Forced Convective Heat Transfer of RP-3 Kerosene at Supercritical Pressure inside a Miniature Tube

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Abstract. In order to obtain heat transfer characteristics of RP-3 kerosene flowing in cooling channels of scramjet under supercritical pressure, experiments on heat transfer to RP-3 kerosene flowing in a miniature tube are conducted. The experimental parameters are as follows, heat flux varies from 0.3MW/m² to 0.5MW/m², mass flow rate is 1.3g/s, pressure is 5MPa and fluid temperature is from 20°C to 550°C . Results indicate that there are three regimes for heat transfer of RP-3 kerosene under supercritical pressure, namely the common heat transfer, the enhanced heat transfer and the deteriorated heat transfer. When bulk temperature is from 20°C to 275°C, it is common heat transfer regime. Heat transfer coefficient increases with bulk temperature, but the increment is relatively small. Enhanced heat transfer regime is from 275°C to 500°C. Heat transfer coefficient increases much more rapidly with bulk temperature and reaches relatively high value. Deteriorated heat transfer regime is from 500°C to 550°C. Heat transfer coefficient decreases when bulk temperature increases. Mechanism of these three regimes are analyzed. Variations of properties and laminar flow are responsible for common heat transfer. Turbulence is the main reason for enhanced heat transfer. Heat release reactions (combination of small molecules into big molecules) are attributed to the heat transfer deterioration.

1. Introduction
Hypersonic vehicles are of great value for their potential application in military and commercial field [1]. Active cooling is the most promising way to solve thermal protection right now [2].

Many studies are made on heat transfer of hydrocarbon fuels under supercritical pressures. Zhong et al. [3] pointed out that heat transfer enhancement happens when inner wall temperature approaches the critical temperature of the fuel. Hu et al. [4] found another enhancement when heat flux and inner wall temperature are extremely high. Li et al. [5] found that enhancement does not always happen. Hua et al. [6] indicated that when inner wall temperature is higher than the pseudo-critical temperature of n-heptane, heat transfer deterioration happens. Zhu et al. [7] conducted numerical studies on heat transfer and resistance characteristics of RP-3 kerosene under supercritical pressures. Tao et al. [8] numerically investigated the heat transfer characteristics and flow resistance of n-decane, considering pyrolysis effects.

The parameters, such as mass flow rate, heat flux, and size of the cooling channels, are not the same as that in a practical scramjet engine. For example, Zheng et al. [9] pointed out that heat flux in a practical scramjet engine varies from 0.3MW/m² to 0.7MW/m² at Mach 6. However, the heat flux in the previous researches is usually larger.

In this paper, parameters are as follows: The inner diameter of the cooling channel is 1.6mm, mass flow rate is 1.3g/s, heat flux is from 0.3MW/m² to 0.5MW/m², pressure inside the channel is 5MPa.
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](image)

RP-3 kerosene is stored in a tank and pumped to the preheater, which is made of a stainless tube (1Cr18Ni9Ti) with inner diameter of 1.6mm and length of 1600mm. The tube is directly heated by an electrical heater with maximum power of 28KW. So the kerosene flowing inside it is preheated. Then the kerosene flows into 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 fuel and wall temperatures along the test section are measured. At last the kerosene flows through a cooler and then into a fuel sump. There is a valve between the cooler and the sump, in order to adjust the test section pressure.

The measuring apparatus and uncertainty are listed below.

| Parameter          | Apparatus                        | Model         | Uncertainty |
|--------------------|----------------------------------|---------------|-------------|
| Mass flow rate     | Coriolis-force flow meter        | DMF-1-1-A, SiMite | 0.2%        |
| Pressure           | Pressure gage transducer         | MPM480, Maike | 0.1%        |
| Fuel temperature   | K-type armored thermocouple      | φ0.5mm, Zhongse | 0.75%       |
| Wall temperature   | K-type thermocouple              | φ0.08mm, Omega | 0.4         |

3. Results and Discussion
Figure 2 shows the HTC (heat transfer coefficient) variations with fuel temperature. It can be divided into three parts. When fuel temperature is less than about 275°C, HTC increases slowly with fuel temperature. For example, HTC grows from 878W/m²K to 1049W/m²K with amplitude of 19% when fuel temperature increases from 71°C to 172°C. We considered it as common heat transfer regime. When fuel temperature is from 275°C to about 500°C, HTC increases much more quickly with fuel temperature. HTC grows from 4187W/m²K to 9576W/m²K with amplitude of 130% when fuel temperature increases from 405°C to 505°C. We call it enhanced heat transfer regime. When fuel temperature is above 500°C, HTC decreases when fuel temperature increases. We call it deteriorated heat transfer regime.
Figure 2. Heat transfer coefficient variations with fuel temperature (0.3MW/m², 5MPa, 1.3g/s).

