



## The Effect of Linear Change of Tube Diameter on Subcooled Flow Boiling and Critical Heat Flux

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### ABSTRACT

One of the major industry problems is the flow boiling, where reaching to the critical heat flux (CHF) condition can lead to a temperature jump and damage of the systems. In the present study, the effects of a uniform change in tube diameter on subcooled flow boiling and CHF was numerically investigated. The Euler-Euler model was used to investigate the relationship between the two liquid and vapor phases. The ANSYS Fluent code was used for simulation. According to the results, a linear increase in the tube diameter leads to increase of vapor volume fraction adjacent to the tube wall, as compared to a regular tube with a fixed-diameter, which leads to increase of the tube wall temperature due to the low value of the heat transfer coefficient. At CHF conditions, where the tube wall temperature is much higher than that in subcooled flow boiling, an increase in tube diameter may lead to higher tube wall temperature before the temperature jump, as compared to the post-jump temperature of a tube with a constant diameter. The best approach for decreasing the tube wall temperature was found to be a linear decrease in tube diameter. For the tube diameter change angles of  $\theta < -0.0383^\circ$ , tube wall temperature exhibited a decreasing trend from the inlet of the tube to its end.

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## 1. INTRODUCTION

In many industrial applications, the fluid flow is used for heat transfer, such as heating spaces, electricity production, etc [1, 2]. Also, fluid flow boiling is used for heat transfer because during the fluid phase change, the amount of heat transfer is much higher than the convection heat transfer [3, 4]. By increasing the vapor volume fraction adjacent to the heated wall, which causes decreasing the heat transfer coefficient, the tube wall temperature increases, which can eventually lead to thawing and degradation of the wall. The heat flux at which temperature jump occurs is called the critical heat flux (CHF) [5, 6]. Therefore, CHF should be prevented. Also, in order to have higher heat transfer, the CHF should be increased. A useful way to increase the heat transfer coefficient and CHF value is using nanofluids [7, 8]. Also, the convective heat transfer and the amount of CHF depends on various factors such as geometry, fluid

and nanofluid properties, surface roughness, and working conditions [7-10].

Many studies on enhancement of the CHF by adding nanoparticles to base fluid, have shown that when nanofluid is used instead of pure fluid, the CHF increases significantly (up to 100% has been reported) [10, 11].

The nucleation site density (NSD) on the heated wall where the vapor bubbles are formed is generally estimated using the Lemmert-Chawla model [12], which is a very simple relation and depends only on the fluid saturation temperature and the heated wall temperature. This relationship has been widely used to simulate the subcooled flow boiling that has good accuracy [5, 13]. Also, some researchers have used this relationship to simulate the pure fluid flow boiling at CHF conditions that have achieved acceptable results [14].

Also, working conditions such as pressure and the fluid inlet temperature, affect the fluid flow boiling and the CHF value. By increasing the working pressure of the fluid flow, the saturation temperature will also increase,

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which will increase the amount of heat received by the liquid to occur evaporation, thereby increasing the CHF [15]. Increasing the fluid inlet temperature also causes the liquid to evaporate at lower heat flux, then reduces the amount of CHF [16].

Netz et al. [17] experimented vertical channel with a wavy wall with 0.25, 0.5, and 0.75 mm amplitude. They observed that at 0.25 and 0.75 mm amplitude wavy wall, the mean wall temperature decreases and increases respectively at constant heat flux in comparison to the straight channel. They concluded that more experimental analysis is needed to find the best wavy amplitude for reducing the wall temperature.

In a study carried out by Patil et al. [18], the experimental and simulation data showed that by using the bump in the divergent channel, the heat transfer coefficient increases 25 to 35% as compared to the plain divergent channel. Also, they observed that pressure drop is reduced by using the divergent channel with internal bump instead of the cylindrical tube. They observed that using the water-ethylene glycol mixture will increase the Nusselt number in comparison with pure water.

