POLİTEKNİK DERGİSİ

JOURNAL of POLYTECHNIC

ISSN: 1302-0900 (PRINT), ISSN: 2147-9429 (ONLINE)
URL: http://dergipark.org.tr/politeknik

A numerical study on performance improvement in boiling heat transfer via dichloromethane-based nanofluid utilization

Diklorometan esaslı nanoakışkan kullanımıyla kaynama ısı transferinde performans iyileştirme üzerine sayısal bir çalışma

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Bu makaleye şu şekilde atıfta bulunabilirsiniz(To cite to this article): Çiftçi E. and Sözen A., "A numerical study on performance improvement in boiling heat transfer via dichloromethane-based nanofluid utilization", ***Politeknik Dergisi***, 23(3): 849-857, (2020).

Erişim linki (To link to this article): http://dergipark.org.tr/politeknik/archive

DOI: **10.2339/politeknik.697085**

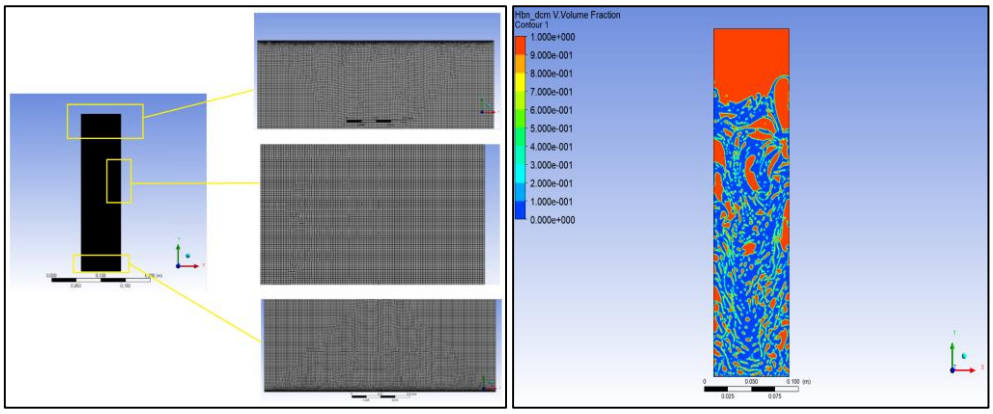
A Numerical Study on Performance Improvement in Boiling Heat Transfer via Dichloromethane-Based Nanofluid Utilization

Highlights

- *Boiling heat transfer characteristics of hexagonal boron nitride nanoparticles containing dichloromethane nanofluid (h-BN/DCM) were numerically investigated.*
- *Vapor volume fractions, velocity & temperature contours and velocity vectors were illustrated both for base fluid and nanofluid suspension.*
- *Nanoparticle addition into the base fluid enhanced the heat transfer characteristics under pool boiling conditions.*

Graphical Abstract

A series of numerical simulation was carried out for determining the pool boiling heat transfer properties of solvent-based nanofluid (h-BN/DCM) solution.



(a) **(b)**

Figure. The generated mesh model (a) and vapor volume fractions at the end of the analysis

Aim

Numerically specify the pool boiling heat transfer characteristics of h-BN/DCM nanofluid.

Design & Methodology

ANSYS Fluent was used in numerical simulations. Nanoparticle concentration and heat flux were 1.0% and 200 W/m^2, respectively.

Originality

A solvent-based nanofluid was analyzed, heat transfer and fluid flow characteristics were determined.

Findings

The beginning time of the boiling for the base fluid (DCM) and nanofluid solution (h-BN/DCM) were observed as 230 s and 215 s, respectively.

Conclusion

Nanoparticle addition into the base fluid enhanced the heat transfer characteristics under pool boiling conditions.

Declaration of Ethical Standards

The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Diklorometan Esaslı Nanoakışkan Kullanımıyla Kaynama Isı Transferinde Performans İyileştirme Üzerine Sayısal Bir Çalışma

Araştırma Makalesi / Research Article

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(Geliş/Received : 02.09.2019 ; Kabul/Accepted : 24.12.2019)

ÖZ

Nanoakışkanlar koloidal süspansiyonlardır ve ısıtmadan soğutmaya kadar birçok ısı transfer uygulamasında sıklıkla kullanılmaktadır. Bu çalışmada temel akışkan içerisine nanoparçacık ilavesinin havuz kaynama ısı transferi üzerindeki etkisini sayısal olarak belirlemek amacıyla nanoparçacık ve temel akışkan malzemeleri olarak sırasıyla hekzagonal bor nitrür ve diklorometan kullanılarak bir dizi sayısal analiz gerçekleştirilmiştir. Nanoakışkan çözeltisi, hekzagonal bor nitrür nanoparçacıklarının diklorometan ile hacimce %1.0 oranında karıştırılmasıyla hazırlanmış ve sistemin çalışması esnasında nanoparçacıkların topaklanmasını önlemek için bu çözeltiye Sodyum Dodesil Benzen Sülfonat ilave edilmiştir. Hesaplamalı Akışkanlar Dinamiği (HAD) yaklaşımının kullanıldığı bu çalışmada, sayısal analizler için ANSYS Fluent yazılımı kullanılmıştır. Karşılaştırma yapabilmek için, hem diklorometan hem de hekzagonal bor nitrür nanoparçacıkları içeren diklorometan (nanoakışkan) çözeltileri için analizler yapılmıştır. Her iş akışkanı için buhar hacim fraksiyonları, hız vektörleri ve hız konturları belirlenerek elde edilen sonuçlar irdelenmiştir.

Anahtar Kelimeler: Havuz kaynama, nanoakışkan, hekzagonal bor nitrür, Hesaplamalı Akışkanlar Dinamiği.

