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Experimental Investigation on Heat Transfer of N-heptane at Subcritical and Supercritical Pressures

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Abstract. This paper has presented experimental results on heat transfer of n-heptane, the surrogate of kerosene, at subcritical and supercritical pressures. Results indicate that as for liquid heat transfer, slender boiling happens at the near wall zones when heat flux is high. When heat flux is low, both wall and bulk temperature increase. As for two-phase heat transfer, nucleate boiling happens at the anterior part of the tube. Heat transfer coefficient is extremely high. At the anterior part of the tube, film boiling happens, making heat transfer deteriorated. As for gas heat transfer, both wall and bulk temperatures increase, but heat transfer coefficient nearly keeps constant. Heat transfer under supercritical pressure is similar to liquid heat transfer at low heat flux. Both wall and bulk temperature increase along the tube, and heat transfer coefficient increases with bulk temperature.

1. Introduction

Active cooling is considered as the most promising way to solve thermal protecting problem for scramjet [1]. Fuel such as kerosene flows through the cooling channels and absorbs the heat. Heat transfer under supercritical pressures is much different from that under sub-critical pressures.

Many experimental and numerical studies are made on supercritical heat transfer of hydrocarbon fuels. Zhong et al. [2] showed that when the inner wall temperature approaches the critical temperature, heat transfer enhancement happens. Linne et al. [3] thought that this enhancement is like nucleate boiling under subcritical pressure. Experiments by Hu et al. [4] confirmed this and found that there is another enhancement which happens when the inner wall temperature and heat flux are extremely high, and this enhancement is caused by cracking reactions. Li et al. [5] found that enhancement does not always happen when inner wall temperature is higher than the critical temperature. Effects of centrifugal force on heat transfer were also studied [6]. Numerical research of Meng et al. [7] indicates that heat transfer deterioration happens when inner wall temperature is higher than the pseudo-critical temperature.

Few researches are made on comparison of the heat transfer under sub-critical and supercritical pressures.

In this paper, comparison of heat transfer of n-heptane flowing in mini-channel under subcritical and supercritical pressures were investigated. The test conditions are as follows: heat flux is 0.3MW/m², mass flow rate is 1.3g/s. The mini-channel is 400mm in length with inner diameter of 1.6mm and outer diameter of 2.4mm. Pressure inside the channel is 0.5MPa (sub-critical pressure test condition) and 4MPa (supercritical pressure test condition), respectively.



2. Experimental Setup

The experimental setup is shown in figure 1. It mainly consists of four parts, the fuel storage and supply system, the electric heater, the test section and the measure system.

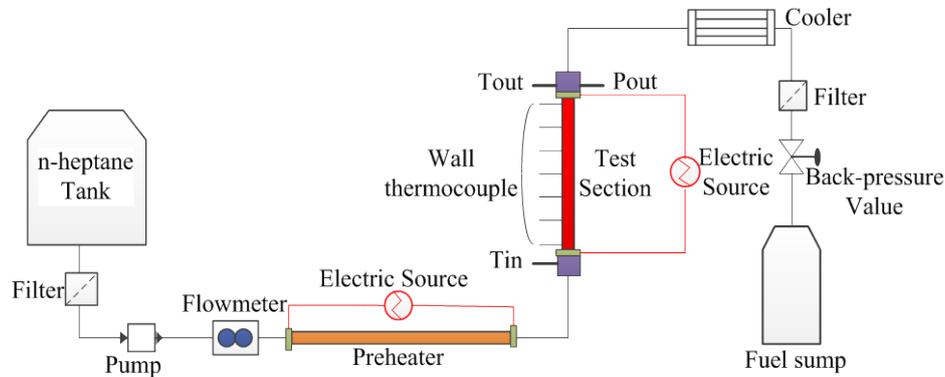


Figure 1. Experimental setup

N-heptane is stored in a tank and pumped to the preheater and test section. A stainless tube (1Cr18Ni9Ti) with inner diameter of 1.6mm and length of 1600mm serves as preheater. An electrical heater with maximum power of 28KW heats the preheater and the n-heptane flowing inside it. Then the heated fuel flows through the test section, which is also a stainless tube (1Cr18Ni9Ti) with inner diameter of 1.6mm and length of 400mm. Another electrical heater with power of 6KW heats the test section. The fluid temperatures at the inlet and outlet of the test section and the wall temperatures along it are measured and analyzed. Then the fuel flows through a cooler and at last into a fuel sump. There is a back-pressure valve between the cooler and the sump, in order to adjust the pressure inside the test section.