After the experimental study on sinusoidal wavy minichannel by Khoshvaght-Aliabadi et al. [19], they proposed two correlations for Nusselt number and friction factor for convective fluid flow inside sinusoidal wavy minichannel. Their correlations were based on  $Re$ ,  $Pr$ , wavy amplitude, hydraulic diameter, and tube length. Al-Asadi et al. [20] simulated laminar fluid flow convection in the microchannel, which used a cylindrical vortex generator. They observed that using the quarter-circle vortex generator was not effective on increasing the heat transfer coefficient, but half-circle spanned the whole width of the microchannel and increased the heat transfer coefficient.

Akbarzadeh et al. [21] examined the flow of fluid through channels with different walls and found that the channel with the sinusoidal wall had the highest heat transfer rate. Vo et al. [22] investigated the nanofluid flow inside the sinusoidal channel. The used nanoparticles with different shapes, which eventually showed that the platelet shape and brick shape nanoparticles had the highest and lowest heat transfer coefficients, respectively. The results showed that the Nusselt number had a sudden change in the location of bumps and indents of the channel wall. Also, the fluid temperature in those locations was higher than elsewhere.

In this study, the effect of the linear changing tube diameter on subcooled flow boiling and CHF value of water flow is investigated. For validating the simulation results, the results of subcooled flow boiling in regular tubes with a uniform diameter are used. The results reported by Krepper et al. [13] are used for the simulation of subcooled flow boiling and the results presented by Kim et al. [23] are used for validating the simulation at the CHF condition. The main purpose of the present

study is to reduce the temperature of the tube wall and to increase the amount of CHF. After verification of the numerical results with the experimental data, tubes with different changing diameters are modeled, and the subcooled flow boiling at constant heat flux is simulated. To estimate the CHF value, in each tube, the flow boiling is simulated at the desired heat flux; if temperature jumping didn't occur on the tube wall, the simulation would be repeated by an increased heat flux; and this procedure is continued until temperature jump occurs, which indicates the CHF.

## 2. MATHEMATICAL MODELLING

In the simulation carried out in this study, subcooled flow boiling has been used. During boiling, two phases of liquid water and vapor have been used. The Euler-Euler model has been used to investigate the relationship between the two liquid and vapor phases.

Euler-Euler conservation equations include mass, momentum, and energy conservation equations for each of the phases. The governing equations have been described in our previous research [5].

To simulate the turbulent fluid flow, including boiling in the CHF state, the turbulent  $k$ - $\epsilon$  model, and the near-wall conditions have been used.

## 3. GEOMETRY AND BOUNDARY CONDITIONS

In this study, for simulation of subcooled flow boiling (case 1), the data of Krepper et al. [13] is used and to investigate the simulation results of subcooled flow boiling at the CHF condition (case 2), the data of Kim et al. [23] is used. Table 1 presents the geometry and operating conditions of each case.

In order to investigate the effect of tube diameter change on flow boiling, in each of the studied cases, it is assumed that the tube diameter change is uniform with angle  $\theta$  relative to the inlet tube diameter (Figure 1 (a)). If  $\theta$  is equal to zero, the tube diameter is constant and represents the original state (according to Table 1). If the value of  $\theta$  is greater than zero, the tube diameter is

**TABLE 1.** Geometry specifications and working conditions of the samples

Conditions	Case 1 [13]	Case 2 [23]
Tube length (m)	2	0.1
Tube diameter (mm)	15.4	5.53
Pressure (kPa)	4500	101
Mass flux (kg/m <sup>2</sup> .s)	900	2000-2500
Heat flux (kW/m <sup>2</sup> )	570	4500-6000

incremental, and if the value of  $\theta$  is negative, the tube diameter is considered as decreasing relative to the base tube diameter (as shown in Table 1). Also, a sample grid is shown in Figure 1 (b). The used grids for the tube domain are structured, and all cells are rectangular.