A Numerical Study on Performance Improvement in Boiling Heat Transfer via Dichloromethane-Based Nanofluid Utilization

ABSTRACT

Nanofluids are colloidal suspensions and have been utilized frequently in heat transfer implementations ranging from heating to cooling. In this study, for numerically specifying the influence of nanoparticle addition inside the base fluid on pool boiling heat transfer, a series of numerical analyses were performed by using hexagonal boron nitride and dichloromethane as nanoparticle and base fluid material, respectively. The nanofluid solution was prepared by doping hexagonal boron nitride nanoparticles into the dichloromethane at the rate of 1.0% (vol.) and Sodium Dodecyl Benzene Sulfonate was added into this solution to prevent nanoparticle compilation during operation. Computational Fluid Dynamics (CFD) approach was preferred and ANSYS Fluent software was used for numerical analysis. In order to be able to make comparison, analysis was performed both dichloromethane and hexagonal boron nitride nanoparticles containing dichloromethane, i.e. nanofluid, solutions. Vapour volume fractions, velocity vectors, and contours for each working fluid were determined and discussed.

Keywords: Pool boiling, nanofluid, hexagonal boron nitride, Computational Fluid Dynamics.

1. INTRODUCTION

Increasing energy demand and environmental pollution, together with developing technology, have caused to emerge new technologies for the development of energy systems. Nanoparticle technology, which includes the production and characterization processes of nanoparticles used in many different areas varying from thin-film layers to fuel cells, has also great importance on that development. Through this technology, more efficient and faster heat transfer can be realized by preparing nanoparticle-containing working fluids. These nanoparticle-containing colloidal solutions are generally called as nanofluid. It is a known fact that liquids have lower thermal conductivity than solids and this has led to the emergence of nanofluids [1]. Nanofluids generally consist of three main components as follows: a nanoscale form of a material (metal oxides, ceramics, etc.), i.e. nanoparticles, a base fluid (deionized water, ethylene glycol, etc.), and a surfactant (such as SDBS (Sodium Dodecyl Benzene Sulfonate)). Nanofluid solutions are obtained by mixing these three basic components in certain proportions.

Convective heat transfer taking place at solid-liquid interface is called boiling. The boiling process in which high heat fluxes have emerged is largely faced in many heat transfer processes like nuclear plants and HVAC systems. For improving the heat transfer performance in

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boiling, in general, following two methods can be used both separately and/or at the same time: Modifications in surface roughness of the heater, which led bubble formation and its departure to vary, and enhancement of wetting capability of the working fluid by using hydrophilicity or hydrophobicity properties of a material [2]. Besides, the thermophysical properties of the working fluid have a great influence on boiling heat transfer performance as well. Hence, the more the thermophysical properties of the working fluid are enhanced, the higher the thermal performance.

Numerical analysis has been widely used for describing the details that cannot be obtained by experiments like velocity and temperature distributions in fluid flow, heat and mass transfer problems faced in engineering systems. It also helps reducing the number of tests in experimental work. Hence, as can be estimated, boiling phenomena was investigated with a numerical analysis approach by many researchers as well. Ham and Cho (2016) numerically investigated the influence of volume concentration and size of the nanoparticle on nanofluid boiling, by using the HFP (heat flux partitioning) model consisting of evaporation, quenching, and natural convection mechanisms, together with variations in contact angle. They used alumina nanofluid with varying concentrations, light transmission, and dispersion stability characteristics in the analysis. They specified the bubble departure diameter, departure frequency and density of the nucleate site. They also considered the influence of contact angle in their numerical models for the exact estimation of the boiling phenomenon. As nanoparticle size, they used nanoparticles in 25 nm, 50 nm, and 75 nm size. They compared to their numerical analysis results with varying experimental and numerical analysis results. They reported that the frequency of bubble departure declined and the bubble departure diameter increased at higher nanofluid concentration. Moreover, they observed that surface wettability for all nanoparticle sizes increased with the increase of the nanofluid concentration and slightly increased with the increase of nanoparticle size [3]. Ebrahimian and Ansarifar (2016) investigated numerically the nanofluid utilization as a coolant in a nuclear reactor. They used low concentration alumina nanoparticles containing nanofluid ranging from 0.001% to 0.05% in their analysis. The sizes of the nanoparticles they used were 10 nm, 20 nm, 50 nm, 70 nm, and 100 nm. They simulated the fuel assembly in a hot channel by using the Computational Fluid Dynamics approach. To provide such thermophysical properties of the nanofluid as density, specific heat, viscosity and thermal conductivity for boundary conditions of their numerical simulations, they employed theoretically derived equations. They investigated the influence of nanoparticles on the heat transfer coefficient with the alterations of volume concentration and nanoparticle size. They concluded that the temperature of the fuel centre utilizing nanofluid was declined, because of the fact that nanoparticle size became smaller and the volume fraction was increased. They observed a remarkable increment in the convection heat transfer coefficient because nanoparticle size became smaller and the volume fraction was increased [4]. Shoghl et al. (2014) performed a numerical study on bubble dynamics in pool boiling of nanofluid with coated and Sodium Dodecyl Sulfonate (SDS) solution with different nanoparticles for mathematical modeling of bubbles in the boiling of deionized water. They also experimentally investigated the shapes, numbers, contact angle of bubbles, and verified them by findings obtained from the numerical analysis. They obtained extensive changes in bubble dynamics and surface wettability by a porous layer of nanoparticles and SDS solution. They illustrated that the growth time of bubbles altered by the presence of porous layers and SDS surfactant solution, which resulted from a change in surface tension force [5].

