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Pool Boiling Heat Transfer Properties of Water-Based Dilute Fe+ZnO Hybrid Nanofluid under Low Heat Flux Condition: A Numerical Study

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Abstract

Thermophysical properties of the working fluid of a fluid-driven heat transfer system is the key parameter in determination of heat transfer performance of the system they were used. The nanofluids, nanoparticles containing colloidal suspensions, have been extensively used for performance enhancement in many applications, however, the nanoparticles cannot have both high thermal conductivity and good stability simultaneously. To provide these characteristics together, hybrid utilization of nanoparticles has emerged. In this numerical study, pool boiling heat transfer characteristics of dilute Fe+ZnO/deionized water hybrid nanofluid were investigated under low heat flux condition (50 W). The hybrid nanofluid suspension at the volumetric rate of 0.5% and Fe+ZnO combination of (50:50) were taken into account. For numerical simulations, Computational Fluid Dynamics approach and Volume-of-Fluid multiphase model were employed. Vapor volume fractions and velocity vectors in fluid medium were obtained for deionized water, and the hybrid nanofluid aforementioned. The start-up of the bubbles and departures with time were investigated for each working fluid. Under the same conditions, the start-up time of the boiling for deionized water and dilute hybrid nanofluid were observed as 468. and 441. seconds, respectively. The numerical findings also displayed that hybrid nanofluids can be used for pool boiling implementations in order to provide improved heat transfer characteristics.

Su Esaslı Seyreltik Fe+ZnO Hibrit Nanoakışkanının Düşük Isı Akısı Şartında Havuz Kaynama Isı Transferi Özellikleri: Sayısal Bir Çalışma

Öz

Akışkanla çalışan bir ısı transfer sisteminin çalışma akışkanının termofiziksel özellikleri, kullanıldıkları sistemin ısı transfer performansının belirlenmesinde anahtar parametredir. Nanokışkanlar, nanoparçacıklar içeren koloidal süspansiyonlar, birçok uygulamada performans iyileştirme amacıyla yaygın olarak kullanılmıştır, ancak nanoparçacıklar aynı anda hem yüksek ısıl iletkenlik hem de iyi derecede kararlılık sağlayamamaktadır. Bu özellikleri bir arada sağlamak için nanoparçacıkların hibrit kullanımı ortaya çıkmıştır. Bu sayısal çalışmada, seyreltik Fe + ZnO/saf su hibrit nanoakışkanın havuz kaynama ısı transfer özellikleri düşük ısı akısı koşulu (50 W) altında incelenmiştir. Analizlerde, %0,5 hacimsel oranda hibrit nanoakışkan süspansiyonu ve Fe+ZnO kombinasyonu (50:50) olarak dikkate alınmıştır. Sayısal simülasyonlar için Hesaplamalı Akışkanlar Dinamiği yaklaşımı ve Akışkan Hacmi çok fazlı modeli kullanılmıştır. Hem saf su hem de bahsi geçen hibrit nanoakışkan için akışkan ortamındaki buhar hacmi fraksiyonları ve hız vektörleri elde edilmiştir. Her bir çalışma akışkanı için kabarcıklanma başlangıcı ve zamanla bunların yüzeyden ayrılışları incelenmiştir. Aynı şartlar altında saf suyun ve hibrit nanoakışkanın sırasıyla 468. ve 441. saniyelerde kaynamaya başladığı gözlemlenmiştir. Sayısal bulgular, hibrit nanoakışkanların iyileştirilmiş ısı transfer özellikleri sağlamak için havuz kaynama uygulamalarında kullanılabileceğini göstermiştir.