Common heat transfer regime is determined by thermal properties of kerosene and flow regimes. Figure 3 shows variations of the thermal property. In common heat transfer regime, viscosity, density and thermal conductivity decrease while isobaric specific heat capacity increases. When density decreases, velocity increases. When viscosity decreases, the mass and heat transfer processes between molecules become more active. When isobaric specific heat capacity increases, the capability for absorbing heat is promoted. Variations of these three properties are beneficial to heat transfer. Decrease of thermal conductivity plays a negative role in heat transfer. However, the combined effects of property variations on heat transfer is positive.

Figure 3. Variations of kerosene thermal properties under 5MPa.
In common heat transfer regime, Reynolds number increases from 958 to 9404 when fuel temperature changes from 20°C to 275°C. The flow in the tube is still laminar and transitional. Thus mass and heat transfer between molecules are weak. That is why the HTC is low and grows slowly in this regime.

In enhanced heat transfer regime, HTC is much higher than that in common heat transfer regime, and it increases rapidly with fuel temperature. Properties of RP-3 change remarkably in this regime, as can be seen in figure 5. More importantly, Reynolds number increases from 9404 to 33371 when fuel temperature changes from 275°C to 500°C, indicating that flow in the tube has changed from laminar to turbulent. The mass and heat transfer processes between molecules become much more drastic. As a result, HTC in this regime increases rapidly.

In deteriorated heat transfer regime, HTC decreases with fuel temperature. Specific heat and thermal conductivity increase in this regime. Density decreases and viscosity nearly keeps constant. Variations of all these four properties are beneficial to heat transfer. Furthermore, Reynolds number in this regime is between 33371 and 37756. Flow is fully developed turbulent. Thus, according to the property variations and flow regime, heat transfer should be enhanced in this regime. However, heat transfer is deteriorated and HTC decreases with fuel temperature.

Previous studies show that buoyancy effects and thermal accelerating may lead to heat transfer deterioration for supercritical fluids. However, it is for upstream flow that buoyancy effects cause heat transfer deterioration. As for horizontal flow presented in this paper, buoyancy effects only lead to heterogeneous heat transfer in radial section. Thus, the heat transfer deteriorated shown in figure 3 cannot be caused by buoyancy effects.

McEligot et al. [10] proposed a dimensionless parameter Kv, named thermal accelerating factor. Generally speaking, when \(Kv > 3 \times 10^{-6}\), effects of thermal accelerating is remarkable and heat transfer is deteriorated. Variation of \(Kv\) for supercritical RP-3 kerosene under 0.3MW/m² test condition is shown in figure 4. \(Kv\) is always smaller than \(3 \times 10^{-6}\). Thus, it is not thermal accelerating that causes heat transfer deterioration.

![Figure 4. Variations of Kv with bulk temperature (0.3MW/m², 5MPa, 1.3g/s).](image)

As for hydrocarbon fuels, cracking reactions would happen when temperature is high. Figure 5 shows the chemical heat sink variations of RP-3 kerosene. When temperature is lower than 400°C, the chemical heat sink is 0, indicating that there are no cracking reactions happened. When temperature is higher than 400°C, chemical heat sink is negative until 650°C. Negative value means that cracking reactions release heat in this temperature range, and these reactions are probably that combine small molecules into big ones. This is the reason for heat transfer deterioration.
4. Conclusion
Heat transfer of RP-3 kerosene at supercritical pressure is experimentally studied in this paper. The main conclusions are as follows. It can be divided into common heat transfer, enhanced heat transfer and deteriorated heat transfer for RP-3 under supercritical pressure. Variations of properties and laminar flow are responsible for the common heat transfer. Flow regime transition (laminar to turbulent) is the main reason of enhanced heat transfer. Heat release reactions (combination of small molecules into big molecules) are attributed to the heat transfer deterioration.

5. References
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