Hexagonal boron nitride ($h-BN$) is a white, non-toxic and slippery material, and is of 2.27 g/cm3 density. Its crystal structure is similar to graphite; nevertheless, the main difference from graphite is high electrical resistance and colour. It does not react chemically, and has resistance to very high temperature values. In addition to being stable against thermal shocks, it has high thermal conductivity, superior electrical insulation as well as copper and superior lubrication specifications. Furthermore, dichloromethane is a synthetic chemical substance that is not found in nature. It is colourless, has a soft, sweet smell and is liquid at room temperature. Its boiling temperature, specific heat capacity, and thermal conductivity values are 40℃, 1.188 J/g°C, and 0.1392 W/mK at 20℃, respectively. It is extensively used in industry as a paint remover, as a solvent in aerosols, as a propellant and drug production. Besides, it is very volatile and insoluble in water.

In this study, heat and fluid flow characteristics of hexagonal boron nitride (*h-BN*) nanoparticles containing working fluid under pool boiling conditions were analysed numerically. Analysis were also performed for base fluid (dichloromethane, DCM) to illustrate the effects of nanoparticle addition inside base fluid on pool boiling heat transfer performance. It was assumed in the numerical analysis as a boundary condition that nanofluid solution was prepared by mixing h-BN nanoparticles at the rate of 1.0% (vol.) and SDBS at the rate of 0.2% (vol.) with dichloromethane. In order to show off the evaporation-condensation process step-by-step, the transient solution method was used. When taking into account the studies above, it was seen that mostly deionized water was employed as a base fluid in the preparation of nanofluid solutions. In a similar way, metallic materials were preferred by them as nanoparticle material. The novelty of this study is that the boiling heat transfer characteristics of h-BN/DCM nanofluid has not been numerically investigated before.

2. NUMERICAL ANALYSIS

There are 3 analysing methods for the solution of the engineering problems, namely; experimental, numerical

and theoretical solutions. Numerical analysis is one of the mostly-employed solution methods of them for solution of fluid flow, heat and mass transfer problems due to the fact that it is a cheap, easily applicable most of the time and the results obtained from the numerical analysis provides a better understanding and elaborately illustrates the flow characteristics, temperature and pressure distributions that cannot be attained in experiments [6-8]. ANSYS Fluent software (18.2 ed.) was used for numerical simulation of evaporation-condensation phenomena during boiling processes. At first, a 2D model was generated in DesignModeler module of the software as a rectangular boiling area. The generated 2D model had 80 mm in width and 300 mm in height. It contained 2 principle sections as an evaporator for heat intake and condenser for heat dissipation processes, respectively. The meshing step of the generated model (Figure 1) was realized in the MESH sub-program in ANSYS software by using quadrilateral mesh structure and considering the precedent studies of ref. [9-12]. The generated mesh model contained 107254 nodes and 106107 elements. This model was decided after mesh independency pre-study was conducted. In this pre-study, 5 different mesh models were generated and alterations in important mesh parameters, together with vapour temperature (T_v), the average temperature beneath the condenser section, were monitored. The obtained results were presented in Table 1. As can be seen in Table 1, the MS_5 mesh structure was the most appropriate one, hence all analysis was fulfilled by considering MS_5 mesh model.

Simulations were performed in transient and multiphase flow conditions considering the gravity as 9.81 m/s^2 on – *y* direction. Volume-of-fluid (VOF) multiphase analysis model was employed for simulating the evaporation-condensation phenomena. As an initial condition, it was assumed that there was no vapor in the system, and thereby vapor volume fraction was entered as 0 (zero) onto the software (Table 2). Moreover, the thermophysical properties of both DCM and h-BN/DCM nanofluid were set onto the program since there were no properties of each fluid in the Fluent database (Table 3). The provided thermophysical properties in Table 3 were obtained from the data sheet of dichloromethane and experimental measurements [11].

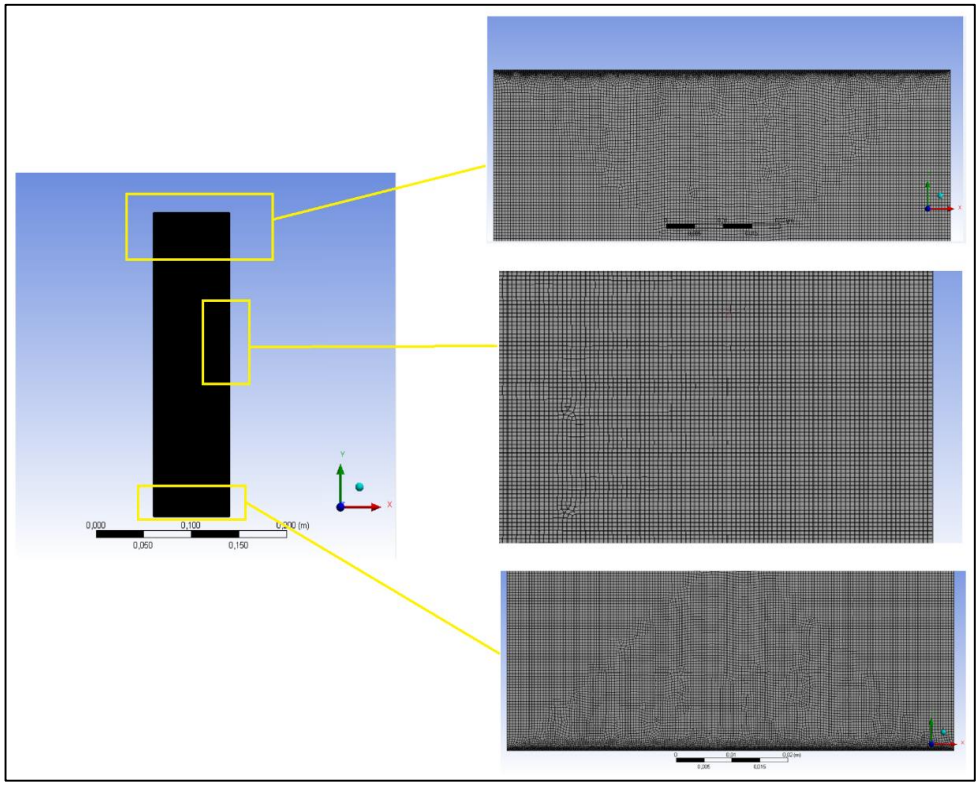

Figure 1. Details of the generated mesh model

Table 1. Obtained results from the pre-study (Mesh independency)