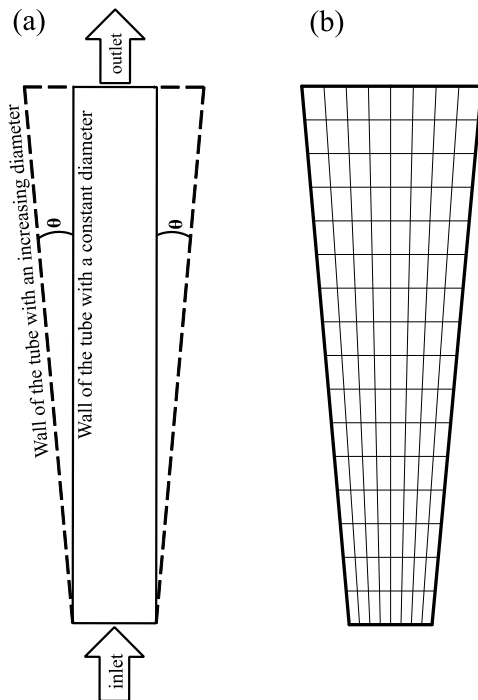
**4. RESULTS**

The results of the simulations in this section are divided into two parts: simulation of subcooled flow boiling and subcooled flow boiling at CHF condition.

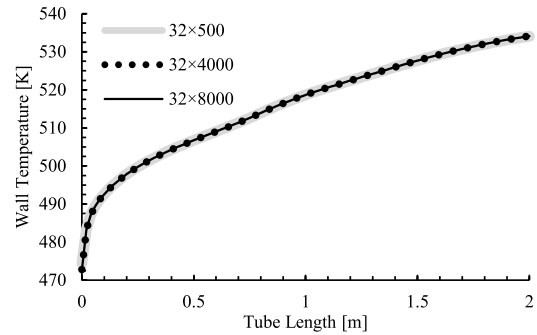
**4. 1. Subcooled Flow Boiling Simulation**

Krepper et al. [13] used 20 cells in the radial direction and 150 cells in the longitudinal direction of the tube for simulating the flow boiling according to case 1. In this paper, a domain with different grids was used to investigate the independence of the results from the grid (based on Figure 1(b)). Figures 2 and 3 show the simulation results for different grids. Based on the results and to facilitate the simulations, a grid with 32 cells in the radial direction and 500 cells in the longitudinal direction of the tube was used, while Krepper et al. [13] used 20 cells in the radial direction and 150 cells in the longitudinal direction of the tube.

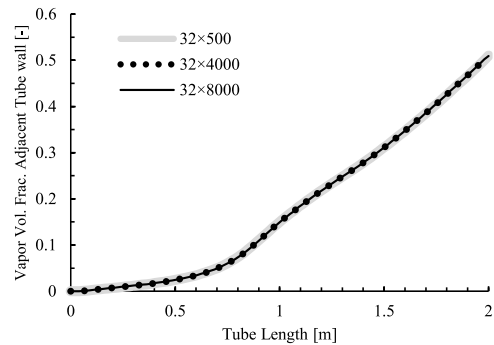
In Figures 4 and 5, the results obtained in this study are compared with the experimental results, which have very similarities and can be used for other simulations.



**Figure 1.** (a) Scheme of a tube with constant diameter and linear variable diameter with positive  $\theta$  [deg] and (b) a sample of structured grid



**Figure 2.** Influence of grid size on tube wall temperature

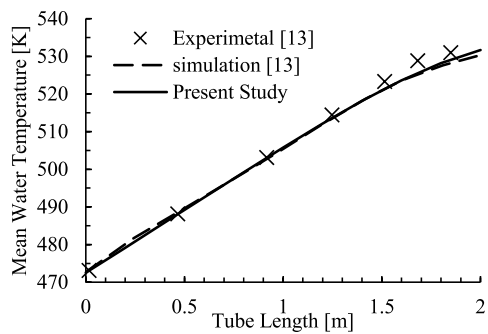


**Figure 3.** Influence of grid size on vapor volume fraction adjacent to the tube wall

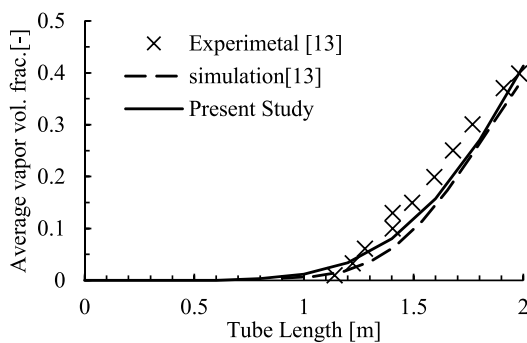
Figure 6 shows the velocity profiles for each of the tubes with constant, decreasing, and increasing diameters at 1m distance from the tube inlet. It should be noted that the diameter of the tube is proportional to the  $\theta$  [deg], which is why the maximum vertical axis value for the tubes are different. At constant mass flux, as the tube diameter increases linearly, the axial velocity decreases, and as the tube diameter decreases, the axial velocity increases. Increasing the velocity adjacent to the tube wall causes the vapor bubbles to be separated more rapidly from the surface of the tube wall.

