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Investigation on heat transfer characteristics and flow performance of Methane at supercritical pressures

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Abstract. The aim of this study is to investigate the heat transfer and flow characteristic of cryogenic methane in regenerative cooling system at supercritical pressures. The thermo-physical properties of supercritical methane were obtained from the National institute of Standards and Technology (NIST) webbook. The numerical model was developed based on the assumptions of steady, turbulent and Newtonian flow. For mesh independence test and model validation, the simulation results were compared with published experimental results. The effect of four different performance parameter ranges namely inlet pressure (5 to 8 MPa), inlet temperature (120 to 150 K), heat flux (2 to 5 MW/m^2) and mass flux (7000 to 15000 kg/m^{2}s) on heat transfer and flow performances were investigated. It was found that the simulation results showed good agreement with experimental data with maximum deviation of 10 % which indicates the validity of the developed model. At low inlet temperature, the change of specific heat capacity at near-wall region along the tube length was not significant while the pressure drop registered was high. However, significant variation was observed for the case of higher inlet temperature. It was also observed that the heat transfer performance and pressure drop penalty increased when the mass flux was increased. Regarding the effect of inlet pressure, the heat transfer performance and pressure drop results decreased when the inlet pressure is increased.

1. Introduction

In this modern age, most of our activities in daily life such as using hand phone, house appliances, and plants in industrial sectors need great amount of electricity. To generate huge amount of electricity, coals and fossil fuels are burnt to provide heat energy in power plants. Burning of these two substances can lead to many environmental problems such as changes of ground surface, emission of carbon dioxide, reduction of renewable energy resources and others. The emission of carbon dioxide leads to greenhouse effect, acid rain and change of climate [1-4]. To reduce these problems, biogas and biofuel can be used to replace coal and fossil fuels as they are more environmental friendly.

Biogas is made up of CH_4 (65-70%), carbon dioxide CO_2 (30-35%) and other gases [5]. It is produced through the breakdown of organic substances without existence of oxygen and this process is known as anaerobic digestion. Anaerobic digestion of wastes, harvests, and residues can reduce the

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emission of greenhouse gases and develop sustainable energy supplies such as biogas [6]. Biogas is another alternative choice for renewable energy, as methane produced can be used to replace fossil fuels in both heat and power generation and as a vehicle fuel in the form of Liquid Natural Gas (LNG) or Compressed Natural Gas (CNG).

Biogas is mostly used in engine-based combined heat and power (CHP) plants as it can achieve higher efficiency on producing heat and electricity than coal and gas-fired power stations. The electricity produced from power plant can be supplied to public and industrial sectors. The waste heat rejected can be reused in other subsystems for additional power generation hence reduces fossil fuels needed for burning.

Engine can be easily get heated due to long time operation. Methane has good properties as coolant at supercritical pressure and it is normally used in the regenerative cooling system of liquid rocket engine and gas turbine engines. In rocket combustion engines, the combustion chamber wall will undergo high heat flux and to maintain the engine lifetime, it needs to be cooled. It is done by building a cooling jacket around the combustion chamber and putting the supercritical-pressure fluid in the cooling jacket to cool it. Usually, before injecting cryogenic methane into combustion chamber, the working pressure of methane is above its thermodynamic critical pressure and no phase change will occur. At a high working pressure, very high specific heat capacity will occur if temperature near the pseudo-critical temperature. In this condition, the regenerative cooling capability can be enhanced. From studies, methane at supercritical pressure shows significant changes in thermo-physical properties at small temperature and pressure changes. Thus, extensive studies on thermo-physical properties of methane at supercritical pressures are vital. A supercritical status is defined as the temperature and pressure of a working fluid exceeds its critical temperature and critical pressure. Supercritical fluids have few advantages including increased species mixing, heat and mass transfer, fast reaction, environmental friendly, good scalability, as well as being simple and easy for continuous production [7].