Mesh Metrics / Mesh Structures	**MS_1**	**MS_2**	**MS_3**	**MS_4**	**MS_5**
The number of elements	12450	25100	51204	81750	106107
The number of nodes	11280	26400	56300	82104	107254
Maximum skewness	5e-04	4e-04	5.5e-05	3e-06	6e-06
Element quality (ave.)	0.889	0.895	0.912	0.949	0.974
T_v temperature (K)	313.38	312.85	313.55	313.35	313.72

Table 2. The models/properties employed in the analysis

Model	**Submodel / Description**
Multiphase	Volume-of-Fluid
Energy	On (Activated)
Viscous	k-ε RNG, Enhanced wall treatment, Thermal effects
Surface tension	On (0.028 N/m)

Table 3. Thermophysical properties of *DCM* and *h-BN/DCM* working fluids

Thermophysical property	**DCM**		**h-BN / DCM**	
	Liquid phase	**Vapor phase**	**Liquid phase**	**Vapor phase**
Density*(kg/m^3)*	1330	2.93	1330	2.93
Specific heat capacity *(j/kgK)*	1.188	615	1.188	617
Thermal conductivity *(W/mK)*	0.1392	0.1392	0.1596	0.1596
Viscosity *(kg/ms)*	0.000413	0.000413	0.00051	0.00051
Molar weight *(kg/kmol)*	84.93			
Standard state enthalpy *(j/kgmol)*	-9.552826e+07			
Reference temperature *(K)*	298			

As is known to all, governing equations are discretized and solved for a definite domain in numerical analysis. These equations can be summarized as follows [12, 14]:

The mass conservation is:

$$\frac{\partial}{\partial t}\left(\alpha_q\rho_q\right)+\nabla.\left(\alpha_q\rho_q\vec{v}_q\right)=\sum_{p=1}^{n}(\dot{m}_{pq}-\dot{m}_{qp})+S_q \quad (1)$$

where $\vec{v}_q$, α_q, $\dot{m}_{pq}$, $\dot{m}_{qp}$ and S_q stand for velocity of phase q, the volume fraction of phase q, mass transfer between p and q phases, mass transfer between q and p phases and the source term, respectively.

Momentum equation based on the volume fraction of all actual phases by the properties of μ and ρ:

$$\frac{\partial}{\partial t}\left(\alpha_q\rho_q\vec{v}_q\right)+\nabla.\left(\alpha_q\rho_q\vec{v}_q\vec{v}_q\right)=-\alpha_q\nabla\mathrm{p}+\nabla.\bar{\bar{\tau}}_q+\alpha_q\rho_q\vec{g}+\sum_{p=1}^{n}\left(\vec{R}_{pq}+\dot{m}_{pq}\vec{v}_{pq}-\dot{m}_{qp}\vec{v}_{qp}\right)+(\vec{F}_q+\vec{F}_{lift,q}+\vec{F}_{wl,q}+\vec{F}_{vm,q}+\vec{F}_{td,q}) \quad (2)$$

In Eq.(2), $\vec{F}_q$ stands for external body force, $\vec{F}_{lift,q}$ denotes the lift force, $\vec{F}_{wl,q}$ corresponds to lubricant force of wall, $\vec{F}_{vm,q}$ is virtual mass force, $\vec{F}_{td,q}$ is turbulent dispersion force, $\vec{R}_{pq}$ denotes the interaction force between the phases, $\vec{v}_{pq}$ represents interphase velocity, and $\bar{\bar{\tau}}_q$ denotes stress-strain tensor of q phase expressed as:

$$\bar{\bar{\tau}}_q=\alpha_q\mu_q\left(\nabla\vec{v}_q+\nabla\vec{v}_q^{T}\right)+\alpha_q\left(\lambda_q-\frac{2}{3}\mu_q\right).\nabla\vec{v}_q\bar{\bar{I}} \quad (3)$$

where λ_q and μ_q are bulk and shear viscosity of phase q, respectively.

Energy equation shared between the phases is:

$$\frac{\partial}{\partial t}\left(\alpha_q\rho_q h_q\right)+\nabla\left(\alpha_q\rho_q\vec{u}_q h_q\right)=\alpha_q\frac{dp_q}{dt}+\bar{\bar{\tau}}_q.\nabla.\vec{u}_q-\nabla.\vec{q}_q+S_q+\sum_{p=1}^{n}(Q_{pq}+\dot{m}_{pq}h_{pq}-\dot{m}_{qp}h_{qp}) \quad (4)$$

In Eq. (4), h_q corresponds to specific enthalpy for phase q, $\vec{q}_q$ represents the heat flux, $S_q$is the source term constituting enthalpy, Q_{pq} denotes the intensity of heat transfer between the phases p and q, and h_{pq} stands for the interphase enthalpy.

The VOF model includes both energy(E) and temperature(T) as mass average parameters and therefore it is expressed as follows:

$$E=\frac{\sum_{q=1}^{n}\alpha_q\rho_q E_q}{\sum_{q=1}^{n}\alpha_q\rho_q} \quad (5)$$

where E_q is based on the specific heat of that phase for each phase and common temperature. For the phases, density (ρ) and k_{eff} , i.e. effective thermal conductivity is mutual. The source term, S_h, contains radiation and other kinds of heat sources.