Figure 7 shows the vapor volume fraction on the tube wall. Due to apply of constant heat flux to the tube wall, the vapor volume fraction increases consistently. It can be seen in Figure 7 that vapor volume fraction in tubes with an increasing diameter ( $\theta = 0.0192^\circ$  &  $0.0383^\circ$ ) is higher than the constant diameter tube. On the other hand, decreasing the tube diameter leads to a decrease in vapor volume fraction. As mentioned earlier in Figure 6, the main reason for the variation of vapor volume fraction adjacent to the wall is due to changes in velocity profile, which as the fluid flow velocity in the decreasing diameter tube increases, the vapor volume fraction adjacent the tube wall decreases.

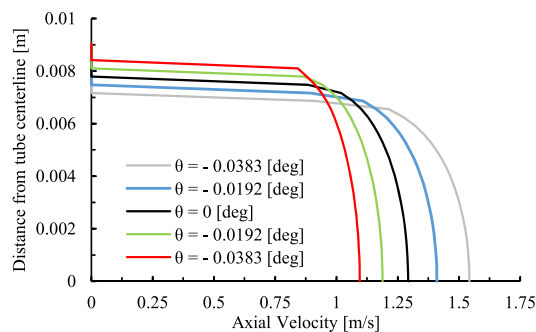
Figure 8 shows the tube wall temperature. It is observed that if the diameter decreases linearly, the tube wall temperature decreases in comparison with the tube with a constant diameter, and as the diameter



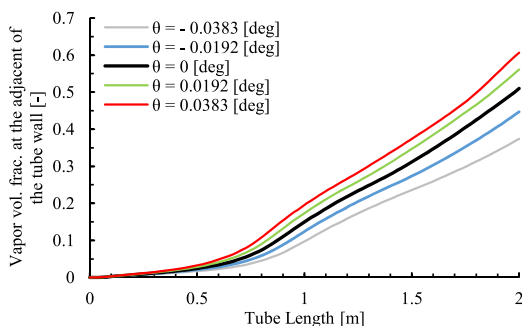
**Figure 4.** Comparison of experimental [13] and simulated results of mean fluid flow temperature (case 1)



**Figure 5.** Comparison of experimental [13] and simulated results of mean vapor volume fraction (case 1)



**Figure 6.** The axial velocity profile in the radial direction in the middle of the tube (based on case 1)

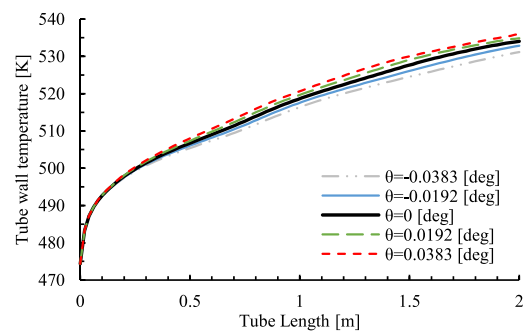


**Figure 7.** Vapor volume fraction adjacent the tube wall (based on case 1)

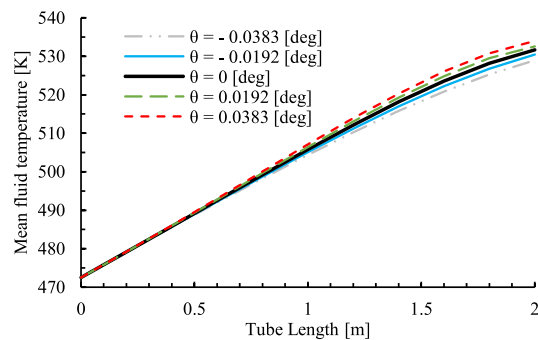
increases, the tube wall temperature increases in comparison with the tube with a constant diameter.