Mass flow rate of the fuel is measured by a Coriolis-force flow meter (Model: DMF-1-1-A, SiMite) with an uncertainty of 0.2%. Pressure in the test section is measured by a pressure gage transducer (Model: MPM480, Maike) with an uncertainty of 0.1%. The inlet and outlet fluid temperatures are measured by K-type armored thermocouples (Model: 0.5mm, Zhongse) with an uncertainty of 0.75%. The wall temperatures of the test section are measured by K-type armored thermocouples (Model: 0.08mm, Omega) with an uncertainty of 0.4%.

3. Results and Discussion

Figure 2 shows the HTC (heat transfer coefficient) variations with fluid temperature in liquid heat transfer regime. HTC increases as fluid temperature increases. When the fluid temperature is approaching the boiling point, HTC increases much more rapidly.

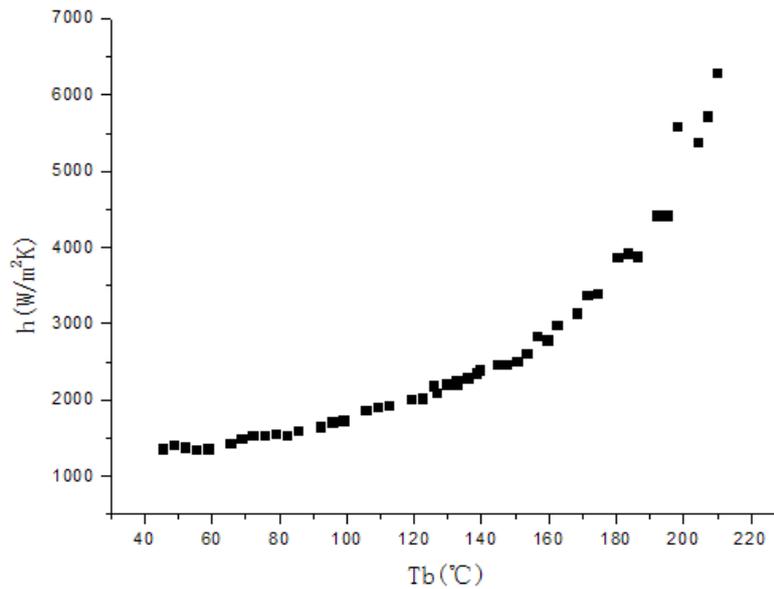


Figure 2. HTC variations with fluid temperature in liquid heat transfer regime.

Figure 3 shows the HTC variations with fluid temperature in two-phase heat transfer regime. At the anterior part of the channel, it is nucleate boiling and HTC is high, nearly at approximately $20000\text{W/m}^2\text{K}$; at the posterior part of the channel, it is film boiling and HTC decreases to about $3500\text{W/m}^2\text{K}$.