Concerning the volume fraction, the following equation is utilized:

$$\frac{1}{\rho_q}\left[\frac{\partial}{\partial t}\left(\alpha_q\rho_q\right)+\nabla.\left(\alpha_q\rho_q\vec{v}_q\right)=S_{\alpha_q}+\sum_{p=1}^{n}(\dot{m}_{pq}-\dot{m}_{qp})\right] \quad (6)$$

In Eq. (6), $\dot{m}_{qp}$ is the mass transfer from phase q to phase p, and $\dot{m}_{pq}$ denotes the mass transfer from phase p to phase q.

In the volume-of-fluid model, the governing equation for diffusion is;

$$\frac{\partial}{\partial t}\left(\alpha_q\rho_q\right)+\nabla.\left(\alpha_q\rho_q\vec{v}_q\right)=\nabla.\left(\gamma_q\nabla\alpha_q\right)+\sum_{p=1}^{n}(\dot{m}_{pq}-\dot{m}_{qp})+S_q \quad (7)$$

where γ_q and $\nabla.\left(\gamma_q\nabla\alpha_q\right)$ denote the diffusion coefficient in phase q and turbulent dispersion term, respectively.

As specified earlier, k-ε RNG turbulent model with thermal effects and enhanced wall treatment was used for the solution of the problem. Equations for k-ε turbulent model can be written as:

$$\frac{\partial}{\partial t}(\rho_m k) + \nabla(\rho_m k \vec{v}_m) = \nabla(\alpha_k \mu_m \nabla \mathrm{k}) + G_{k,m} - \rho_m \varepsilon + S_{k,m} \quad (8)$$

$$\frac{\partial}{\partial t}(\rho_m \varepsilon) + \nabla(\rho_m \varepsilon \vec{v}_m) = \nabla(\alpha_\varepsilon \mu_m \nabla \mathrm{k}) + \frac{\varepsilon}{k}\left(C_{1\varepsilon} G_{k,m} - C_{2\varepsilon}\rho_m \varepsilon\right) - R_\varepsilon + S_{\varepsilon,m} \quad (9)$$

$$\mu_m = \alpha_p \mu_p + \alpha_q \mu_q \quad (10)$$

where $\vec{v}_m$ represents mixture velocity, ρ_m stands for the density of the mixture, μ_m denotes viscosity of the mixture, $S_{\varepsilon,m}$ and $S_{k,m}$ represents the source terms, α_k and α_ε denote inverse effective Prandtl numbers, R is the Reynolds number, $C_{1\varepsilon}$ and $C_{2\varepsilon}$ are constant factors as $C_{1\varepsilon}$=1.42 and $C_{2\varepsilon}$=1.68, and $G_{k,m}$ presents turbulent kinetic energy generation.

As working fluid in numerical analysis, dichloromethane(DCM) and $h-BN/DCM$ nanofluids were used. During all simulations, a nanofluid solution was taken into consideration as a homogenous mixture. The evaporation-condensation mechanism was also activated for visualization of boiling mode. Numerical simulations were conducted for 200 W/m^2 heat flux and 1.0% (vol.) nanoparticle concentration. The time step size and the number of iterations were specified as 0.005 s and 5000, respectively.

3. RESULTS & DISCUSSION

3.1. Results for Dichloromethane Fluid

In order to compare the effects of nanoparticle addition inside the base fluid on heat transfer characteristics of boiling, numerical simulations were initially performed for dichloromethane. Vapor volume fractions were obtained for different time-step sizes. Temperature distribution, velocity contour and velocity vectors at the end of the analysis were also investigated. The obtained vapor volume fraction at the end of the numerical simulation was illustrated in Figure 2. As can be clearly seen in this figure that ¼ of the overall volume was covered by dichloromethane's vapor. It was also obvious that boiling bubbles was dissipated after generated on the heater surface.

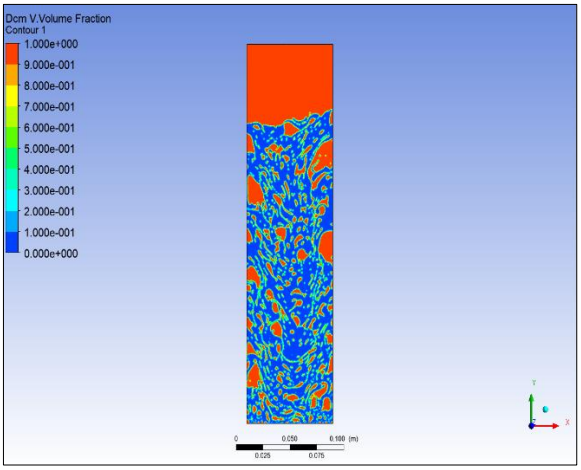

Figure 2. Volume fractions at the end of the analysis

Vapor volume fractions in varying time steps were also investigated to determine the beginning time of the boiling process (Figure 3). As regards the obtained illustrations, it was understood that the boiling process started at about 230 seconds time step when dichloromethane was used as a working fluid. Figure 3 also depicted that a continuous phase change cycle, i.e. evaporation-condensation, can be achieved in numerical analysis because of the temperature difference between the condenser and the heater sections.

Temperature distribution along the model was presented in Figure 4. A stratified temperature distribution was monitored inside the model. It was thought that this was because of the continuously-realized evaporation and condensation processes. As expected, the minimum and maximum temperature values were monitored in upper and inner areas, respectively.

