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ORIGINAL RESEARCH PAPER

Investigation of critical heat flux (CHF) enhancement in flow boiling using carbon nanotubes/ water nanofluid

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ABSTRACT: Many studies have shown critical heat flux (CHF) enhancement by adding metals and nonmetals nanoparticles to water in flow boiling. In this study, we investigated critical heat flux enhancement mechanism by adding multi-walled carbon nanotubes (MWCNTs) to pure water in flow boiling in a 2 m horizontal tube under atmospheric pressure. Also, the feasibility of MWCNTs-GA/water nanofluid as an advanced and economic coolant was assessed for cooling the high power thermal systems. For preparing this nanofluid, gum Arabic as a surfactant and MWCNTs as nanoparticles were used in the ratio 1:1 with concentrations of 0.001, 0.005, 0.01 wt%. The measuring zeta potential showed nanofluid stability. Results indicated the relative stability of suspension in all concentrations. Also the results of the experiments showed that the critical heat flux of the nanofluid increases with increasing in concentration and mass flux at the inlet temperatures of 60 and 70 °C. The CHF enhancement was observed for nanofluids and it was greater than that for pure water. It is due to the deposition of MWCNTs nanoparticles and improvement of wettability in the heat transfer surface. The maximum CHF enhancement was observed at 0.01 wt% concentration, a mass flux of 620 kg/m^{2}s and the inlet temperature of 60 ^{o}C. The local exit equality of the nanofluid in a fixed mass flux at the inlet temperatures was less than that for pure water and the lowest local exit equality of nanofluid was at inlet temperature of 60 °C and concentration of 0.001wt%.

KEYWORDS*: Carbon nanotubes; Critical heat flux; Flow boiling; Nanofluid.*

INTRODUCTION

The highest limit of the heat flux in boiling heat transfer when surface temperature is intensively increased, is known as critical heat flux (CHF). The critical heat flux is a very important parameter in designing and employing advanced coolants in thermal systems [1-6]. In the boiling heat transfer, base fluid of the nanofluid is evaporated by nucleate boiling created on the surface of heat transfer and formed a layer of nanoparticles on that. This layer improves surface wettability and its increase caused the critical heat flux enhancement [3, 7]. Enhancement of CHF using nanofluid coolants is a new technique for achieving higher thermal power, greater safety and better economy under operation conditions in thermal systems with high thermal power [6]. Nanofluids are colloidal suspensions of solid particles less than 100 nm in size within a base fluid which was first introduced in 1995 by Choi [8]. One of the important parameters for improving heat transfer is thermal conductivity which in a nanofluid it depends on the type of nanoparticles and base fluid used. The higher thermal conductivity of the nanofluids can increase CHF for practical applications [3]. Although many studies have focused on CHF enhancement mechanism using nanofluids and have shown its increase up to 200% in boiling pool [9-12], there is little about the CHF enhancement in flow boiling.

A review of recent studies on CHF enhancement in flow boiling showed parameters as follow [13-15]:

1- Nanoparticles used for nanofluids include metal nanoparticles such as cooper, silver and non-metal nanaoparticles such as alumina, silica, magnetic and diamond. The base fluid used for nanofluid was water.
2- Thermal conductivity of the most nanparticles was lower than MWCNTs, as seen in Table 1[16].

Table 1
Thermal conductivity of the nanoparticles.

Nanoparticles	**Thermal conductivity (Wm^{-1}K^{-1}) (T=300 K)**
CuO	76.5
Al_2O_3	40
SiC	120
Zinc-oxide	85

3- The fluid flow was vertically upward and the test section tube length was less than 600 mm. The CHF phenomenon is coupled with phase change and extremely depends on parameters such as heated length, diameter, mass flux, and flow passage except when the mass flux is very high [17].
4- CHF increased at relatively low nanoparticles concentrations.