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1. INTRODUCTION

Boiling occurs in many industrial processes and it provides a great number of heat fluxes because of higher values of convective heat transfer coefficients, compared to its counterparts. Even though higher heat transfer coefficients exist, the necessity of a bit difference between the temperatures of liquid and the heater in boiling processes can adversely affect the overall system performance (specifically in low heat flux conditions), which limits to obtain optimum heat transfer properties. To deal with this issue, the following two methods suggested by many researchers can be utilized: (1) modifying the surface-related properties (e.g. roughness) of the heater, and (2) enhancing the thermophysical properties (e.g. thermal conductivity) of the working fluid [1]. As stated by many researchers, an increase in the amount of generated bubbles in the liquid media accounts for the increases not just on nucleation sites, but also convective (boiling) heat transfer coefficient [2-4]. The unary and hybrid nanofluids have been utilized as working fluid in many thermal systems by many researchers and the common idea is that nanofluids, in general, enhance the thermophysical properties of the base fluid they were added, and hence, provides an efficient heat transfer. To illustrate; Gupta et al. numerically analyzed the pool boiling heat transfer characteristics of alumina-water nanofluid prepared under varying concentrations (0.001%, 0.005%, 0.01%, and 0.05% vol.). They stated that under constant heat flux, the heat transfer coefficient increased with increasing pressure, and an increment in nanoparticle concentration corresponded to an increase in boiling heat transfer coefficient, which was because of the increase in thermal conductivity of the nanofluid, compared to base fluid (water) [5]. Salehi and Hormozi numerically studied the nucleate pool boiling processes of water/silica nanofluid (0.1% vol.) and water considering the Euler multiphase approach. For the parameters associated with the bubbles generated during boiling, they employed the heat flux division model and verified their findings with empirical results. Moreover, they utilized some verified correlations to define nucleation sites, the density of bubbles, and bubble departure frequency, and remarked that the Hibiki-Ishii and Hattan-Hall correlations were the best ones. They also observed that the nanoparticles accumulated on the heater surface impacted the boiling heat transfer characteristics remarkably [6]. Via numerical simulations, Hussien et al. investigated the heat transfer upgrading of water-based alumina-graphene binary hybrid nanofluid that flows in a mini tube. They tested the working fluids they prepared in a variety of mini tube sizes (2.1 mm - 0.8 mm) and generated a homogeneous numerical model to specify the heat transfer performance of hybrid nanofluids. Their findings presented that alumina-water nanofluid usage increased the convection heat transfer characteristics significantly. Another significant point reported by the investigators was the maximum enhancement rate in heat transfer coefficient as up to 13.7% [7]. Aminfar et al. investigated the nucleate pool boiling heat transfer characteristics of nanofluids prepared by using alumina and silica nanoparticles via a series of CFD (Computational Fluid Dynamics) analyses. By utilizing two-phase and three-phase mixture models, they achieved the boiling curves, vapor fractions, velocity vectors, and streamlines at the end of the boiling process of the nanofluid. They also compared their results with experimental data and concluded that both results were in good agreement with each other, with deviations of 5.33% for alumina nanofluid, and 8.22% for silica nanofluid. Furthermore, they compared their data with the correlations validated in previous studies [8]. Rahimian et al. experimentally studied the pool boiling properties of the water-based silicon dioxide and titanium dioxide nanofluid suspensions on a cylindrical, stainless steel heater that is of 15 mm in diameter, 80 mm in length. They formed the boiling curves for each fluid by carrying out temperature measurements on the center of the heater. Their main observation was the accumulation of silica and titanium dioxide nanoparticles on the heater surface, which caused critical heat flux to increase at the rate of 120%. Furthermore, the film boiling heat transfer, which was another parameter they considered, also improved with the use of nanofluid suspensions [9]. Mohammed et al. carried out a numerical study for specifying the influences of concentration rate of nanoparticle, boiler temperature, and fluid velocity on the boiling and phase change characteristics by utilizing the CFD method considering the user-defined function they derived. They utilized, in their numerical calculations, four phases as liquid acetone, vapor acetone, liquid acetone/ZnBr2 solution, and solid nanoparticles. They used ANSYS Fluent 15.0 software by activating the Volume-of-Fluid (VOF) multiphase model, and their results depicted that the vapor volume fraction and heat transfer coefficient increased with increasing nanoparticle concentration (0% - 1%) [10].

Numerical analysis is widely preferred, especially in the validation of the results obtained by experimental studies, and can be performed on almost all heat transfer and fluid flow problems via factual assumptions [11, 12]. In order to reduce the number of tests required in the solution of such problems, a range of analyses can be carried out. CFD approach, as known to all, is a numerical analysis method utilized to solve fluid flow, heat, and mass transfer problems. In this approach, detailed information regarding the solution domain (shear stress, pressure, etc.) can be obtained by solving a set of equations that define the fluid motion in a volume of interest [13]. It is also known that in numerical analysis, a set of equations that were set up by the user are solved on the solution domain. In this study, the equations of conservation of mass, conservation of energy, governing equation for diffusion in VOF(Volume-of-Fluid) multiphase flow model, and RNG k-ε turbulent model were solved. The theoretical background for these equations can be found in the references [11] and [12].

In this numerical study, pool boiling heat transfer characteristics of dilute hybrid nanofluid at the volumetric concentration of 0.5% were investigated. The reason why choosing the combination of Fe and ZnO nanoparticles is to exploit the higher thermal conductivity properties of Fe nanoparticles and better stability characteristics of the ZnO nanoparticles simultaneously. The other thermophysical properties of each nanoparticle, which are relatively better than other kinds of materials, are also another reason for this selection. A cylindrical boiling cell in which a cylindrical heater was mounted was taken into account. The 2D model of the boiling cell was formed, a mesh structure on it was generated and then numerical analyses were performed in ANSYS Fluent software. The calculations were carried out for deionized water and hybrid nanofluid, and vapor volume fractions, velocity contours, and velocity vectors were obtained for each working fluid, and then these data were compared to each other. The usage of hybrid nanofluid suspension in thermal systems is increasing day by day, and thereby, it is thought that outcomes of this study will provide important information on pool boiling heat transfer characteristics of dilute Fe+ZnO/deionized water hybrid nanofluid under low heat flux conditions.

2. MATERIAL & METHOD

2.1. 2D Model & Mesh Generation

ANSYS Fluent was employed in numerical analysis. At first, the 2D pool boiling cell was formed in the Designmodeler section of the software by getting inspired from an experimental rig (Figure 1). Considering the real dimensions of the test rig, the generated 2D boiling cell model was of 0.08 m in width and 0.3 m in length. Besides, the heater was located 0.05 m above from the base and was of 0.042 m width and 0.0127 m length.