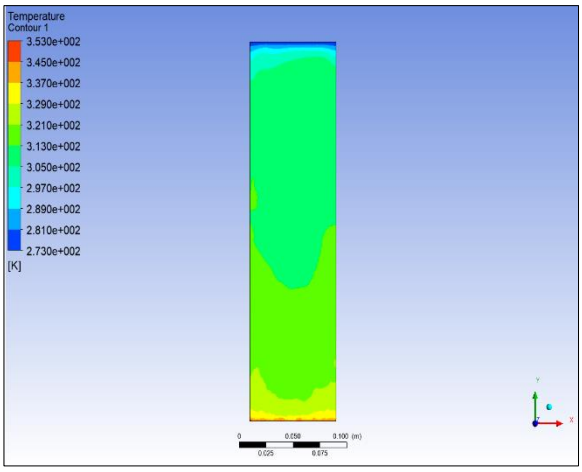

Figure 4. Temperature contour for dichloromethane

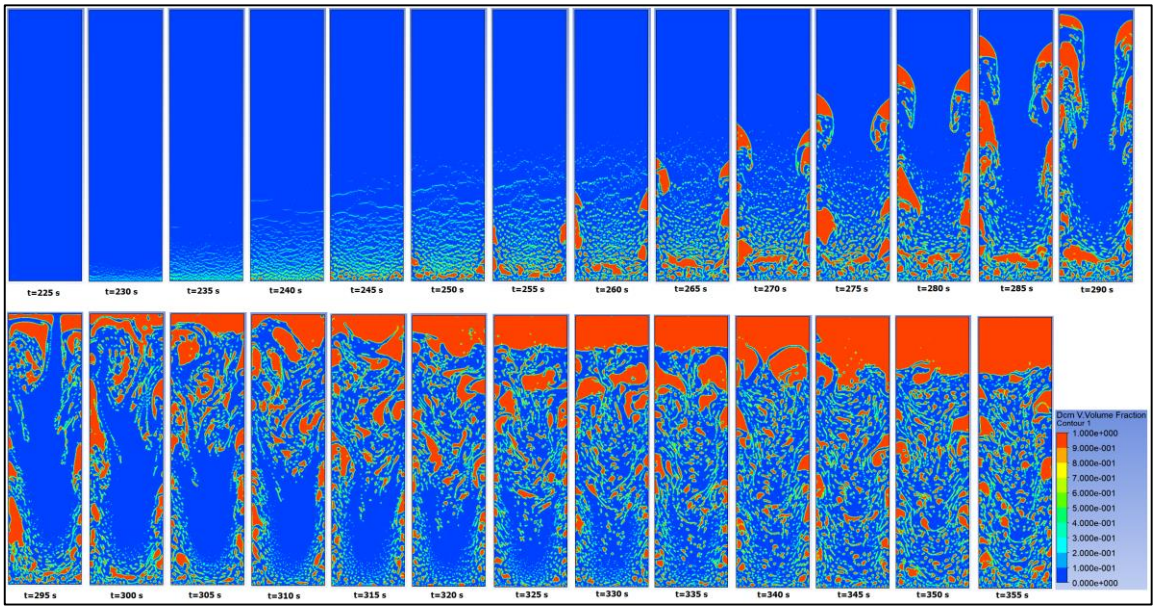

Figure 3. Vapor volume fractions at varying time steps for dichloromethane

Velocity changes in fluid motions were investigated for visualization of fluid flow inside the designed model for the boiling process. Velocity contours and velocity vectors were provided in Figure 5 and Figure 6, respectively. Data both in contour and vectors showed that a fluid flow cycle from the walls to the central range was formed during the boiling process. Heated and thereby evaporating fluids raised to the upwards and dissipated the heat they had, and when they reached the condenser area, they were condensed and poured back downwards, especially on the central range. The mentioned process could be seen readily not just in Figure 5, but also in Figure 6.

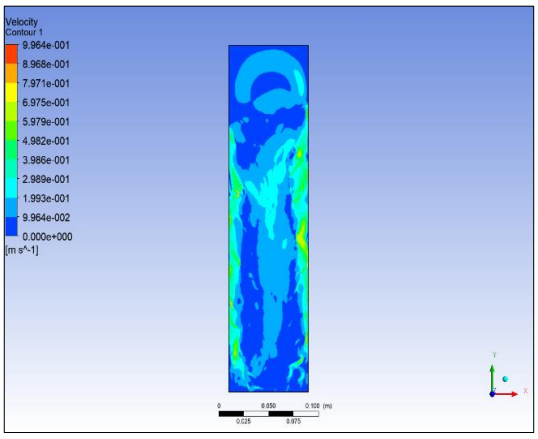

Figure 5. Velocity contour for dichloromethane

3.2. Results for *h-BN/DCM* Nanofluid

The numerical analysis results for hexagonal boron nitride nanoparticles containing dichloromethane nanofluid ($h-BN/DCM$) were presented in this section. The attained vapor volume fraction at the end of the numerical simulation was illustrated in Figure 7. Similarly, vapor volume fractions for $h-BN/DCM$ nanofluid were obtained for different time-step sizes. Temperature distribution, velocity contour and velocity vectors at the end of the analysis were also studied. Vapor volume fractions in varying time steps for nanofluid solutions were illustrated in Figure 8. It was obvious in Figure 8 that the boiling process started at roughly 215 seconds time step, which was nearly 230 seconds time step for dichloromethane when dichloromethane nanofluid was utilized as a working fluid. This finding illustrated that nanoparticle addition inside the base fluid improved the thermal characteristics of the base fluid, and thereby, declined the boiling point. This case also meant that the needed energy amount for boiling could be decreased by nanofluid utilization. When a time step size of 245 seconds was considered for each working fluid, the number of vapor areas were much higher for nanofluid solution than dichloromethane. Another point was that, in the same case, nanofluid solution embarked upon to rise around the wall, whereas no ascent was observed when dichloromethane was used as a working fluid.