According to Figures 7 and 8, when the vapor volume fraction adjacent the tube on the tube wall increases, it means that the heat transfer coefficient from the tube wall to the fluid flow decreases, thereby increasing the tube wall temperature. For this reason, by increasing the vapor volume fraction on the tube wall in tubes with increasing diameter, the tube wall temperature is also higher.

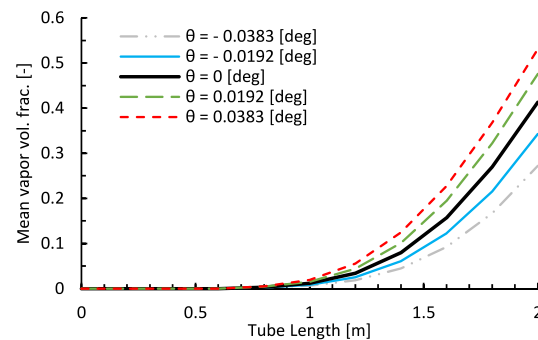
Figures 9 and 10 show the mean fluid temperature and mean volume fraction in the tube, respectively. It is observed that by increasing the diameter of the tube compared to the tube with a constant diameter, the mean fluid temperature increases in different sections.



**Figure 8.** Tube wall temperature (based on case 1)



**Figure 9.** Mean fluid temperature (based on case 1)



**Figure 10.** Mean vapor volume fraction (based on case 1)

In this study, the amount of heat flux applied to the tube wall is constant, which is defined as  $W/m^2$ . As the tube diameter varies, the total heat applied to the tube also changes, which means that as the tube diameter increases, the total heat flux applied to the tube increases, and vice versa, which naturally will be effective on the amount of produced vapor on the tube wall. Figure 11 shows the total heat applied to tubes with varying diameters. As the tube diameter and surface area increase, the amount of heat applied to the tube and fluid flow increases, which itself increases the vapor production.

Then, assuming that for all tubes with varying diameters, the total value of applied heat is equal to the amount of heat applied to the tube with a constant diameter, the vapor volume fraction and tube wall temperature are investigated (Figures 12 and 13). Assuming a heat flux value of  $q=570 \text{ kW/m}^2$  and a constant diameter of 0.0154 m, the total heat absorbed by the tube with a constant diameter will be  $Q=55.14 \text{ kW}$ . By using this value, the value of heat flux is estimated for different types of tubes.

According to Figure 12, the vapor volume fraction on the tube wall decreases with decreasing tube diameter, which mentioned in describing Figure 7. It should be noted, however, that in tubes with increased diameter, the amount of vapor fraction is somewhat equal to the amount of vapor fraction in the tube with a constant

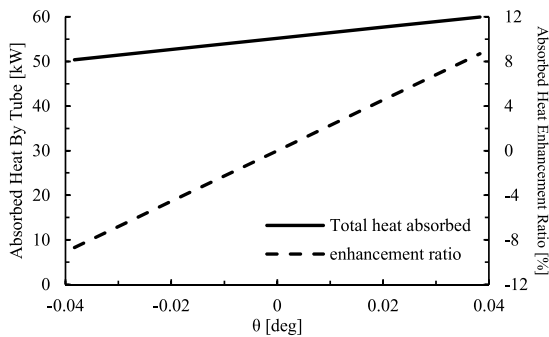


Figure 11. Effect of changing tube diameter (by  $\theta$ ) on the amount of heat applied to the tube

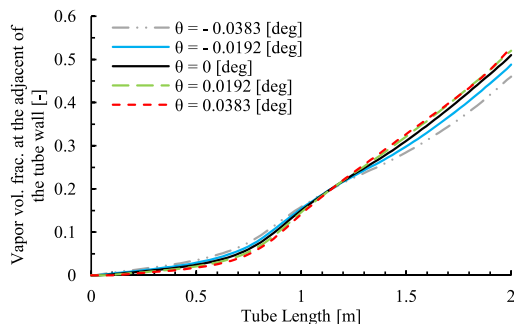


Figure 12. Vapor volume fraction adjacent the tube wall (based on case 1 &  $Q=55.14 \text{ kW}$ )

diameter. The tube wall temperature is equal for different tubes (Figure 13); the main reason is that the amount of heat absorbed by the tube is constant, while the vapor on the tube wall is also somewhat equal for the tubes, and causing the heat transfer coefficient from the tube wall to the fluid flow be close together for different tubes.