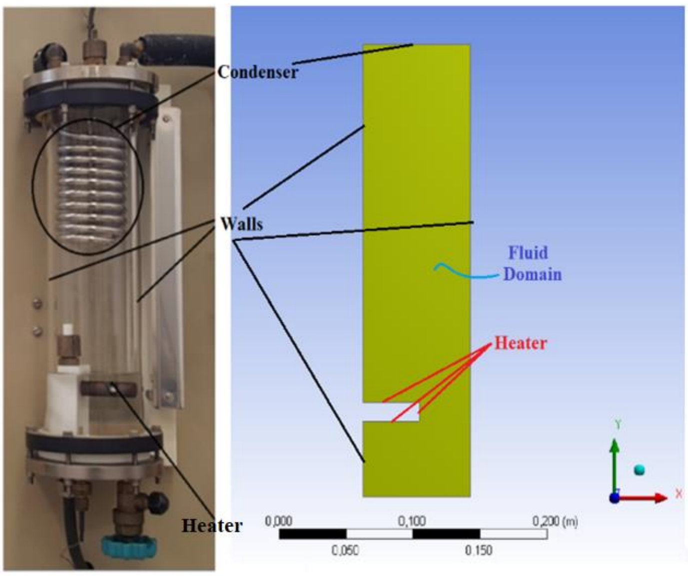


Figure 1. *The generated model in Designmodeler*

With the usage of this model, the boiling regimes of transition boiling and film boiling can be easily illustrated because it is too tough to see these kinds of boiling modes in an empirical study. Right after forming the model on ANSYS Designmodeler, the solution area (mesh structure) was constituted in the Mesh module taking into account the similar approach implemented in the reference study [14]. As illustrated in Figure 2, the mesh structure was comprised of quadrilateral elements. Moreover, in Table 1, some mesh metrics were presented.

Table 1. *Some mesh metrics for the solution domain*

Metrics	Value
Elements	105316
Nodes	106565
Skewness (avg.)	0.00256
Element quality (avg.)	0.9621
Orthogonal quality (avg.)	0.9938

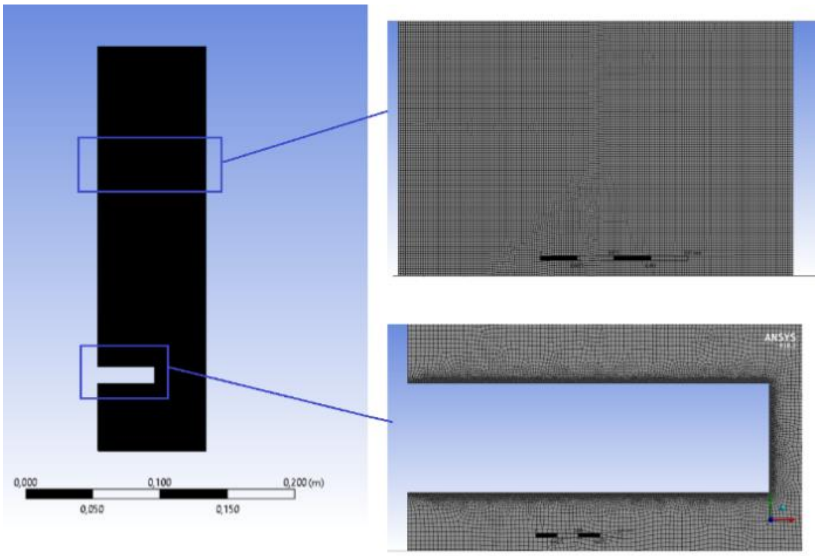


Figure 2. *The mesh model generated for numerical analysis*

As stated earlier, the RNG k-ε turbulence model was employed in simulations because nanoparticles added into the distilled water increase the turbulence intensity of the fluid as a result of the interactions & collisions between the nanoparticles [11]. Moreover, the pool boiling regime contains non-uniform, perpetual movements of bubbles during the bubble generation and bubble extinction process. Thus, a turbulence model was utilized in numerical analysis to provide more actual results. RNG k- ε turbulence model yielded more accurate and reliable outcomes than the standard k- ε turbulence model for wider flow classification. Therefore, the RNG k- ε turbulence model was preferred in the solution.

2.2. Operating & Boundary Conditions

Nucleate pool boiling heat transfer characteristics of dilute Fe+ZnO/deionized water hybrid nanofluid were investigated under low heat flux condition. To make a comparison for illustration of the effects of hybrid nanoparticles on bubble-associated properties during pool boiling, the analysis was initially carried out for deionized water and dilute hybrid nanofluid. Such thermophysical properties of the nanofluid as viscosity, density, and thermal conductivity were manually entered into the Fluent software interface because they were unconventional fluids. All these thermophysical properties were theoretically calculated by using the correlations in literature [15]. The main assumption for hybrid nanofluid simulation was that the fluid was uniform. Besides, the evaporation-condensation mechanism was enabled for the demonstration of boiling regimes. The dilute hybrid nanofluid at the final volumetric rate of 0.5% was also taken into consideration in simulations. Since the time-dependent (transient) solution method was used, time step size and number of time steps were set as 0.0003 s and 2500, respectively.