Pseudocritical properties are the unusual properties behaviour which near the pseudocritical point. Usually, pseudocritical points are referenced to pseudocritical temperature. Pseudocritical temperature is defined as the temperature where specific heat capacity, C_p reaches a maximum value at a given supercritical pressure [8]. Thermo-physical and transport properties such as density, specific heat, viscosity and thermal conductivity have great variation within a narrow region near the critical point.

Gu et al. [9] in 2013 carried out experimental investigation on convective heat transfer of supercritical methane in a horizontal miniature tube. It is found that heat transfer enhancement could occur at high mass velocity and low heat flux whereas deterioration was observed at high heat flux and low mass velocity in pseudocritical region. Two conventional single phase empirical correlations which are Dittus-Boelter and Gnielinski correlations were used to compare the Nusselt number with experimental data. It is found that both correlations cannot be used for estimating the heat transfer of supercritical methane due to large variation of thermo-physical properties causing overestimation of readings near the pseudocritical temperature region. Recent research on supercritical n-decane in small vertical tubes with 0.95 mm and 2mm inner diameter was carried out by Liu et al. [10] in 2015 experimentally. From their result, high inlet Reynolds number (>7000) will lead to increase of local wall temperature without abnormal temperature distribution for both upward and download flows. On the other hand, for low inlet Reynolds number (2700-4000), buoyancy will cause heat transfer deterioration for upward flow and enhance heat transfer for downward flow.

There are some researchers did their numerical studies on supercritical methane. For instance, Pizzarelli et al. [11] in 2014 analyzed heat transfer behavior of supercritical methane in a asymmetrically heated rectangular-cross-sectional channel (base = 1 mm, height = 3 mm, rib base = 1 mm, internal wall thickness = 1 mm and channel length = 300 mm) using a three-dimensional conjugate heat transfer model. Different coolant pressures and surface roughness were used to determine heat transfer of the cooling system. It was found that at surface roughness = 10 μm, heat transfer deterioration did not occur but coolant pressure drop was increased; at high coolant pressure or rougher surface, heat transfer deterioration is reduced but pressure drop of coolant occurs, same result as Cp et al. [12] obtained in their numerical study in 2010; at lower roughness level, maximum wall temperature is lower but heat deterioration did not vanish. Pizzarelli et al. [13] in 2010 numerically studied the turbulent two-dimensional axisymmetric flow of cryogenic methane at near-critical region in a heated straight tube. Present result and past studies showed that heat transfer deterioration can occur if wall heat flux is high at supercritical pressures [14, 15].

Three-dimensional numerical study on supercritical heat transfer of cryogenic methane in rectangular engine cooling channels with asymmetric heating on top channel surface was conducted by Ruan and Meng [16] in 2012. Their results showed that heat transfer deterioration occurs when supercritical pressure is lowered and wall heat flux is increased. This is due to the abrupt variation of thermo-physical properties near pseudocritical points. Shallow cooling channels showed high Nusselt number and good heat transfer at supercritical pressure but pressure loss is high. A numerical study on cryogenic methane at supercritical pressure of 8 MPa in ribbed circular cooling tube (2mm inner diameter, 3 mm outer diameter and 300 mm heating section) is carried out by Xu et al. [17] in 2015 to investigate the effects of influential parameters on both heat transfer enhancement and pressure loss. Their result showed that rib has no effects on bulk fluid temperature but surface temperature of tube wall is reduced. More recently, Han et al. [18] in 2016 numerically investigated convective heat transfer of supercritical liquefied natural gas (LNG) in a horizontal serpentine tube. Shear-Stress Model (SST) with enhanced wall treatment method worked the most accurately in predicting outlet temperature. At constant mass flux, when bulk LNG temperature is near to pseudocritical point, the surface heat transfer coefficient is maximum. Due to abrupt change of thermo-physical properties, the transport of heat from near wall region to bulk LNG increases which lead to heat transfer enhancement.