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	Nomenclature		
	Greek symbol		**Subscripts**
C_p	special heat capacity (J Kg^{-1} K^{-1})	*bf*	Base fluid
D	tube diameter (m)	*cr*	Critical
h	length heat (J g^{-1})	*e*	exit
I	measured current (A)	*fg*	Vaporization
L	length (m)	*i*	Inlet
$\dot{m}$	mass flow rate (Kg s^{-1})	*nf*	nanofluid
q''	critical heat flux (Wm^{-2})	*sat*	Saturate
Q	heat loss of test section		**Abbreviation**
T	temperature (°C)	*MWCNTs*	Multi-walled carbon nanotubes
V	measured voltage (V)	*MWCNT-GA*	Functionalization of MWCNT with gum Arabic
X	steam quality	*CNTs*	Carbon nanotubes
		TCs	Thermocouples

5- All of them reported enhancement of the CHF up to 30% in flow boiling.

Lee et al. [1] studied CHF enhancement using Al_2O_3/water and SiC/water nanofluids with 0.01 vol%. concentration, mass fluxes of 100-250 kg/m^2s and inlet temperatures of 25 and 50 o C. Enhancement of the CHF was observed up to 15% with Al_2O_3 nanofluid at an inlet temperature of 50 o C and a mass flux of 200 kg/m^2s, and up to 41% with SiC nanofluid at an inlet temperature of 25^{o}C and a mass flux of 150 kg/m^2s. The CHF enhancement using SiC/water nanofluid was higher than of Al_2O_3/water nanofluid.

They showed that this increase is due to higher thermal conductivity of SiC nanoparticles. Kim et al. [2] studied CHF enhancement using Al_2O_3 nanofluid at mass fluxes of 100-300 kg/m^2s, inlet temperature of 25 and 50^{o}C, and 0.001- 0.1 vol% concentrations.

The maximum CHF enhancement was 70% which was due to enhanced wettability of the liquid film on the heated surface.

Kim et al. [13] performed flow boiling CHF experiments using Al_2O_3 nanofluid with 10^{-4} and 10^{-3} vol% concentrations, mass fluxes of 500-1500 kg/m^2s and inlet temperature of 75^{o}C. Their results showed that the CHF increase up to 80% in all experimental conditions. Kim et al. [14] also performed CHF experiments using alumina, zinc-oxide, and diamond nanofluids with 0.001- 0.1 vol% concentrations, mass fluxes of 1500- 2500 kg/m^2s, and an inlet temperature of 80^{o}C. The maximum CHF enhancement was 53% with alumina and zinc oxide nanofluids, and 38% with diamond nanofluid.

We used MWCNTs-GA/water nanofluid with relatively low concentrations and high mass fluxes in a horizontal tube. The most famous carbon nanostructures are carbon nanotubes (CNTs).

The carbon nanotubes have relatively helpful advantages such as high thermal conductivity and high surface/volume ratio.

The CNT's instability in polar solvents such as water is a challenge that can be compensated with begetting non-covalent hydrophilic bonds by surfactants in different ratios [18]. Surfactants are used to preserve suspended nanoparticles, avoid deposition of nanoparticles, and increase the kinetic stability of emulsion [18].

The surfactant characteristics such as stability, deployment in different ratios in aqueous suspensions, and impact on physical properties of nanofluids, were investigated by Shanbedi et al. [19-20]. They suggested GA as a new surfactant and the best stability of that was demonstrated in the ratio 1:1 in different aqueous suspension concentrations.

While there are a couple of articles employing the carbon nanostructures in pool boiling [5, 21-22], there is no article with the focus on flow boiling. In this study, we will first synthesize a homogenous CNT/water nanofluid with good suspension ability at high temperature by employing GA.

Then, we follow our main aim: investigation of the critical heat flux (CHF) enhancement in flow boiling using MWCNTs-GA/water nanofluid as a new working fluid in high inlet temperatures (60 and 70^{o}C). The higher thermal conductivity of CNTs may lead to higher CHF enhancement than other nanoparticles.