Figure 14 shows the vapor volume fraction at the outlet of different tubes. If the amount of applied heat flux to the tube wall is constant, due to the change in diameter and surface area of the tube, the total amount of heat received by the fluid flows will be changed, which results in a decrease or increase in the vapor volume fraction at the tube outlet. However, when the total amount of heat received by fluid flow is constant to the total heat applied to the tube with a constant diameter ( $q=570 \text{ kW/m}^2$ ), the vapor volume fraction at the tube outlet is approximately constant for different tubes.

#### 4. 2. Subcooled Flow Boiling Simulation at Chf Condition

For simulating fluid flow boiling based on case 2, a grid with 15 cells in radial and 500 cells in the axis direction of the tube was used. Figure 15 shows the simulated tube wall temperature. At the heat flux of  $5400 \text{ kW/m}^2$ , the tube wall temperature increases with a uniform slope, but when the heat flux is increased to  $5500 \text{ kW/m}^2$  (less than 2%), the wall temperature at the end of the tube rises sharply. The corresponding heat

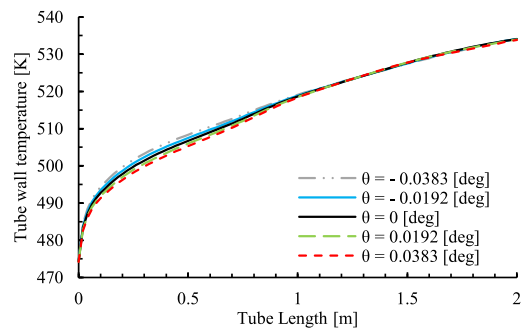


Figure 13. Tube wall temperature (based on case 1 &  $Q=55.14 \text{ kW}$ )

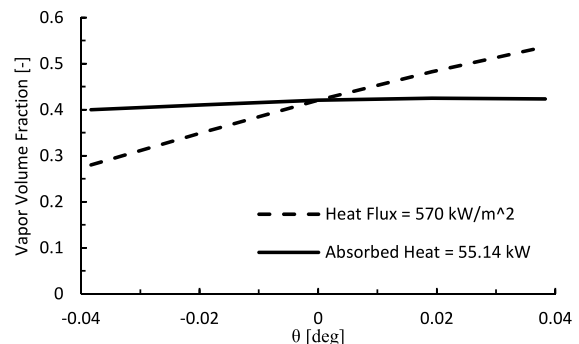


Figure 14. Outlet vapor volume fraction for constant heat flux and constant total heat (based on case 1)

flux is referred to as CHF. As shown in Figure 15, the CHF value is determined when the tube wall temperature has a sudden jump. Preventing the sudden rise in temperature that occurs at CHF is essential to prevent tube damage.

In Figure 16, the CHF values estimated in the present study are compared with the experimental data [23], which indicates the reliability of the simulation results.

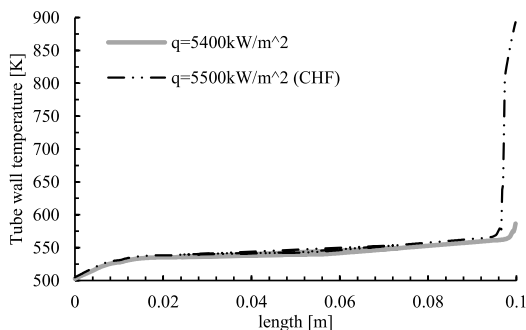
Figure 17 shows the temperature for different tubes, based on case 2. The amount of heat flux applied in each state of Figure 17 is assumed to be just before the sudden jump of temperature. It is observed that when the angle of change of tube diameter is greater than  $\theta > -0.0383^\circ$ , the temperature of the tube wall gradually increases from the inlet to the end of the tube, but when the angle of change of tube diameter is less than  $\theta < -0.0383^\circ$ , the tube wall temperature gradually decreases from the inlet to the end of tube.