Some research works related to heat transfer characteristics of methane have been documented. However, comparing to great amount of studies on supercritical carbon dioxide and water, there are only few papers discussed on heat transfer characteristics of supercritical methane. However, these research works do not extensively investigate the thermal-hydraulic performance of supercritical methane. Therefore, extensive research study is required to find enhanced heat transfer fluids for various engines. The aim of the current work is to investigate the heat transfer characteristics and flow performance of methane at supercritical pressures and temperature.

2. Method of Study

The test section is a horizontal steel miniature circular tube with 200 mm in length, *L* and 1.6 mm diameter, *d* as shown in Figure 1. Constant heat fluxes are applied on the outer wall surface (wall boundary) with cryogenic liquid methane injected into the tube from the left side at supercritical pressures.

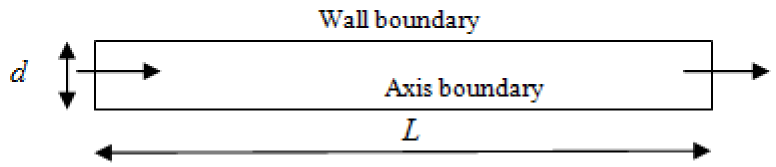


Figure 1. Schematic of the 2D numerical model.

The thermo-physical properties of methane at various supercritical pressures are obtained from NIST database and are entered to the computational fluid dynamics (CFD) software called ANSYS Fluent R17.2. Before analysing the heat transfer performance of supercritical cryogenic methane in circular pipe, mesh independence testing is needed to ensure that the generated results are same for all mesh sizes. Moreover, wall and bulk temperatures are compared to experimental results and it is found that 25,000 mesh size is sufficient to obtain close results respective to experimental data.

Model validation is then carried out to determine whether the developed model is suitable for analysis of heat transfer characteristic and pressure drop in supercritical methane through horizontal tubes. Three different turbulence models namely k-omega SST, k-omega standard and k-epsilon RNG with standard wall function were used. Overall, the k-omega SST showed the lowest discrepancies of results in terms of wall temperature and average fluid bulk temperature for different boundary conditions. Moreover, many research studies have used this turbulence model in their analysis [18, 19]. For model validation, same operating conditions from the experimental work done by Gu et al. [9] are selected.

3. Analysis and Discussion

Effects of inlet pressure, inlet temperature, heat flux and mass flux on heat transfer and flow performance are identified using different boundary conditions.

3.1. Model Validation

Before detail analysis of the heat transfer and pressure drop characteristics of supercritical methane, the developed numerical model should be checked for accuracy. For this, the bulk and wall temperature results from the current model were compared with published experimental data. Figure 2 shows variation of the bulk temperature along the tube length at 7000 kg/m^{2}s, 10 MPa inlet pressure, 130 K inlet temperature and various heat fluxes obtained from the current simulation and experiment. Three different heat fluxes (Q) were applied on the heating section to observe the effect of heat flux on fluid bulk temperature. Similar trend was obtained for each case. As can be seen from the figure, the simulation and experimental results are in good agreement. For 4 MW/m^2 heat flux, the maximum and average deviations between the simulation and experimental results are 2.3 % and 2.2 %, respectively. As the heat flux increases to 5 MW/m2, as expected, the overall fluid bulk temperature increases. Maximum deviation of 3 K between the simulation and experiment results is found at 120 mm from inlet, which is equivalent to 1.6 %. When the heat flux is increased to 6.5 MW/m^2, almost all the simulation and experimental values are close to each other except at the points located at 180 mm onwards. In this case, because of the deviations at the these points, the maximum deviation rose to 2.7%. However, the minimum deviation is only 0.13% and this leads to average deviation of 1% for 6.5 MW/m^2. In all cases, it can be observed that all the average errors are lower than the accepted error of 10% mentioned by most of the previous researchers [18, 19].