EXPERIMENT MATERIAL AND METHOD

Material Preparation

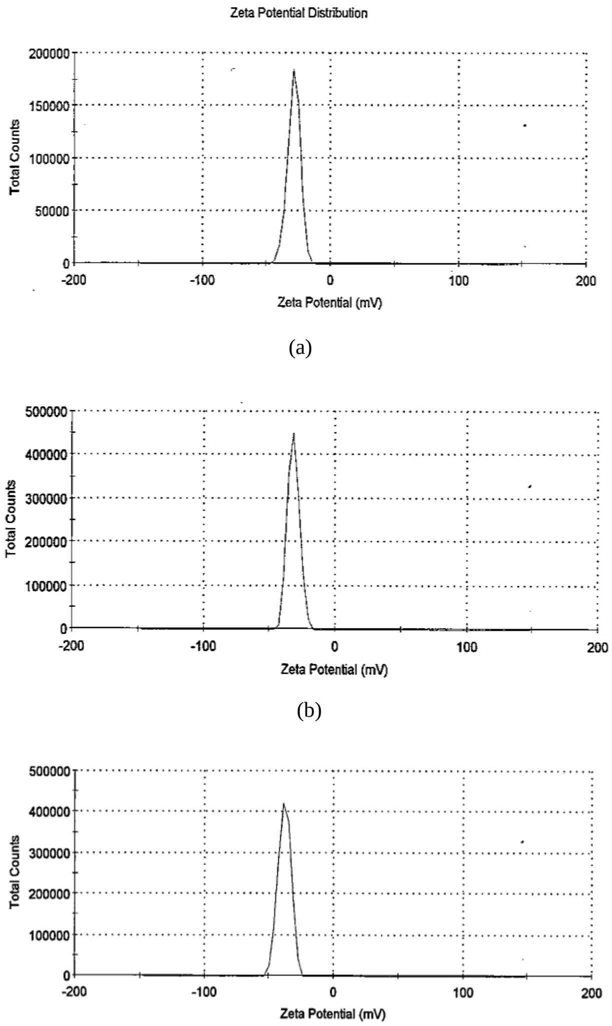
In order to nanofluid preparation MWCNTs nanoparticles and GA surfactant used in the ratio 1:1. The MWCNTs-GA/water aqueous suspension was sonicated for 120 min with a sonicator in an ultrasonic bath. The MWCNTs nanoparticles (Ash < 1.5%, Purity >95%, SSA = 200 m^2g^{-1} , outside diameter = 10-20 nm, Length = 30 μm, True density = 2.1 gcm^{-3}) were purchased from Vira Carbon Nano Materials (VCN Materials) Company, I.R. Iran.

The stability of MWCNTs-GA nanofluid was investigated by zeta potential. The zeta potential of nanofluid was measured using a ZetaSizer Nano zs system (Malvern). This system measure the electrophoretic mobility and the zeta potential was then calculated using the Smoluchowski Equation.

The zeta potential increase cased narrower particles size distribution, lower tendency for particles association, and greater possibility of forming a double electrical layer on the particles surface. Its reduction leads to the dominance of gravitation over repulsion and its final coagulation [23-24].

Zeta potentials of nanofluid for all concentrations obtained in the range of 28-38 mV (negative).

This results indicate that carbon nanotubes dispersion was relatively stable, which is shown in Figure 1.



(a)

(b)

(c)

Fig. 1. Zeta potential distribution of MWCNTs-GA/water nanofluids at different concentrations of a) 0.001 %wt, b) 0.005 %wt, c) 0.01 %wt

Also Figure 2 indicates variations of average zeta potential of nanofluid with different concentrations.

The zeta potentials decreased with an increase of particles concentration from 0.001 to 0.01 wt%.

This results are similar with findings Wasche et al. [25]. They showed that zeta potential Al_2O_3 nanofluid decreased with an increase of particles concentration from 1 vol% to 10 vol%.

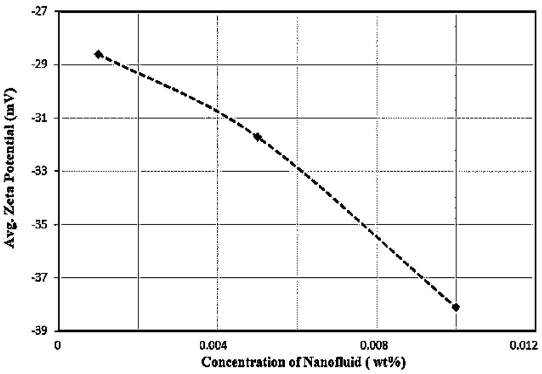


Fig. 2. Average zeta potentials of MWCNTs-GA/water nanofluid with different concentrations

Experimental Setup

The influence of the MWCNTs nanoparticles in flow boiling loop is shown in Figure 3.