It is noticeable in Figure 17, in the tube with increasing diameter, the wall temperature (before the temperature jumps) increases to near the jumped temperature in the tube with a constant diameter. Accordingly, the use of CHF and temperature jump to determine the critical working condition of fluid flow boiling in the tube cannot be defended in this case. The main purpose of the CHF determination is to prevent the

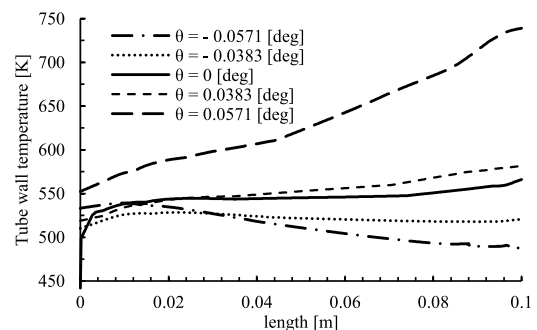
drastic rise in tube temperature and tube degradation, but it is observed that the tube wall temperature before the jump may increase sharply which in turn can lead to tube damage.

Because different tubes are of different materials and the critical temperatures are different and cannot be accurately accessed, Figure 18 shows the CHF which causes the sudden temperature jump occurring at the end of the tube. Based on the previous results, the tube wall temperature was studied in different states, and it is observed that the amount of heat flux, causing the temperature to jump in different tubes has no systematic changes. According to Figure 18, in tubes with diameter change in the range of  $-0.0477^\circ < \theta < 0.0477^\circ$  the amount of heat flux associated with the temperature jump at  $\theta = 0.0962^\circ$  &  $\theta = 0^\circ$  has the highest values. Based on Figure 17, the tube with an angle of change of  $\theta = -0.00962^\circ$  is the best choice for increasing the CHF, because it increase the CHF significantly by slightly increasing the tube wall temperature compared to the tube with a constant diameter.

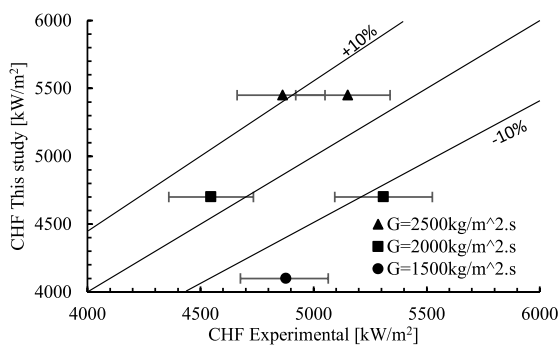
Figure 19 shows the total amount of heat applied to the tube by considering the area of the tube and the amount of heat flux, according to Figure 18. It is observed that the effect of the tube surface area changes on the total amount of heat is much less than the effect of



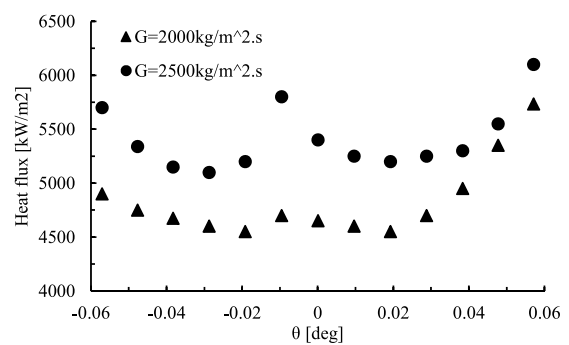
**Figure 15.** Tube wall temperature at  $q=5400$  &  $5500$   $\text{kW/m}^2$  (based on case 2)