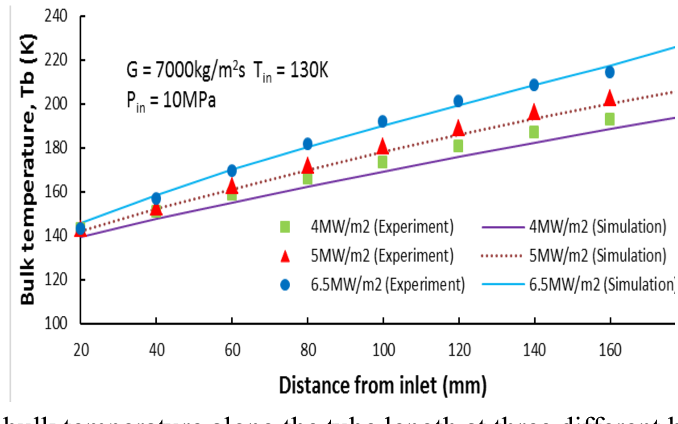


Figure 2. Variation of bulk temperature along the tube length at three different heat fluxes.

Figure 3 shows the effect of three different heat fluxes on wall temperature at the same boundary condition as in Figure 2. All cases show close values between experimental and simulation results. For 4 MW/m^2, the average deviation is found to be 5.9% while the maximum difference is 7.8%. When the heat flux is increased to 5 MW/m^2, both experimental and simulation results show average and maximum deviation of 5.3 % and 8.7% respectively. At 6 MW/m^2, similar trend is shown for both results. There is a sudden increment of wall temperature at 120 mm from inlet. This is due to the supercritical properties of methane at high pressure, in which sudden drop of specific heat capacity leads to sudden change of temperature. For this case, the maximum deviation of wall temperature is 9.6% which is acceptable generally and the average deviation is 5.3%. Overall, the average deviation for all the three cases is about 5 to 6%. This further verifies the validity and accuracy of the developed model used in this study.

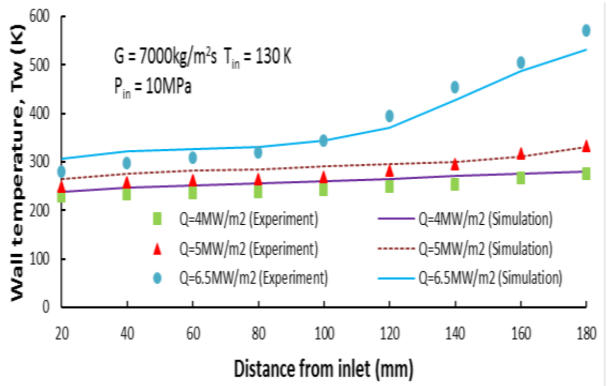
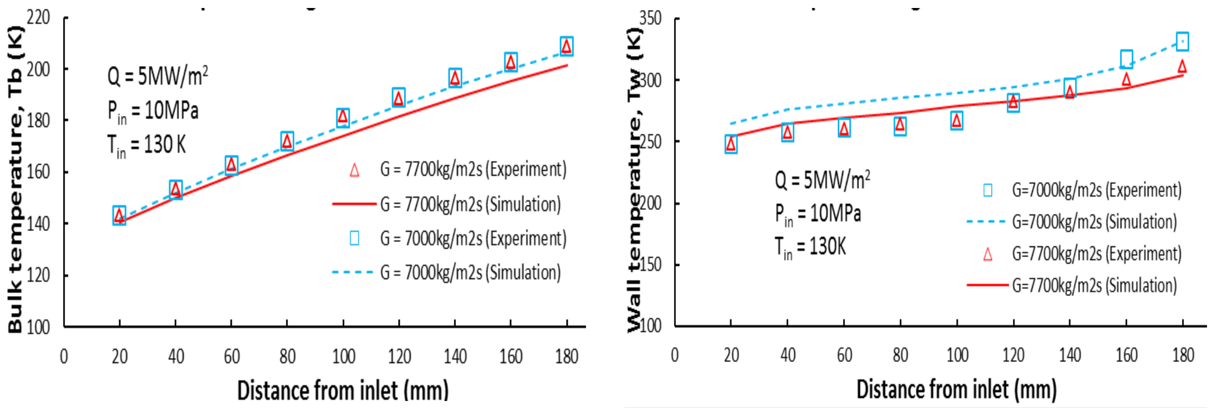


Figure 3. Variation of wall along the tube length at constant mass flux.