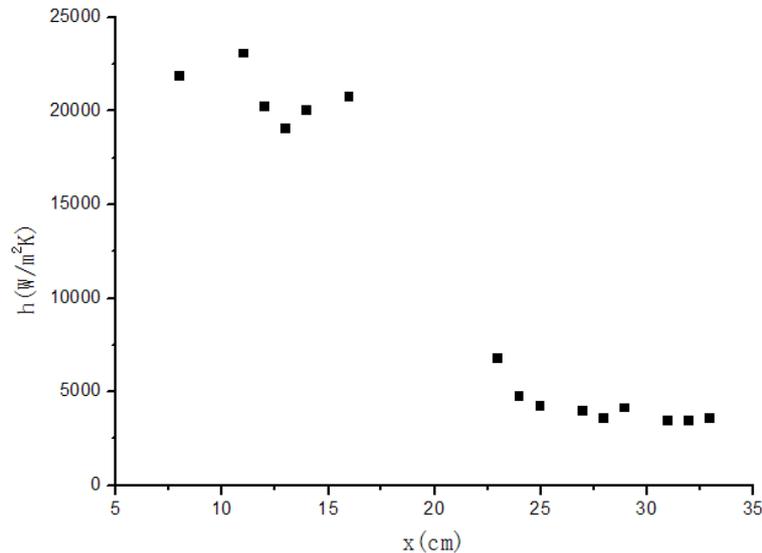


Figure 3. HTC variations with fluid temperature in two-phase heat transfer regime

Figure 4 shows the HTC variations with fluid temperature in gas heat transfer regime. HTC is much higher than that in liquid heat transfer regime and film boiling heat transfer regime, but lower than that in nucleate boiling heat transfer regime. HTC varies in the range of $8000\text{W/m}^2\text{K}$ ~ $12000\text{W/m}^2\text{K}$ and doesn't change with fluid temperature. The reason is that Reynolds number in this regime is from 81131 to 110774, indicating that flow in the channel is fully-developed turbulent. The mass and heat transfer processes between molecules are remarkable and play dominant role in heat transfer. Effects of fuel property variations on heat transfer are weak.

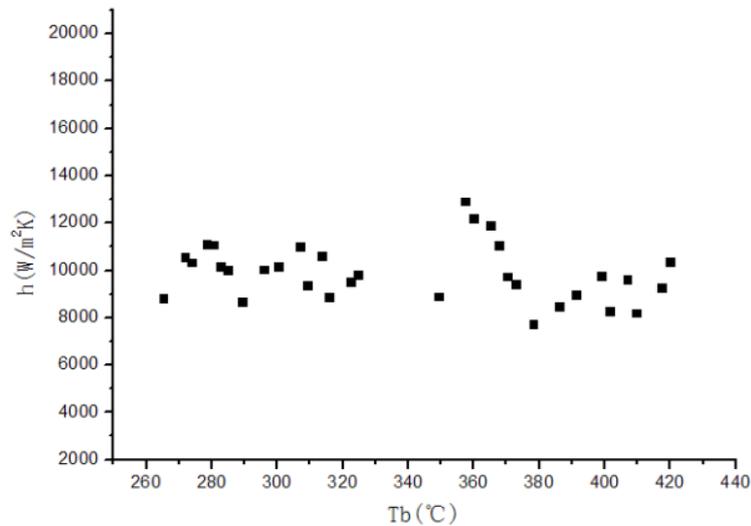


Figure 4. HTC variations with fluid temperature in gas heat transfer regime

Figure 5 shows comparison of HTC under sub-critical and supercritical pressures. Boiling point under 0.5MPa is 250°C. The pseudo-critical temperature under 4MPa is 377°C. They are both marked in the figure.

As for the sub-critical pressure condition, when temperature is less than 250°C, the fluid is liquid, marked as red circular dots in the figure; when temperature is larger than 250°C, the fluid is gas, marked as blue trigonal dots. As for the supercritical pressure condition, there is no phase change anymore. The fluid will transfer from super-pressed to supercritical when temperature rises above 377°C, marked as black foursquare dots.

It can be divided into three parts in figure 5 according to the boiling point and pseudo-critical temperature, namely part A, B and C. In part A, when temperature is less than 200°C, HTC of heat transfer under 4MPa is comparable to that under 0.5MPa. However, when temperature is larger than 200°C, HTC under 4MPa is smaller than that under 0.5MPa. In part B, HTC under 0.5MPa becomes very high and is much larger than that under 4MPa. In part C, HTC under these two pressures becomes comparative again.