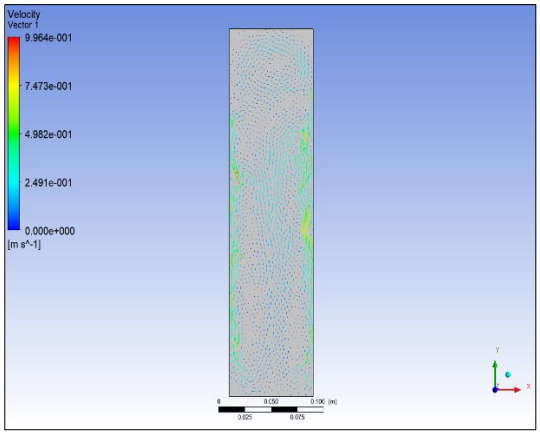

Figure 6. Velocity vectors for dichloromethane

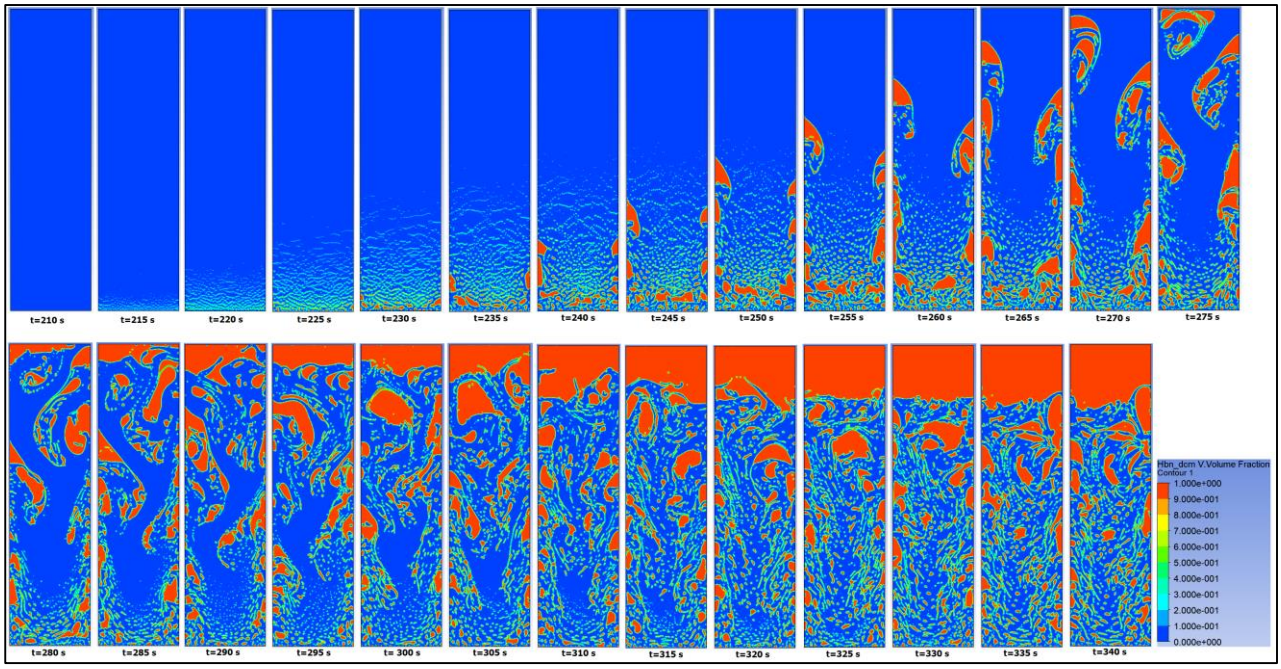

Figure 8. Vapor volume fractions at varying time steps for *h-BN/DCM* nanofluid

In a similar way, when 275 seconds time step size for nanofluid solution was taken into account, a big vapor area beneath the condenser section was stood out, although there was a similar, but a smaller formation could be monitored for 290 seconds time step size. As far as all these findings were considered, it was contemplated that nanoparticles not only positively affect the heat transfer characteristics but also formations of the bubble nucleation.

Temperature distribution along the model was illustrated in Figure 9 for the nanofluid solution. A similar trend was observed in temperature distribution; however, the average temperature was lower around the condenser section than that of dichloromethane, which meant that heat transfer realized in a shorter time compared to the same result with dichloromethane. As a result, the favourable influence of nanoparticles, as in vapor fraction figures, on heat transfer characteristics was observed. In addition, it was contemplated that this was because nanoparticles formed some additional areas in which heat transfer occurs within the base fluid. The velocity contour and velocity vector for nanofluid solution were illustrated in Figure 10 and Figure 11, respectively. It was showed off that fluid flow was realized in walls of the model noticeably. This figure also displayed that fluid flow fields were larger when hexagonal boron nitride nanoparticles–including working fluid was utilized in place of dichloromethane. Moreover, the fluid flow characteristics seen in Figure 11 revealed the continuous cycle in the evaporation-condensation process was taken place.

