EXPERIMENTAL INVESTIGATION ON THE HEAT TRANSFER AND HEAT SINK CHARACTERISTICS OF THE KEROSENE-WATER EMULSION IN A RECTANGULAR CHANNEL

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ABSTRACT

To investigate the heat transfer and heat sink characteristics of the kerosene-water emulsion in a rectangular channel, experiments were conducted at the pressure of 3.0MPa, the mass flow rate of 0.5-2.6g/s and the water content of 10-50 wt.%. Compared with the pure kerosene, obvious heat transfer deteriorations caused by the dryout of the water in the emulsion could be observed at the middle part of the channel. With the increase of the heat flux, the deterioration point moved towards to the inlet of the channel. The heat transfer performance of the channel with the catalyst sprayed inside was better than that of the raw channel, but the catalyst had little influence on the heat sink of the emulsion. Under the same outlet fuel temperature, better heat transfer performance could be achieved at higher mass flow rate. However the heat sink of the emulsion decreased with the increase of the mass flow rate. At low outlet temperature, the increase of the water content would lead to a higher heat sink. The heat sink differences between different water content decreased with the increase of temperature and vanished when the fuel temperature reached 700 ℃. The increase of the water content was detrimental to the heat transfer near the outlet.

NOMENCLATURE

A	[m^2]	Area
L	[m]	Length
h	[W/m^{2}K]	Heat transfer coefficient
H	[MJ/kg]	Heat sink
m	[g/s]	Mass flow rate
Pow	[W]	Heating power
q	[kW/m^2]	Heat flux
S	[m^2]	Area of the cross section
T	[℃]	Temperature
Special characters		
ϕ	[W/m^3]	Inner heat source
λ	[W/mK]	Thermal conductivity
δ	[m]	Thickness of the catalyst
Δ	[m]	Thickness of the channel wall
ε	[-]	Water content
Subscripts		
b		Bulk
c		Catalyst
eff		Effective
i		Inner
loss		Heat loss
o		Outer
r		Raw channel

INTRODUCTION

The active regenerative cooling technology[1] has been widely implemented in the thermal protection of the scramjet. In this technology, the endothermic hydrocarbon fuel flows through the minor channels in the wall of the engine, absorbing the aerodynamic heat and cracking into small molecules which significantly contribute to the combustion process.

The heat sink and heat transfer characteristics of the fuel are vital important to the design and safe operation of the thermal protection structure. Nowadays, much work has been carried out on these characteristics of the hydrocarbon fuel[2-6]. Jia[3] experimentally investigated the convection heat transfer of supercritical RP-3 in a vertical tube. Heat transfer deterioration was found in the upward flow. The influences of the buoyancy and the thermal acceleration on heat transfer were discussed by Wang[4], and a new heat transfer correlation considering the revision of the Prandtl number as well as the thermal conductivity was put forward.

As the speed of the aircraft increases to the hypersonic regime, the physical and chemical heat sink of the fuel can't meet the cooling requirement[7]. What's worse, coke deposition in the channel attribute to the thermal cracking of the fuel would impair the heat transfer and block the fuel channels of the aircraft. The kerosene-water emulsion has been viewed as the most promising surrogate fuel with higher heat sink and less coke deposition rate in recent years[8-11]. However, few studies have been performed on the heat sink and heat transfer characteristics of emulsified kerosene[12-14]. At the temperature of 684℃, 25% of the total heat sink was dedicated by the chemical heat sink of the catalytic reforming when the fuel was emulsified with 10 wt.% water[12]. The heat transfer properties of emulsified kerosene was only numerical investigated by Hou[14]. It was found that emulsified kerosene could bring down the wall temperature and restrain coke deposition compared with pure kerosene. The increase of water content would result in a better heat transfer performance, but the reduction of coke deposition was not sensitive to the water content. Experimental investigation on the heat transfer of emulsified kerosene hasn't been reported.

In this paper, a synthetic kerosene including cycloalkanes 61.11 wt.%, olefins 21.95 wt.%, paraffin 14.28 wt% and aromatics 2.66 wt.% was used as the base fuel. The critical point of the kerosene is at 2.16MPa and 395.8℃ according to the opalescence phenomenon. Experiments were conducted at different mass flow rate and different water content to study the heat transfer and heat sink of the kerosene-water emulsion.

EXPERIMENTAL FACILITIES AND METHODS

The schematic diagram of the experiment system is shown in Figure 1. The kerosene-water emulsion was prepared in a fuel tank, and the span 80 was used to emulsify the kerosene with the ratio of 0.2 wt.%. Due to the density different between kerosene and water, the mixture was easy to separate, so a circulating pump was applied to mix the kerosene and water. The emulsion in the fuel tank was driven by a piston pump which could accurately control the volume flow rate with the precision of 1mL/min. Then the emulsion flowed through a mass flow meter and the test section. The pressure drop of the test section was monitored by a differential pressure transducer. The outlet fuel temperature and the pressure of the test loop were measured by a sheathed thermocouple and a pressure transducer respectively. The high temperature fuel from the outlet of the test section flowed through a filter and was cooled down to the ambient temperature by a heat exchanger. The pressure of the test loop was kept at 3.0MPa by a back pressure valve. The reaction product from the test section was separated in a gas-liquid separator.