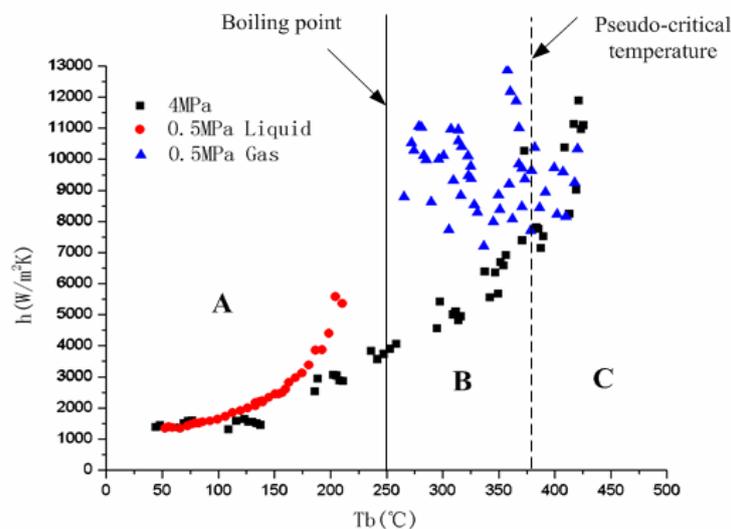


Figure 5. Comparison of HTC under sub-critical and supercritical.

The difference of HTC under sub-critical and supercritical pressures is mainly caused by three factors: property variations, boiling and flow regime (laminar or turbulent). Property and Reynolds number variations with temperature under 0.5MPa and 4MPa are shown in figure 6 and figure 7, respectively.

As can be seen in figure 6 and 7, in part A, properties and Reynolds number under 0.5MPa and 4MPa are nearly the same. However, when temperature approaches the boiling point, slender boiling near wall happens under 0.5MPa, as described in previous discussion. And heat transfer is enhanced. However, there is no boiling for supercritical pressure condition. Thus, HTC under 4MPa is as much as that under 0.5MPa before 200°C and smaller than that under 0.5MPa when temperature is higher than 200°C, just as shown in figure 2.

In part B, the four properties under 4MPa are all larger than that under 0.5MPa. Generally speaking, larger specific heat and thermal conductivity are beneficial to heat transfer while larger density and viscosity play a negative role in heat transfer. The Reynolds number under 0.5MPa is much larger than that under 4MPa, as can be seen in figure 6. When temperature is 250°C, Reynolds number under 0.5MPa is 112266, indicating that flow in the channel is fully-developed turbulent. However, Reynolds number under 4MPa at temperature 250°C is only 8022, and the flow in the channel is still transitional. Thus, in part B, HTC under 4MPa is smaller than that under 0.5MPa.

In part C, Reynolds number under 4MPa becomes larger than 23510. Flow in the channel has also become fully-developed turbulent. Heat transfer is enhanced, thus HTC is almost comparable to that under 0.5MPa.