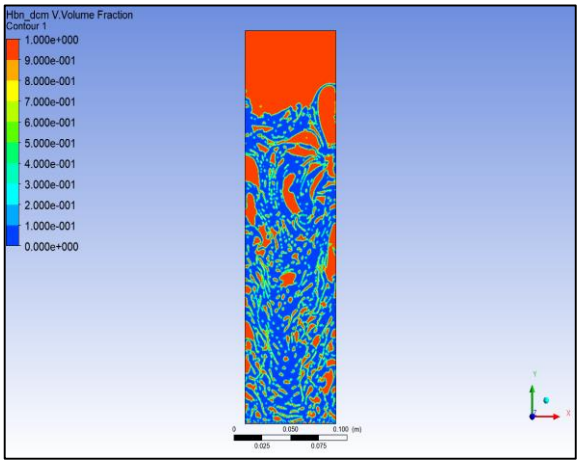

Figure 7. Volume fractions for h-BN/DCM nanofluid at the end of the analysis

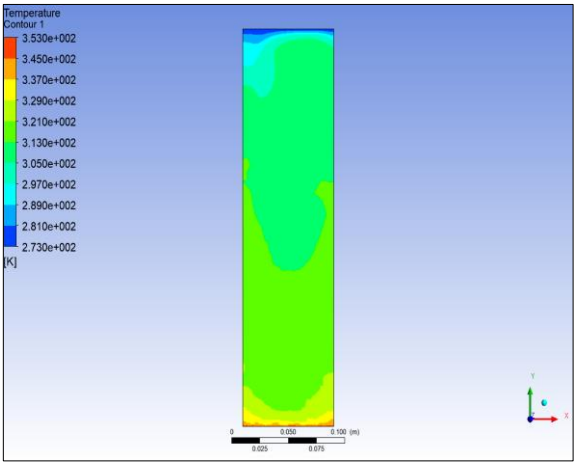

Figure 9. Temperature contour for *h-BN/DCM* nanofluid

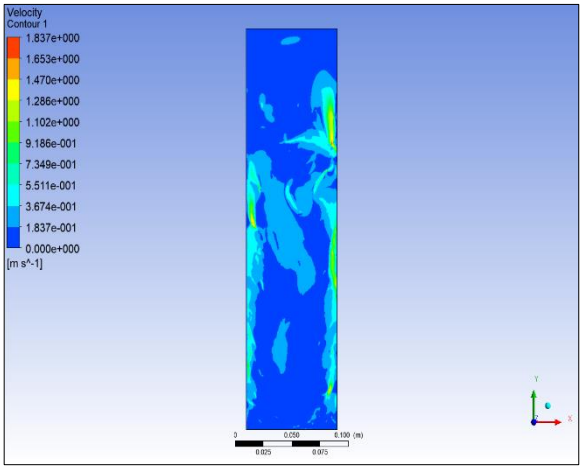

Figure 10. Velocity contour for *h-BN/DCM* nanofluid

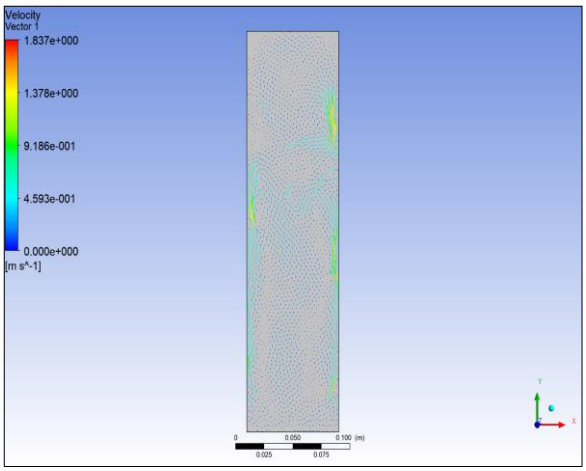

Figure 11. Velocity vectors for *h-BN/DCM* nanofluid

As to comparing our results to the relevant studies in literature, it was observed that investigators reported similar results. To illustrate; Ebrahimian and Ansarifar (2016) investigated the thermal–hydraulic influences of nanofluid as coolant in a nuclear reactor with annular fuel. Their numerical analysis results showed that the heat transfer coefficient, i.e., hat transfer rate could be enhanced by nanoparticle utilization [4]. Mohammed et al., (2018) exhibited in their study that increasing nanoparticle concentration from 0% to 1% led vapor volume fraction and heat transfer coefficient to increase. They utilized ANSYS Fluent 15.0 and Volume-of-Fluid (VOF) model when obtaining these results [15]. In a similar manner, Sato and Niceno, (2018) performed lots of numerical simulations for analysing both nucleate and film boiling modes under saturated conditions and determination of temperature distributions. They figured concluded that the overall heat transfer coefficient could be estimated via the CFD approach [16].

4. CONCLUSIONS

A series of numerical analyses were carried out to specify the effects of nanoparticle addition inside the base fluid on heat transfer characteristics in boiling processes. Dichloromethane based nanofluid solution that includes hexagonal boron nitride nanoparticles at a rate of 1.0% (vol.) were employed in the analysis. Nanofluid solution was taken into consideration as a homogenous mixture during all analysis. Numerical simulations were conducted for 200 W/m^2 heat flux. The time step size and the number of iterations were specified as 0.005 s and 5000, respectively. The important findings of this numerical study were as follows:

- Vapor volume fractions of each working fluid were obtained and compared to each other. It was reported that nanoparticle addition inside the base fluid enhanced the heat transfer characteristics.
- Temperature distributions were examined for dichloromethane and $h-BN/DCM$ nanofluid and it was seen that nanoparticles improved the heat transfer, especially in the condenser section.
- Fluid flow characteristics for both dichloromethane and $h-BN/DCM$ nanofluid were revealed by velocity vectors and velocity contours.
- When nanoparticle-containing dichloromethane fluid was employed as a working fluid, the average temperature beneath the condenser section was lowered, which displayed that heat transfer happened swiftly, compared to dichloromethane.

NOMENCLATURE

v	*Vapour*
vol.	*Volumetric concentration*
T	*Temperature [K]*
CFD	*Computational Fluid Dynamics*
DCM	*Dichloromethane*
h-BN	*Hexagonal Boron Nitride*
MS	*Mesh Structure*
SDBS	*Sodium Dodecyl Benzene Sulfonate*
VOF	*Volume-of-Fluid*

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