Graphs shown in Figures 4a and 4b are variations of bulk and wall temperature along the tube length at various mass fluxes. Both temperatures decreased when the mass flux is increased from 7000 kg/m^{2}s to 7700 kg/m^{2}s for both simulation and experimental data. When the mass flux increases, inlet velocity increases and this leads to more heat at the wall region to be absorbed by the cryogenic methane in the tube. For wall temperature at G = 7000 kg/m^{2}s, there is slight increment of wall temperature at 160 mm from inlet, this is due to the specific heat capacity of methane at this point starts decreasing which leads to heat transfer deterioration and thus wall temperature becomes higher.



(a) (b)

Figure 4. Mass flux effect on (a) bulk temperature and (b) wall temperature.

3.2. Heat Transfer Performance

The performance of heat transfer is proportional to specific heat capacity. Thus, it is important to see how the heat transfer coefficient varies with inlet temperature. Shown in Figure 5 is variation of specific heat capacity at near-wall region along the tube length at various inlet temperatures. At low inlet temperature, the change of specific heat capacity at near-wall region along the tube length is not significant. However, significant variation is observed for the case of higher inlet temperature. It can be clearly seen from the figure that the specific heat capacity at near-wall region increases with inlet temperature at all positions. For instance, at inlet temperature of 150 K, the specific heat capacity starts to increase starting from 120 mm and this leads to enhanced heat transfer performance at the same location as shown in Figure 6. As mentioned earlier, the decrement of specific heat capacity leads to the slight increment of wall temperature and this causes heat transfer performance to drop. For 120 K, 130 K and 140 K, the heat transfer performance is lower due to lower increment of specific heat capacity.

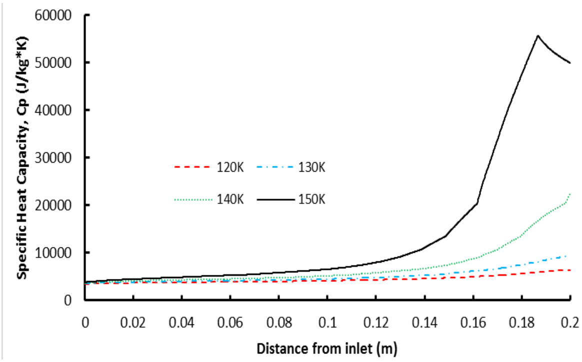


Figure 5. Effect of inlet temperature on specific heat capacity at 5 MPa, 4 MW/m^2 and 10000 kg/m^{2}s. (near-wall region)

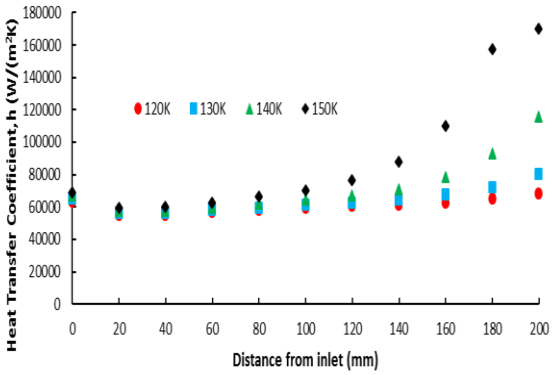


Figure 6. Effect of inlet temperature on heat transfer performance at 5 MPa, 4 MW/m^2, and 10000 kg/m^{2}s.