The pressure-based solver was used for all analyses. The other operating & boundary conditions can be seen in Table 2. Besides, the thermophysical properties of each working fluid were presented in Table 3.

Table 2. *The boundary & operating conditions employed in simulations*

Model	**Sub-model / Definition**
Multiphase	Volume-of-Fluid (VOF), Implicit Body Force, Explicit Formulation
Energy	Enabled
Gravity	Enabled (y direction, -9.81 m/s^2)
Turbulence model	RNG k-ε, Enhanced Wall Treatment, Thermal Effects, Curvature Correction
Number of time steps	2500
Time step size	0.0003 s
Heat flux	50 W/m^2
Heater material	Copper (smooth)

Table 3. *Thermophysical properties of each working fluid utilized in the analysis*

Working Fluid Type / Thermophysical Property	**Deionized Water**		**Fe+ZnO/Deionized Water**	
	Liquid	**Vapor**	**Liquid**	**Vapor**
Density (kg/m^3)	998.2	0.5542	1025.54	0.6
Specific heat (j/kgK)	4182	4180	4058	2300
Thermal conductivity (W/mK)	0.6	0.0261	0.622	0.71
Viscosity (kg/ms)	0.001003	0.0000134	0.0014528	0.00065
Reference temperature (K)	298.15			

Since constant heat flux boundary condition (50 W/m^2) was identified for the heater, its surface temperature was not considered. Besides, it is thought that heater surface temperature does not become constant at any time because of the continuous movement of working fluid. The thermophysical properties of each nanoparticle constituting the assumed hybrid nanofluid were also provided in Table 4.

Table 4. *Thermophysical properties of Fe and ZnO nanoparticles*

Physical / Thermophysical Properties	**Fe (Iron)**	**ZnO (Zinc Oxide)**
Molar mass (g/mol)	55.85	81.406
Melting point (K)	1809	2247
Density (g/cm^3)	7.8	5.61
Thermal conductivity (W/mK)	76.2	50
Heat capacity (J/kgK)	440	495.21

2.3. Grid (mesh) Independency

The obtained results from numerical analysis are acceptable on condition that alterations in mesh properties do not affect the results, and hence a mesh independence study should also be performed in numerical simulations. In this study, for meshing independency, 5 various mesh (grid) structures varying from the coarse to the fine, each of which includes a different number of elements and nodes were generated, and the changes in vapor temperature around the condenser area were traced. In Table 5, details of the formed meshes, some mesh metrics of each, and vapor temperature values acquired from the simulations were presented. As far as all results were evaluated simultaneously, it was concluded that the most suitable mesh was the Mesh4, and thereby, all simulations were carried out using this mesh.

Table 5. *The obtained results for mesh independency*

Mesh details	$Mesh_1$	$Mesh_2$	$Mesh_3$	$Mesh_4$	$Mesh_5$
Elements	11550	23200	49300	105316	105990
Nodes	10827	25365	54027	106565	107137
Skewness (max.)	$5.3x10^{-4}$	$3.4x10^{-4}$	$6.1x10^{-5}$	$4.8x10^{-6}$	$6.2x10^{-6}$
Element quality (avg.)	0.85	0.88	0.91	0.94	0.97
Vapor temperature (K)	381.32	381.86	381.15	381.15	381.17

3. RESULTS & DISCUSSION

As stated before, vapor volume fractions, velocity contour, and velocity vectors on the solution area were investigated. The vapor volume fractions illustrate the bubble characteristics such as bubble generation, bubble departure and so on, as well as the boiling regime. The obtained results for deionized water were provided in Figure 3 and Figure 4. Vapor volume fractions for different times were presented in Figure 3, whilst Figure 4 displayed both the velocity contour and the velocity vectors. The first observation in Figure 3 was that the bubble formations were started to be observed at nearly 468. seconds, when deionized water was used as working fluid. With increasing time, the number of bubble formation areas (i.e. bubble generation) was increasing gradually as a result of the increasing bulk temperature of the liquid. The increment in bulk liquid temperature also contributed to the departure of the bubbles, as can be seen specifically in the final phases of the analysis.

The velocity contours and velocity vectors in the solution domain gave an idea about the fluid motion during the nucleate pool boiling process. When deionized water was simulated, the fluid movement mainly concentrated around the heater, as expected, since increasing temperature difference between the heater and the liquid caused convection to occur. Besides, both the vectors and the contour obtained confirmed that the evaporation-condensation phenomenon was successfully identified in Fluent software.