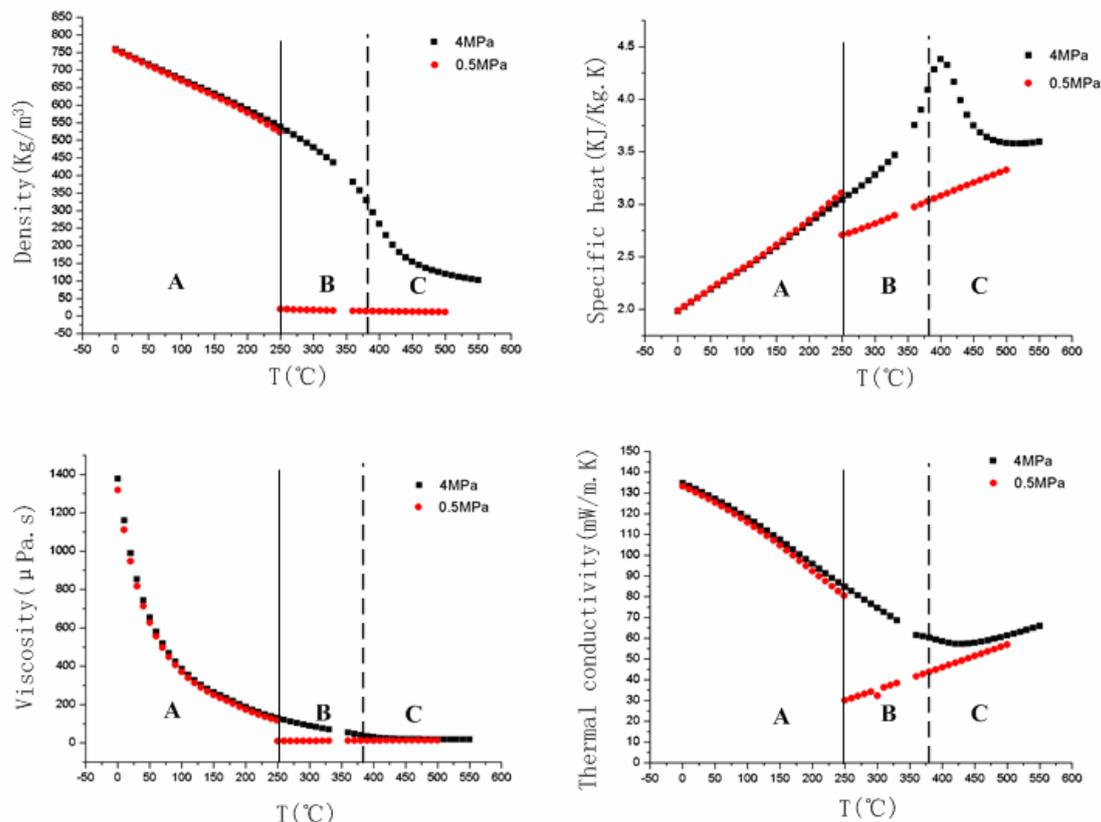


Figure 6. Comparison of HTC under sub-critical and supercritical.

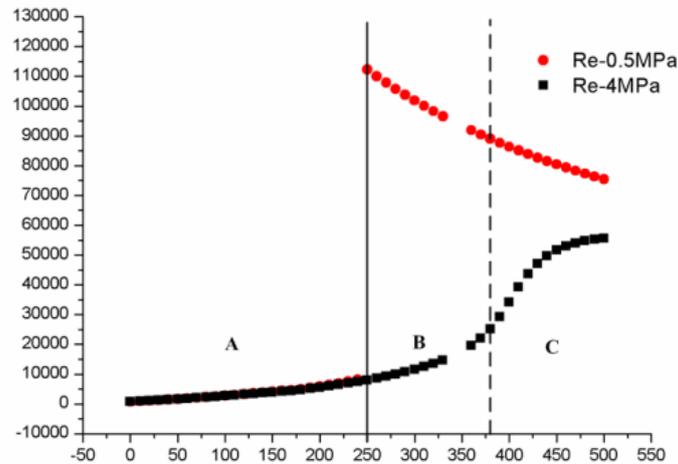


Figure 7. Variations of Reynolds number with temperature under sub-critical and supercritical pressure.

4. Conclusion

Heat transfer characteristics of n-heptane flowing in mini-channel under subcritical and supercritical pressures are experimentally investigated in this paper. The main conclusions are as follows.

Comparison of HTC under subcritical and supercritical pressures shows that, when temperature is lower than the boiling point, HTC under supercritical pressure is comparable to that under subcritical pressure; when temperature is between the boiling point and the pseudo-critical temperature, HTC under supercritical pressure is much smaller than that under subcritical pressure; when temperature is higher than the pseudo-critical temperature, HTC under supercritical pressure becomes comparable to that under subcritical pressure again. Property variations and flow regime (laminar or turbulent) are responsible to the difference of HTC under subcritical and supercritical pressures.

5. References

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