Shown in Figure 7 is variation of heat transfer coefficient with inlet mass flux. The fixed boundary conditions in this case are 5 MPa inlet pressure, 120 K inlet temperature and 4 MW/m^2 heat flux. The mass fluxes range from 7000 to 15000 kg/m^{2}s. As shown in the figure, the heat transfer performance increases when the mass flux is increased. The same type of result was obtained in another simulation work by Han et al. [18] and it was explained that due to the large variation of thermo-physical properties at near-wall region which lead to enhanced heat transfer performance. However, heat transfer performance increment along the tube length is not significant for G = 10000 and 15000 kg/m^{2}s. This is due to the insignificant change of the specific heat capacity of methane at near-wall region for this two mass fluxes. For near-wall region, the specific heat capacity at G = 7000 kg/m^{2}s is about 12.6 times higher than that of 15000 kg/m^{2}s at outlet. This results in the great difference in variation of heat transfer performance increment. Another point is that the fluid velocity increases when mass flux increases and this will lead to more heat can be transferred away before the fluid temperature becomes higher. Thus, both bulk and wall temperatures are decreasing with increasing mass flux which enhances heat transfer performance.

Another factor that affects the heat transfer performance is inlet pressure. For this, the inlet pressures used are 5 to 8 MPa. The other boundary conditions fixed are mass flux of 10000 kg/m^{2}s, 4 MW/m^2 heat flux and 120 K inlet temperature. The variations of bulk and wall temperature are not shown due to the small difference between each point for every inlet pressure. As shown in Figure 8, the heat transfer performance increases along the tube length for all inlet pressures. For the heat transfer coefficient at 20 mm from inlet, it is higher than that at 40 mm. On the other hand, heat transfer performance decreases when the inlet pressure is increased. This is due to the great difference in thermo-physical properties between these pressures. The same argument was made by Gu et al.[9]. The variation of specific heat capacity at near-wall region for all inlet pressures has the same trend. When it comes to 0.18 m from inlet, the specific heat capacity increment based on 8 MPa is 21.9 %, 12.2 % and 5.2 % for 5 MPa, 6 MPa and 7 MPa respectively. As mentioned previously, heat transfer performance is proportional to specific heat capacity and this section further validates this statement. Thus, for lower supercritical pressures, the variation of thermo-physical properties near pseudocritical point is higher and thus heat transfer performance is enhanced more at lower supercritical pressures before pseudocritical point.

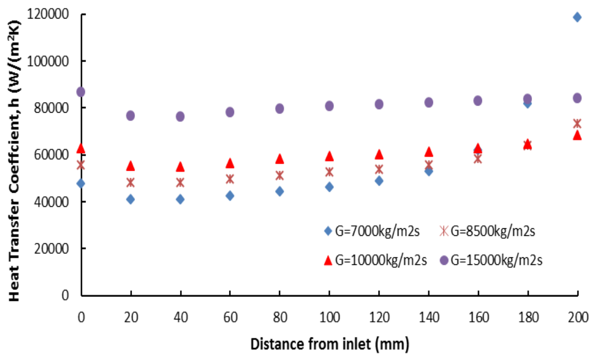


Figure 7. Effect of mass flux on heat transfer performance at 5MPa, 120K and 4 MW/m^2.

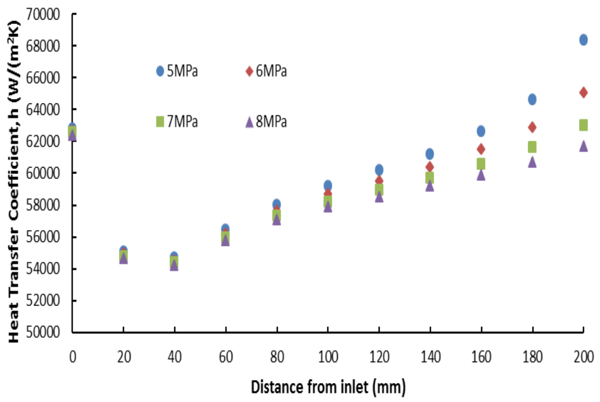


Figure 8. Effect of inlet pressure on heat transfer coefficient at 10000 kg/m^{2}s, 4 MW/m^2 and 120 K.