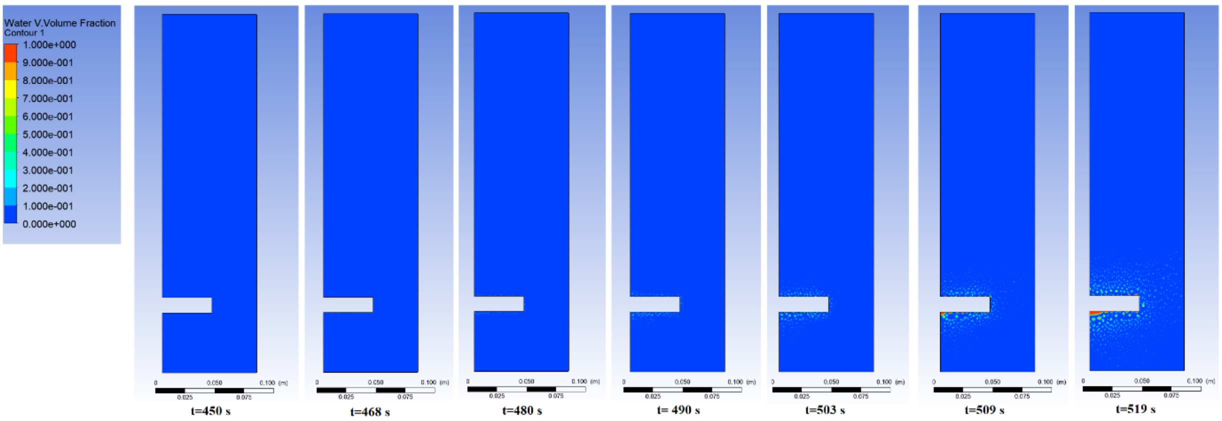


Figure 3. *Vapor volume fractions for deionized water*

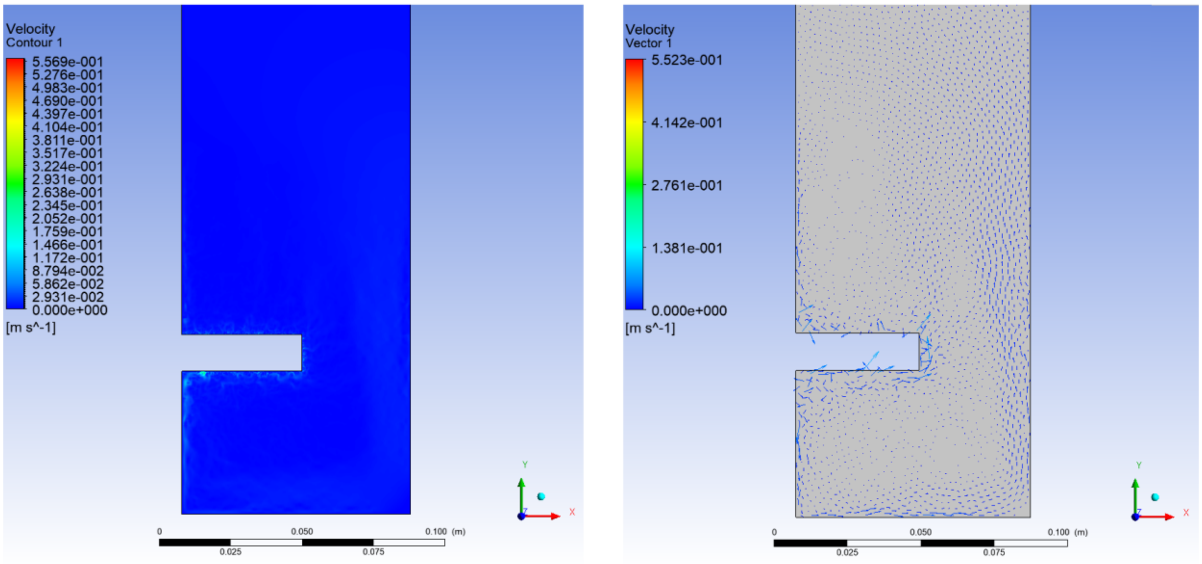


Figure 4. *Velocity contour and velocity vectors for deionized water*

When the analysis was conducted for dilute hybrid nanofluid of Fe+ZnO nanoparticles, the beginning time of the boiling was decreased to around 441 seconds, which was nearly 468 s for deionized water. This result depicted that hybrid nanoparticle addition inside the deionized water improved the heat transfer properties of the fluid.