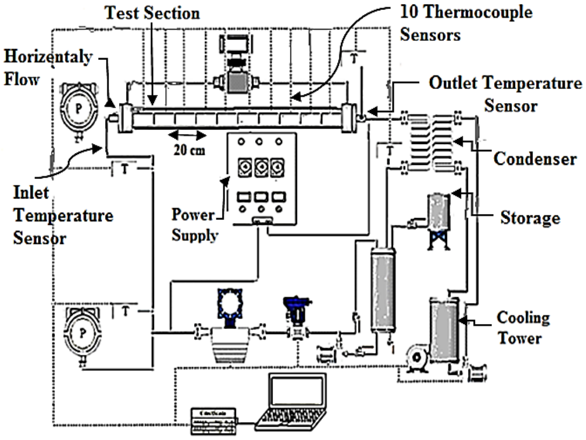


Fig. 3. Schematic of experimental set up

The main components of the test loop include a tank, a gear pump, a flow meter, a shell-and-tube cooler, and a pre-heater.

Also two pressure transmitters and two K-type thermocouples were installed at the test section and heater's inlet and at the inlet and exit of the test section, and 10 TCs were clamped evenly to the outer surface of the tube to determine the temperature of the wall.

In this study, a stainless steel grade 316 tube is used as the test section which directly heated using a 30 kW capacity. The pressure drop of the tube was estimated by a DP Cell/Differential pressure transmitter. Table 2 shows the test conditions.

Table 2

Test matrix.

Fluid flow conditions	
Horizontally working fluid flow	
Pressure	1 bar
Mass flux	320, 620, 920 kg m-2s-1
Inlet temperature	60, 70 ^{o}c
Test fluid	
Total working fluid	20l
Pure water	
Carbon nanotube	0.001, 0.005, 0.01 % wt
Nanofluid	0.0005, 0.005vol%

Experimental Method

The system was filled with test fluid and was run at 60 and 70^{o}C for 1h to desecrate. The voltage of the system are gradually increased until the CHF occurred. The mass flux was fixed at test conditions last for a few minutes.

The CHF occurred at the test section tube exit, which was measured by the TCs near the exit and also the loaded power on the tube was automatically shut down by a sudden rise in the wall tube temperature.

In all of the experiments the maximum surface temperatures were about 180-350^{o}C and the CHF occurred in the dried-out liquid film. As is shown in Figure 4, the location of the CHF is determined the moment the surface temperature exceeds 290^{o}C and it takes only 10 seconds to happen.

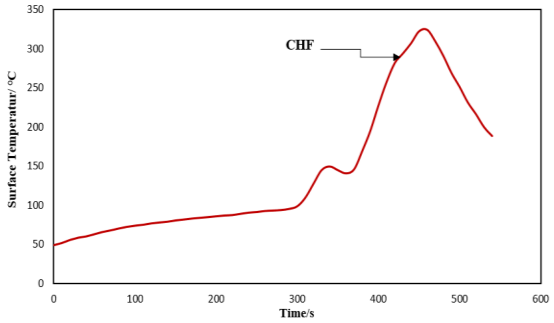


Fig. 4. Surface temperature of the test section at CHF

ANALYSES OF DATA AND UNCERTAINTIES

The heat flux in the test section tube is calculated as [1-7]:

$$q'' = \frac{VI}{\pi D_i L} \tag{1}$$

Where V and I are the measured voltage and current, and D_i and L are the test section tube inner diameter and length, respectively.

The maximum accuracy of measurement for power was ±0.03 and the maximum accuracy of measurement were ±0.1 and ±0.0005 for the test section inner diameter and length, respectively.

The heat loss was measured by the bulk temperature TCs [26]:

$$Q_{loss} = VI - \dot{m}C_p(T_e - T_i) \tag{2}$$

Where $\dot{m}$ is the mass flow rate, T_e and T_i are the exit and inlet temperatures, respectively; and C_p is the between T_i and $T_{e,}$.

