reduces gradually towards the colder region. This trend confirms a larger amount of particle-particle collisions at the high temperature region than that of the cold region in the refrigerant. Henceforth, the heat transfer due to particles collisions will be aggressive near the heater region. Also, the nanoparticles will be diffused towards the colder region. The momentum diffusion profile as shown in Figure 9(b) confirms larger interactions between these diffused particles' surface and the liquid molecules at the colder region of the refrigerant, which in further enhance the convection heat transfer at this region. It is understood from the present

simulation results that the motion dynamics of particles contribute significantly in base fluid heat transfer enhancement.

5. Conclusions

The effect of thermophoresis on the heat transfer behavior of isobutane/CuO nanofluid is numerically investigated, and the following outcomes are observed from the present work:

(i) Thermophysical properties of pure and nanorefrigerants are numerically simulated using ANSYS Fluent code. For 0.01% volume fraction of CuO nanoparticles in R600a, the viscosity and specific heat capacity are marginally increased, while its thermal conductivity is enhanced by 4.6%

(ii) Thermophoretic mobility of CuO nanoparticles in the refrigerant increases with the increase in the surface temperature while it remains unaltered at region far away from the heater zone

(iii) The nanoparticles gain energy near the heater zone and diffuse towards the colder region with thermophoretic force. Thermophoresis effect induces the particles motion in the refrigerant which helps in enhancing the heat transfer rate

(iv) Numerical plots of the diffusion parameters reveal that the heat transfer due to particle movement at the particle-fluid interface (nanoconvection) is predominant to the heat transfer due to particles collisions. Also, heat transport in the refrigerant due to nanoconvection is found to be much faster (in the order of e+03) than heat transfer due to particle collision

Abbreviations

Nomenclature

CFD: Computational fluid dynamics
C_p: Specific heat ($J.kg^{-1}.K^{-1}$)
C_v: Nanoparticles concentration (%)
d: Particle diameter (m)
D: Diffusivity ($m^2.s^{-1}$)
g: Gravitational acceleration ($m.s^{-2}$)
K_b: Boltzmann constant ($W.m^{-2}K^{-4}$)
r: Particle radius (m)
T: Temperature (K)
V: Velocity ($m.s^{-1}$)
k: Thermal conductivity ($W.m^{-1}.K^{-1}$)
p: Pressure (bar)
$\vec{v}$: Velocity vector ($m.s^{-1}$).

Greek Symbols

α: Thermal diffusivity ($m^2.s^{-1}$)
β: Thermal expansion coefficient ($°C^{-1}$)
ρ: Density ($kg.m^{-3}$)
μ: Viscosity (Pa·s)
τ: Time scale (s)
ϑ: Thermophoretic velocity ($m.s^{-1}$)
∇: Gradient (-).

Subscript

p, np: Nanoparticles
r, ref: Refrigerant
p, q: Fluid phases
BD: Brownian diffusion
MD: Momentum diffusion.

Data Availability

The data used to support the findings of this study are available.

Conflicts of Interest

The authors declare no conflicts of interest.

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