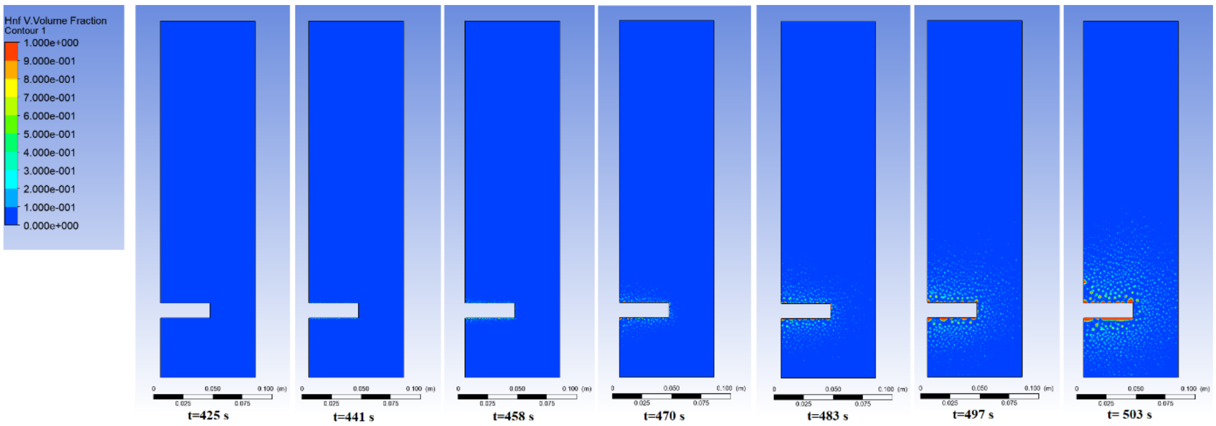


Figure 5. *Vapor volume fractions for Fe+ZnO/deionized water hybrid nanofluid*

The nanoparticles increased the turbulence intensity within the fluid due to interactions as well as collisions in base fluid. Moreover, when the addition of nanoparticles, novel heat transfer areas were emerged inside the fluid, which facilitated the heat transfer both in fluid and between the heater and the fluid of interest. With increasing analysis time, this effect can be clearly seen.

Also, the transition boiling and film boiling regimes can be viewed at 483 seconds and 503 seconds analysis time, respectively. As a comparison, considering the 503. seconds, the number of bubble generation and departing bubbles were much more when dilute hybrid nanofluid was utilized, compared to deionized water, which indicated that heat transfer rate could be enhanced in nucleate pool boiling processes by the addition of Fe+ZnO nanoparticles (Figure 5). As another result, it can be said that the good stability of ZnO nanoparticles and high thermal conductivity of Fe nanoparticles upgraded the heat transfer performance.

As to velocity-related results, when velocity vectors and velocity contour presented in Figure 6 for dilute hybrid nanofluid of Fe+ZnO nanoparticles were considered, it was observed that nanoparticle addition inside the base fluid also increased the mobility in the fluid of interest due to the increasing turbulence in fluid medium. Figure 6 also exhibited that the fluid flow mechanism in the fluid was altered by the addition of nanoparticles. These changes in velocity contours are thought to be due to the onset time of boiling because this process took place before deionized water for dilute hybrid nanofluid.

To better understand how hybrid utilization of nanoparticles affect the boiling regime, the vapor volume fractions of single nanofluids, that is Fe/deionized water and ZnO/deionized water were provided in Figure 7 for 503. seconds of the boiling process. As it is clear that the number of nucleation sites, notably around the heater, is much more for hybrid nanofluid than the single type nanofluid, which denotes that a hybrid combination of nanoparticles increased the thermophysical properties of the nanofluid suspension remarkably.

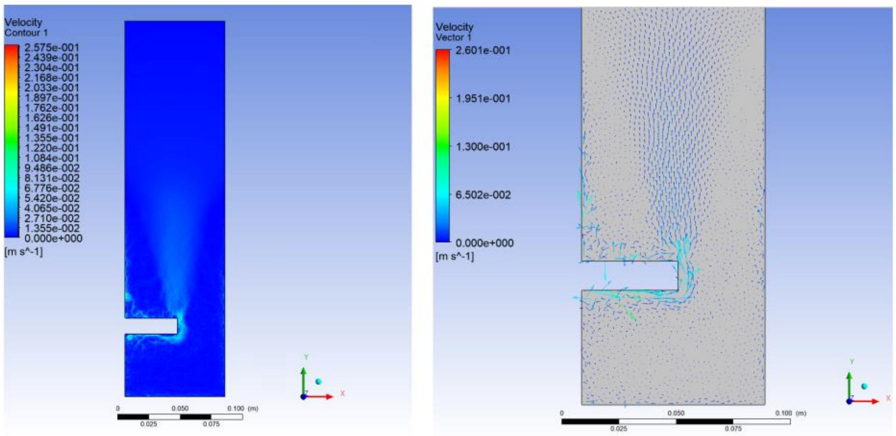
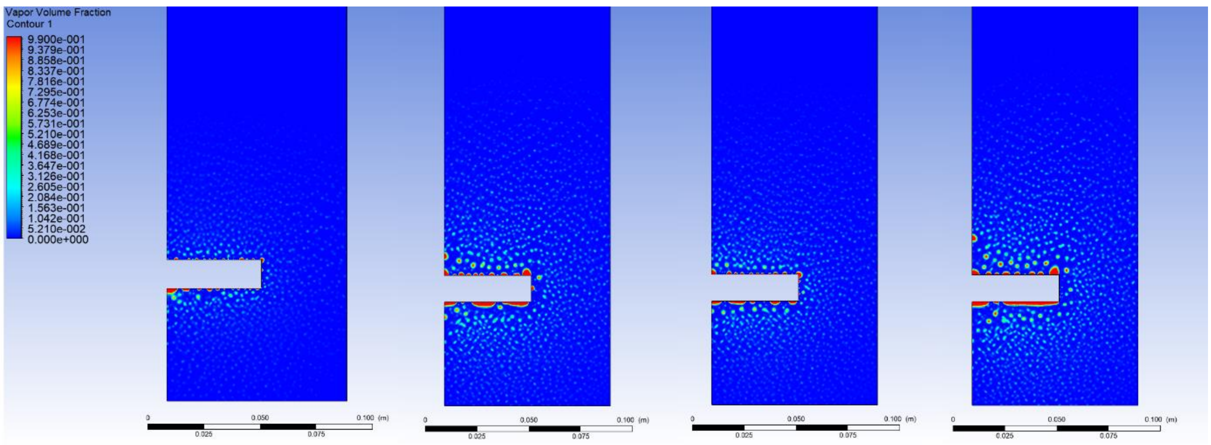