3.3. Flow Performance

To study the effect of inlet temperature on pressure drop along the tube length, the fixed boundary conditions are mass flux of 10000 kg/m^{2}s and heat flux of 4 MW/m^2. Figure 9 shows the pressure drop of supercritical methane along the tube length at different inlet pressure. It can be clearly seen that the pressure drop decreases as the inlet temperature is lower. Considering the inlet temperature of 120 K at 5 MPa as reference point, the increment of pressure drop is 5.2%, 12.6 % and 22.3% when the inlet temperature is increased to 130 K, 140 K and 150 K respectively. The pressure drop increment is due to higher inlet temperature which causes both wall and bulk temperature increase more than that of lower inlet temperature. Thus, the viscosity of methane decreases more and bulk velocity of methane will increase with increasing inlet temperature. Higher fluid velocity leads to higher pressure drop. On the other hand, increasing inlet pressure with constant heat flux lowers down the pressure drop as well. This is due to the less abrupt variation of thermo-physical properties at higher supercritical pressure. In general, increasing inlet temperature leads to increment of pressure drop.

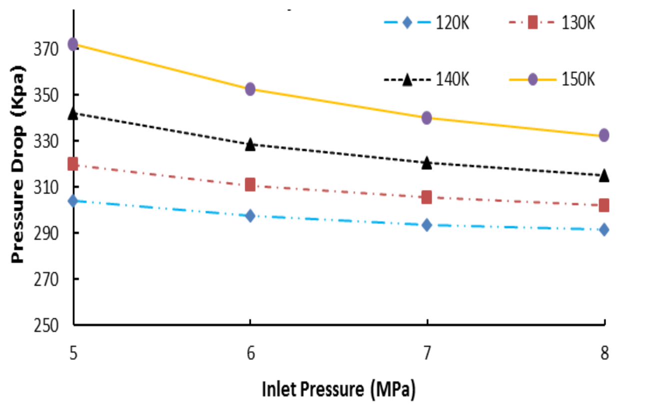


Figure 9. Effect of inlet temperature on pressure drop of methane at 10000kg/m^{2}s, 4 MW/m^2 and various inlet temperatures.

Inlet temperature and heat flux are fixed at 120 K and 4 MW/m^2 respectively. Figure 10 shows the effect of mass flux on pressure drop of methane at different inlet pressure. It is shown that the pressure drop increases when mass flux increases. The huge increment of pressure drop from mass flux of 10000 kg/m^{2}s to 15000 kg/m^{2}s is about 270 kPa for every inlet pressure. This is due to the high increment of average bulk velocity from about 27 m/s to 39 m/s. Since it is found that pressure drop has strong correlation with fluid velocity, it can be concluded that the fluid velocity is always proportional to the pressure drop of supercritical methane in a circular tube. In short, increasing mass flux which increases fluid velocity will lead to increment of pressure drop. On the other hand, the pressure drop decrement is not significant (with maximum deviation of 7 kPa) when the inlet pressure is increased at constant mass flux, this might be due to the low inlet temperature (120 K) and heat flux (4 MW/m^2) used are not sufficient to make the methane bulk temperature near to pseudocritical temperature (which has more abrupt variation of thermo-physical properties) for all inlet pressure.