The maximum accuracy of measurement of the thermocouples and average specific heat of water was ±0.1 ^{o}C and ±0.02, respectively; and also the maximum error in controlling inlet temperature was less than ±2^{o}C.

The critical steam quality was calculated as follows [26]:

$$X_{cri.} = \frac{C_p(T_i - T_{sat})}{h_{fg}} \tag{3}$$

Where T_{sat} is the saturation temperature at atmospheric pressure, and h_{fg} is the latent heat of vaporization. The maximum accuracy of measurement of latent heat of vaporization was ±0.02.

The uncertainty of the measured parameters were performed based on the Holman [27-28] method. Table 3 show this results.

Table 3

Uncertainties of experimental parameters.

Parameters	**Uncertainty**
Power (W)	±0.0001%
Inner diameter of test tube (mm)	±10%
Length of test tube (mm)	±0.05%
Mass flux at 320, 620, and 920 (kg m^{-2} s^{-1})	±2, 1.02, 0.69%
Heat losses (W m^{-2})	±2%
Exit quality	±0.018%
Heat flux (W m^{-2})	±10%

EXPERIMENTAL RESULTS AND DISCUSSION

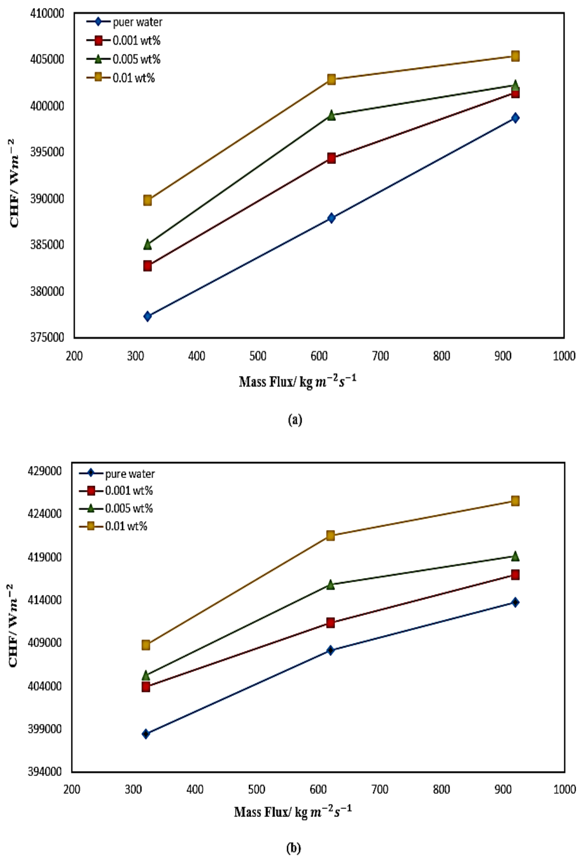
All flow boiling CHF experiments were performed in steady boiling just before the CHF phenomena, steady inlet temperature and mass flux.

The CHF values were measured at least two times for a given mass flux.

Measured CHF values according with different mass fluxes are shown in Figure 5.

It is observed that the CHF of nanofluids increases by increasing in mass flux at inlet temperatures of 60 and 70^{o}C. The enhancement ratio of CHF is defined as impact factor of nanoparticles [26]:

$$Enhancement\ Ratio = \frac{CHF_{nf}}{CHF_{bf}} \tag{4}$$



(a)