Figure 6. *Velocity contour and velocity vectors for Fe+ZnO/deionized water hybrid nanofluid*



Deionized water ***Fe/Deionized water*** ***ZnO/Deionized water*** ***Fe+ZnO/Deionized water***

Figure 7. *Comparison of the nucleation sites at 503. seconds of the process for each working fluid*

Generally speaking, the hybrid nanoparticles also increase the number of possible nucleation sites in the medium. Besides, as known to all, the nanoparticles can flocculate and then precipitate during operation, and in most processes, it is not desired. However, in boiling processes, the nanoparticles accumulating on the heater surface form a layer, which also improves the heat transfer rate that corresponds to a decrease in boiling delay [6]. This layer can be viewed in the velocity contour of dilute hybrid nanofluid when the upper surface of the heater was examined in detail. In addition, an increase in turbulence has positively influenced the heat convection, which also corresponds to an increase in heat transfer-associated characteristics, specifically the heat transfer coefficient. The nanoparticles have higher thermal conductivity rates compared to liquid materials, which was one of the reasons for describing the nanofluids' upgraded thermal performance. Besides, the condensation of fluid at the top of the solution domain could not be observed in the analysis since the heating power is rather low; however, velocity vectors illustrated that continuous evaporation-condensation occurs, which means that the CFD model was described truly and the operating & boundary conditions were applied successfully.

Compared to our findings with a similar study conducted by Gupta et al., almost the same conclusions were obtained; that is, for constant pressure and heat flux conditions, the heat transfer coefficient increased with the help of nanoparticles [5]. As another comparison, Mohammed et al. utilized both ANSYS Fluent 15.0 and Volume-of-Fluid (VOF) mixture multiphase flow model in their simulations for pool boiling and concluded that increasing nanoparticle concentration from 0% to 1% led vapor volume fraction and heat transfer coefficient to increase [10]. Besides, Sato and Niceno performed several numerical analyses for simulating both nucleate and film boiling regimes under atmospheric conditions and illustrated the temperature distributions. As a conclusion, they stated heat transfer properties could be estimated via CFD simulations [16].

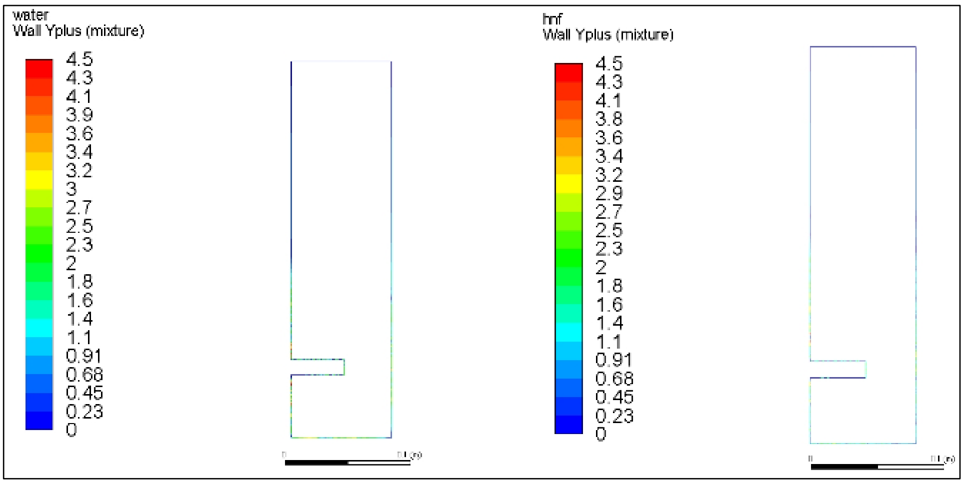


Figure 8. *Wall y^+ values*

The flow behaviour near the wall is generally a complicated phenomenon and in order to distinguish the different regions near the wall, the concept of wall y^+ has been formulated. Therefore, y^+ is a dimensionless quantity and is the distance from the wall measured in terms of viscous lengths. The calculated wall y^+ values were given in Figure 8 as the contours. It can be seen that the calculated y^+ values are in the acceptable range ($y^+<5$).