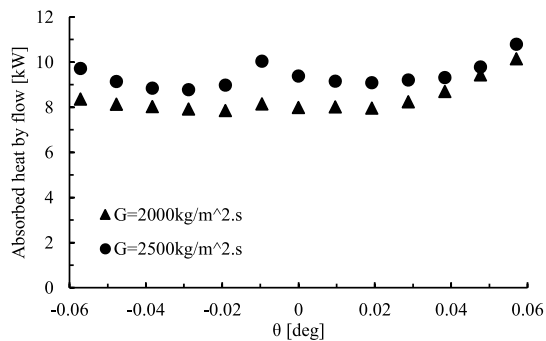
**Figure 17.** CHF and tube wall temperature before sudden temperature jump (based on case 2 &  $G= 2500$   $\text{kg/m}^2\cdot\text{s}$ )



**Figure 16.** Comparison of simulated result and experimental data [23] of CHF (based on case 2)



**Figure 18.** Heat flux at a sudden jump in temperature at the end of the tube (based on case 2)



**Figure 19.** The total amount of heat applied to the tube, based on the heat flux in Figure 18 (based on case 2)

the heat flux changes on the tube, so that even with increasing diameter and area of the tube, the total heat content decreased which is due to the reduced heat flux applied to the tube.

## 5. CONCLUSION

The main purpose of this study was to investigate the effect of linearly decreasing or increasing tube diameter on subcooled flow boiling and CHF values. Based on the theory of the fluid momentum, the results show that in increasing diameter, the vapor phase attracted to the tube wall decreases and in the linearly decreasing diameter, the vapor volume fraction on the tube wall decreases. Increasing or decreasing tube diameter, increases or decreases the fluid heat transfer coefficient, respectively. Due to the low heat transfer of the wall by the vapor phase compared to the liquid phase, the tube wall temperature increases as the tube diameter increases. The best way to reduce the wall temperature is using the tube with a decreasing diameter. In the tube with increasing diameter, the temperature of the tube wall at the end of the tube before the sudden jump is almost equal to the temperature after the sudden jump in the tube with a constant diameter, indicating that the use of the definition of the sudden jump of the wall temperature is not the correct way to determine the CHF because the purpose of CHF determination is to prevent the sudden rise in tube wall temperature and to prevent tube degradation. For the mass fluxes of 2000 and 2500  $\text{kg/m}^2\cdot\text{s}$ , when using a tube with a changing diameter of  $\theta = -0.00962^\circ$  compared to the tube with a constant diameter, the CHF values increased about 2.5% and 8%, respectively, and the total amount of heat transfer also increased by about 2% and 7%, respectively. If the total heat applied to the tube considered constant in the subcooled flow boiling, increasing or decreasing the tube diameter does not affect the tube wall temperature.

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### Persian Abstract

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#### چکیده

یکی از مسائل مهم در صنایع، جوشش جریان سیال است که رسیدن به شرایط شار حرارتی بحرانی، منجر به وقوع پرش دمایی و ایجاد خسارت به سیستم‌ها می‌شود. در مطالعه حاضر به بررسی عددی تأثیر تغییر یکنواخت قطر لوله بر جوشش جریان سیال مادون سرد و در شرایط شار حرارتی بحرانی پرداخته شده است. مدل اویلر-اویلر برای تحلیل ارتباط بین دو فاز مایع و بخار مورد استفاده قرار گرفته است. برای انجام شبیه‌سازی‌ها نیز از نرم‌افزار آنسیس فلونت استفاده شده است. با توجه به نتایج بدست آمده، در مقایسه با لوله معمولی دارای قطر ثابت، افزایش قطر لوله سبب افزایش کسر حجمی بخار در کنار دیواره لوله می‌شود که با کاهش مقدار ضریب انتقال حرارت از دیواره لوله به جریان سیال، سبب افزایش مقدار دمای لوله می‌شود. در محدوده شار حرارتی بحرانی که مقدار دمای دیواره لوله نسبت به شرایط جوشش مادون سرد بیشتر است، افزایش مقدار قطر لوله نسبت به شرایط لوله با قطر ثابت، افزایش دمای لوله قبل از پرش ناگهانی دما را در پی دارد. بهترین روش برای کاهش دمای دیواره لوله، کاهش قطر لوله است. در شرایط تغییرات قطر لوله با زاویه  $-\theta < 0/3830$ ، دمای دیواره لوله از ابتدا تا انتهای لوله نسبت به لوله با قطر ثابت، دارای کاهش است.

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