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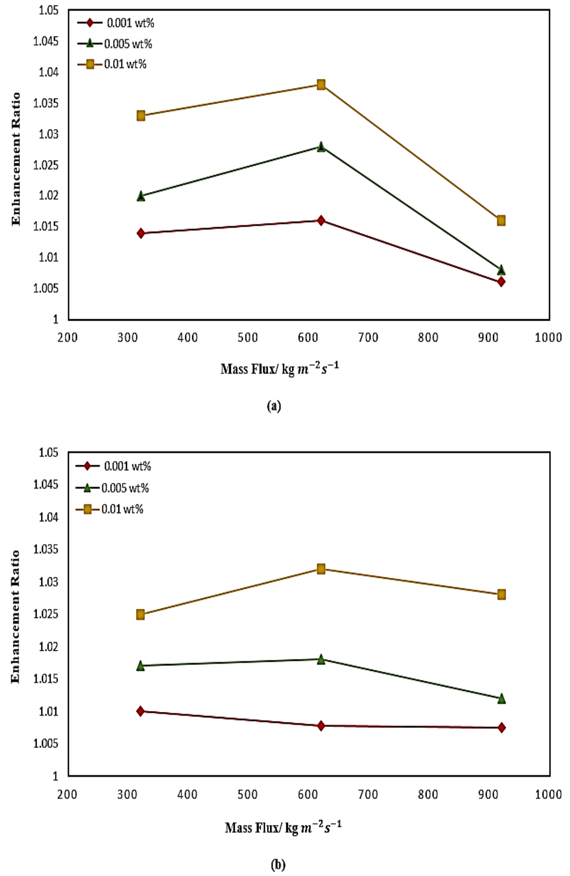
Fig. 5. Measured CHF values according with different mass fluxes for MWCNTs-GA/water nanofluids and pure water at inlet temperatures: a) T_{in}: 60° C and b) T_{in}: 70° C

Figure 6 shows the effect of adding MWCNTs nanoparticles to the pure water. This figure demonstrate that CHF enhancement ratio of nanofluid has a declining trend at inlet temperatures of 60 and 70 ºC. These results almost agree the findings of Lee et al. [1]. The maximum CHF enhancement of nanofluid at 60 and 70 ºC inlet temperatures are 3.8% and 3.2% respectively, with 0.01 wt% concentration and mass flux of 620 kg/m^{2}s. This trend may be due to different deposition structure of the nanoparticles. The flow regime can be slug/plug or annular in horizontal systems. At low mass flux, flow regime is often intermittent (slug/plug) and large bubbles are generated on the heated surface [17].

The critical heat flux can occur when the liquid film is evaporated by separating of large vapor plugs, then a dry/hot patch is formed before repassing vapor plugs. The formation of a nanoparticles layer on dry spots increases wettability of the surface, thus can help delay departure of nuclear boiling (DNB). At high mass flux, flow regime is annular and small bubbles are generated on heated surface [3, 17], then a thin bubbly layer is formed on it. The beneath liquid film of vapor clots evaporates when increased bubbly layer thickening and therefore it led to CHF enhancement. Another reason for this trend can be MWCNTs high thermal conductivity. The thermal conductivity of MWCNTs-GA/water nanofluid is greater than pure water and MWCNTs/water [29]. High thermal conductivity can rapidly increase both heat transfer and its dispersion in the fluid. It also prevents a sharp rise in the wall temperature of the thermal equipment. It seems that a sudden rise in the wall temperature is due to the low thermal conductivity of vapor on the heated surface.



(a)

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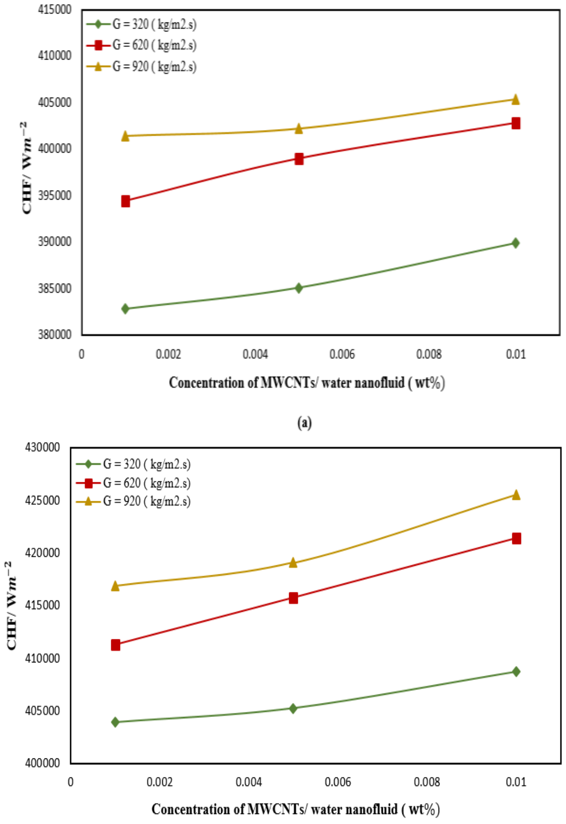
Fig. 6. CHF enhancement ratios according with different mass fluxes for MWCNTs-GA nanofluids at inlet temperatures: a) Tin: 60 ° C and b) Tin: 70 ° C