4. CONCLUSION

Nucleate pool boiling heat transfer characteristics of dilute, aqueous hybrid nanofluid containing Fe and ZnO nanoparticles at the Fe:ZnO combination of 50:50 and the final concentration of 0.5% (vol.) were numerically investigated in this study via ANSYS Fluent. A cylindrical heater-including boiling cell was modeled in DesignModeler module of the software, and then the mesh generation process was performed. For numerical comparison on low heat flux condition, the calculations were carried out for deionized water at first, and then hybrid nanofluid. The findings that cannot be obtained experimentally including volume fractions, velocity contours, and velocity vectors were illustrated for each working fluid. The fundamental outcomes of this study were as follows:

- The starting time of the boiling was recorded as 468. seconds for deionized water, and 441. seconds for dilute hybrid nanofluid, which illustrated that dilute hybrid nanofluid provided more efficient heat transfer between the heater and the fluid than deionized water under low heat flux condition.
- The velocity contours and velocity vectors showed the movement of flow around the heater from the heater to the condenser area.

- Transition and film boiling processes which cannot be viewed in operation or attained from any experiment were illustrated by numerical analysis.
- It was shown that dilute hybrid nanofluids can be used in pool boiling applications even in low heat flux conditions.

REFERENCES

[1] Ham J., Kim H., Shin Y., Cho, H. (2017). Experimental investigation of pool boiling characteristics in Al2O3 nanofluid according to surface roughness and concentration. International Journal of Thermal Sciences, 114, 86-97.

[2] You S.M., Kim J.H., Kim K.H. (2003). Effect of nanoparticles on critical heat flux of water in pool boiling heat transfer. Applied Physics Letters, 83, 374-3376.

[3] Park H., Lee S.J., Jung S.Y. (2019). Effect of nanofluid formation methods on behaviors of boiling bubbles. International Journal of Heat and Mass Transfer, 135, 1312-1318.

[4] Rostamzadeh A., Jafarpur K., Rad E.G. (2016). Numerical investigation of pool nucleate boiling in nanofluid with lattice boltzmann method. Journal of Theoretical and Applied Mechanics, 54, 811-825.

[5] Gupta R.R., Bhambi S., Agarwal, V.K. (2019). CFD modeling for nucleate pool boiling of nanofluids. Numerical Heat Transfer, Part A: Applications, 75, 402-412.

[6] Salehi H., Hormozi F. (2019). Prediction of Al_2O_3–water nanofluids pool boiling heat transfer coefficient at low heat fluxes by using response surface methodology. Journal of Thermal Analysis and Calorimetry, 137, 1069-1082.

[7] Hussien A.A., Yusop N.M., Al-Nimr M.A., Abdullah M.Z., Janvekar A.A., Elnaggar M.H. (2019). Numerical study of heat transfer enhancement using Al2O3-graphene/ water hybrid nanofluid flow in mini tubes. Iranian Journal of Science and Technology, Transactions A, Science, 43, 1989–2000.

[8] Aminfar H., Mohammadpourfard M., Sahraro M. (2012). Numerical simulation of nucleate pool boiling on the horizontal surface for nano-fluid using wall heat flux partitioning method. Computers & Fluids, 66, 29-38.

[9] Rahimian A., Kazeminejad H., Khalafi H., Mirvakili S. M., Akhavan A. (2020). An experimental study of the steel cylinder quenching in water-based nanofluids. International Journal of Engineering Transactions A: Basics, 33, 28-33.

[10] Mohammed H.I., Giddings D., Walker, G.S. (2018). CFD simulation of a concentrated salt nanofluid flow boiling in a rectangular tube. International Journal of Heat and Mass Transfer, 125, 218-228.

[11] Çiftçi E., Sözen A. (2020). A numerical study on performance improvement in boiling heat transfer via dichloromethane-based nanofluid utilization. Politeknik Dergisi, 23(3), 849-857.

[12] Çiftçi E., Sözen A. (2021). Heat transfer enhancement in pool boiling & condensation using h-BN/DCM and SiO2/DCM nanofluids: experimental & numerical comparison. International Journal of Numerical Methods for Heat & Fluid Flow, 31(1), 26-52.

[13] Afshari F., Zavaragh H.G., Di Nicola G. (2018). Numerical analysis of ball-type turbulators in tube heat exchangers with computational fluid dynamic simulations. International Journal of Environmental Science and Technology, 16, 3771-3780.

[14] Spiegel M., Redel T., Zhang Y.J., Struffert T., Hornegger J., Grossman R.G., Karmonik C. (2011). Tetrahedral vs. polyhedral mesh size evaluation on flow velocity and wall shear stress for cerebral hemodynamic simulation. Computer Methods in Biomechanics and Biomedical Engineering, 14, 9-22.

[15] Çiftçi E. (2020). Investigation of the thermophysical properties of AlN+ZnO/deionized water hybrid nanofluid. International Journal of Energy Studies, 5, 59-67.

[16] Sato Y., Niceno, B. (2018). Pool boiling simulation using an interface tracking method: from nucleate boiling to film boiling regime through critical heat flux. International Journal of Heat and Mass Transfer, 125, 876-890.