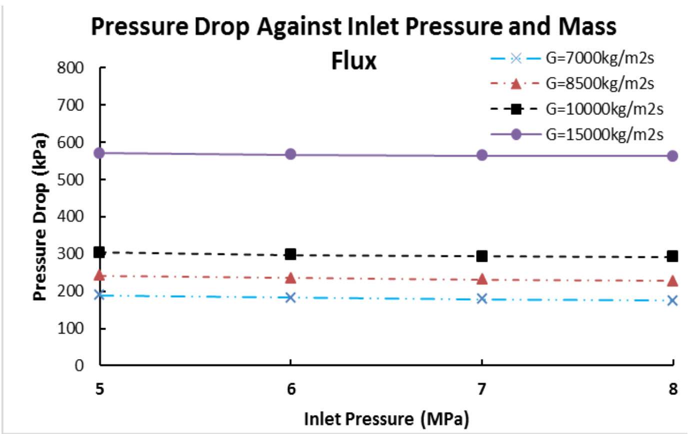


Figure 10. Effect of mass flux on pressure drop of methane at 120 K, 4 MW/m2 and various inlet pressures.

The last parameter examined is inlet pressure. For this, the boundary conditions fixed are inlet temperature of 150 K, mass flux of 10000 kg/m^{2}s and heat flux of 5 MW/m^2. Figure 11 shows the variation of pressure drop and average bulk velocity of supercritical methane. As discussed in the previous section, pressure drop is always proportional to fluid velocity. From this figure, it also shows that pressure drop decreases when average bulk velocity decreases. By comparing with the variation of average bulk velocity through different inlet pressure at G = 10000 kg/m^{2}s it was observed that greater variation of the average bulk velocity even though the mass flux and inlet pressures for both cases are the same. However, this great variation of average bulk velocity is due to the difference of inlet temperature and heat flux applied. This can strengthen the statement made earlier which stated that low inlet temperature and heat flux are not enough to make the methane bulk temperature near to pseudocritical temperature. It can be seen from Figure 11 that when inlet pressure is increased, the pressure drop decreases. This is due to the more abrupt variation of thermo-physical properties of methane at lower supercritical pressures. In short, increasing inlet pressure can help to reduce pressure drop across tube length.

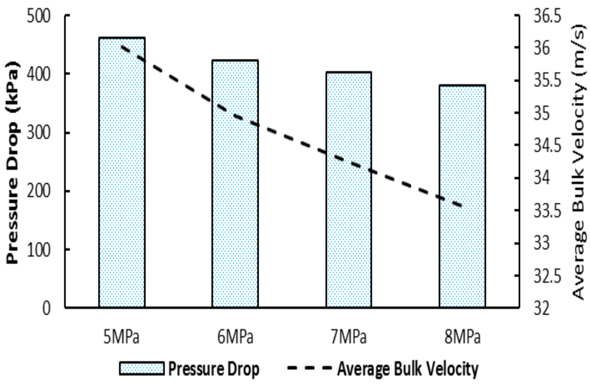


Figure 11. Effect of inlet pressure on pressure drop and average bulk velocity at 150 K, 10000 kg/m^{2}s and 5 MW/m^2.

4. Conclusion

The effect of inlet temperature, mass flux and inlet pressure on heat transfer and flow performance is investigated. High inlet temperature leads to abrupt increment of specific heat capacity which increases heat transfer coefficient after some distance from the inlet of the tube. Next, high mass flux has higher heat transfer coefficient initially but after some distance from inlet, low mass flux which has low flow velocity makes the flowing methane to reach near-pseudocritical temperature which enhances heat transfer performance near the tube outlet due to higher specific heat capacity increment. Lower inlet pressure has higher variation of specific heat capacity and this leads to the increment of heat transfer performance. For pressure drop, it becomes higher when heat flux, inlet temperature and mass flux are increased. Lower inlet pressure leads to higher pressure drop due to the more abrupt variation of thermo-physical properties. Generally, at mass flux of 10,000 kg/m^{2}s and heat flux of 4 MW/m^2, it is found that 150 K inlet temperature with 5 MPa inlet pressure has high heat transfer performance and low pressure drop. Besides that, heat flux of 3 MW/m^2 with mass flux of 15,000 kg/m^{2}s has the highest Goodness factor at 6 MPa inlet pressure and 130 K inlet temperature boundary conditions.

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