As Figure 7 illustrates, the CHF of nanofluid increases with increasing the nanofluid concentration from 0.001 to 0.01 wt% at inlet temperatures of 60 and 70° C. These results are consistent with what Kim et al. [2] observed in other experimental conditions. Such increases can be due to the nanofluid stability and thermal resistance. In nuclear boiling, the diameter of bubbles generated in nanofluids is less than that of the bubbles generated by pure water. High thermal resistance of nanoparticles is due to big bubbles' size that can prevent heat transfer between solid surfaces and liquid, also it can reduce boiling heat transfer of the heated surface. High surface/volume ratio of CNTs causes decrease in diameter of bubbles formed on heated surface as the nanofluid concentration increases.

The relatively big surface of nanoparticles can reduce non-equilibrium effects between the fluid and solid surface. So it can be the reason of nanofluid stability.



(a)

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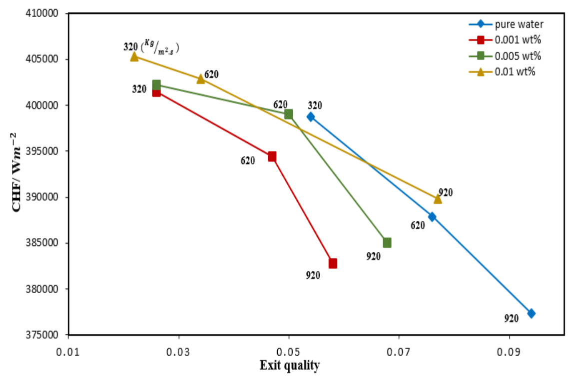
Fig. 7. Measured CHF values according with different concentrations for MWCNTs-GA/water nanofluids at inlet temperatures: a) Tin: 60 °C and b) Tin: 70 °C

Figure 8 shows measured CHF values for the nanofluid and pure water according to exit qualities at inlet temperatures of 60 °C and 70 °C. This results are very similar to the findings Kim et al. [26]. It is observed that CHF decreases, as while local vapor quality increases; but it depend on mass flux.



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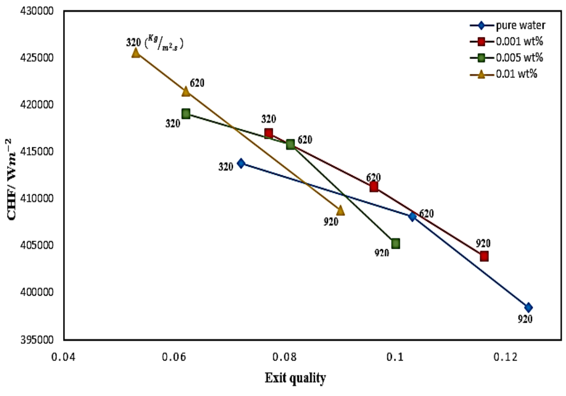
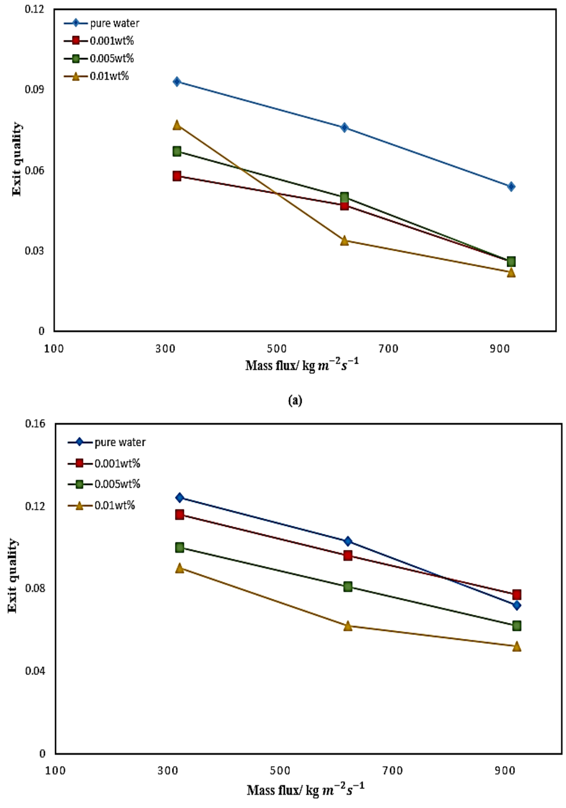


(b)

Fig. 8. Measured CHF values according with different exit qualities for MWCNTs-GA/water nanofluids and pure water at inlet temperatures: a) Tin: 60 °C and b) Tin: 70 °C

At high quantities CHF decreases as mass flux increases, but also at lower quantities this trend is reversed [17]. The deposition of a layer of nanoparticles on heater surface is due to nucleate boiling of nanofluid. This layer can significantly improve the surface wettability and its increase can decrease the formation of hot spot. Figure 9 demonstrates that the exit quality is a function of mass flux at inlet temperatures of 60 and 70 °C.



(a)

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Fig. 9. Variation of exit qualities according with different mass fluxes for MWCNTs-GA/water nanofluids and pure water at inlet temperatures: (a) Tin: 60 °C and (b) Tin: 70 °C

The exit quality of the nanofluid was lower than pure water at mass flux and inlet temperatures, however, the CHF of nanofluid was higher than that of the pure water. These results can be due to increase in thickness of nanoparticles layers and wettability of the heated surface. The entropy cause a decrease in the CHF.

On the other hand, decrease in entropy can lead to increase in irregularities of the system and decrease in temperature of the heated surface from which heat transfer enhances. The entropy generation of pure water is larger than nanofluids at the same conditions according to Mahian et al. [30]. They performed a review on entropy generation in nanofluid. Also, in other studies [31], they studied entropy generation in Al_2O_3/water nanofluid. The results showed that the entropy generation decreases with increasing the nanofluid concentration. Entropy generation is one of influential parameters in CHF enhancement and it has a direct relationship with increase in temperature of the heated surface [27, 29]. Alongside, the entropy generation of MWCNTs-GA/water nanofluid is less than other nanofluids with the same concentrations and pure water at the same conditions. The exit quality of pure water is greater than nanofluids in the inlet temperatures.

Finally, CHF enhancement has a direct relation with mass flux and increase in heat transfer at flow boiling heat transfer. However, the exact comparison of the results of our experiments with other researchers because of different nanoparticles and shape of the test section tube. We think that MWCNTs-GA/water nanofluid can be applied as a new nanofluid in flow boiling heat transfer of CHF due to reducing total costs, and pumping power, and energy saving in thermal systems by CHF enhancement.

CONCLUSION

Flow boiling CHF experiments were performed for the MWCNTs-GA/Water nanofluid of various concentrations. The main finding were as follows:

- Preliminary analyses of MWCNTS's interesting characteristics illustrated that these nanoparticles can be a proper choice for the improvement of the safety margin and economy of the thermal system.
- The CHF of nanofluid increased with increasing mass flux at inlet temperatures of 60 and 70 ^{o}C.
- The CHF of MWCNTs-GA/water nanofluid were almost increased with increasing of concentration from 0.001%wt to 0.01 %wt at inlet temperatures of 60 and 70 ^{o}C.
- The maximum CHF enhancement of the MWCNTs-GA/water nanofluid was 3.8% at 0.01wt% concentration, 60 ^{o} C inlet temperature, and a mass flux of 620 kg/m^{2}s.
- The local exit quality of the nanofluid for a fixed mass flux at the inlet temperatures was less than pure water. Also the lowest local exit equality of nanofluid was at inlet temperature of 60 ° C and a concentration of 0.001wt%.
- The higher thermal conductivity, lower thermal resistance, and minimum entropy generation of MWCNTs-GA/water nanofluid compared to the pure water could cause CHF enhancement.

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