The test section was a rectangular channel manufactured by high temperature alloy GH3128 with the length of 130cm as presented in Figure 2. The heating length was 120cm and 12 K-type thermocouples were spot welded on the right side of the channel with the distance of 10cm. The external dimension of the channel was 4mm in width and 6mm in height. The flow section of a raw channel was a rectangular with the width of 2mm and the height of 3mm. The catalyst layer was plasma sprayed on the inner surface of the channel with the thickness of 0.3mm.

The heat sink of the emulsion could be achieved from the heating power and the heat loss of the channel.

$$H = \left(Pow - q_{\rm loss}A_{\rm o}\right)/m \tag{1}$$

The heat loss was a function of the outer wall temperature of the channel, calibrated by heating the channel without any fuel inside.

The inner wall temperature was calculated by solving the one-dimensional heat conduction equation of the flat plate. For the raw channel, the inner wall temperature is derived as:

$$T_{\rm i} = T_{\rm o} - \frac{1}{2}\frac{\phi}{\lambda}\Delta^2 + \frac{q_{\rm loss}}{\lambda}\Delta \tag{2}$$

The inner heat source is expressed as:

$$\phi = \frac{Pow}{\left(S_{\rm o} - S_{\rm i,\,r}\right)L} \tag{3}$$

The effective heat is defined as:

$$q_{\rm eff} = \left(Pow - q_{\rm loss}A_{\rm o}\right)/A_{\rm i,\,r} \tag{4}$$

The catalyst layer acted as thermal resistance between the fuel and the channel, so the inner wall temperature of the catalytic channel is indicated by eq.(5).

$$T_{\rm i} = T_{\rm o} - \frac{1}{2}\frac{\phi}{\lambda}\Delta^2 + \frac{q_{\rm loss}}{\lambda}\Delta - \frac{q_{\rm eff}\delta}{\lambda_{\rm c}} \tag{5}$$

The inner heat source of the catalytic channel has the same form as that of the raw channel. The inner surface of the catalytic channel is smaller than that of the raw channel, so the effective heat flux is calculated by eq.(6).

$$q_{\rm eff} = \left(Pow - q_{\rm loss}A_{\rm o}\right)/A_{\rm i,\,c} \tag{6}$$

The local fuel temperature is obtained by the relationship between the effective heat absorption and the heat sink of the fuel.

$$T_b = f^{-1}\left(H, \left(Pow - q_{\rm loss}A_{\rm o}\right)x/mL\right) \tag{7}$$

The local heat transfer coefficient is evaluated by eq.(8).

$$h = \frac{q_{eff}}{T_{\rm i} - T_{\rm b}} \tag{8}$$

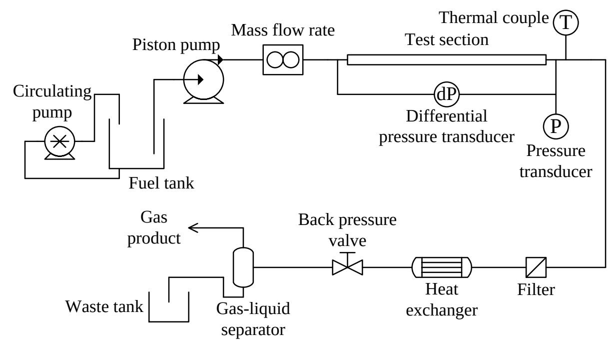

Figure 1 Schematic diagram of the test loop

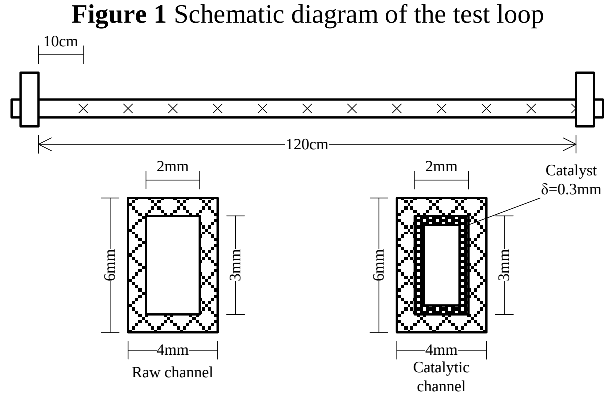

Figure 2 Schematic diagram of the test section

RESULTS AND DISCUSSION

The heat transfer characteristics of emulsified kerosene

The heat transfer characters of pure kerosene and emulsified kerosene at different outlet temperature are depicted in Figure 3 and Figure 4 respectively. At a certain outlet fuel temperature, the heat transfer coefficient of pure kerosene increased along the channel. Heat transfer deterioration didn't appear throughout the channel. When the outlet fuel temperature reached 640℃, the heat transfer performance was restrained at

70-120cm. It could be attributed to the coke deposition at high temperature, which functioned as thermal resistance between the channel and the fuel.

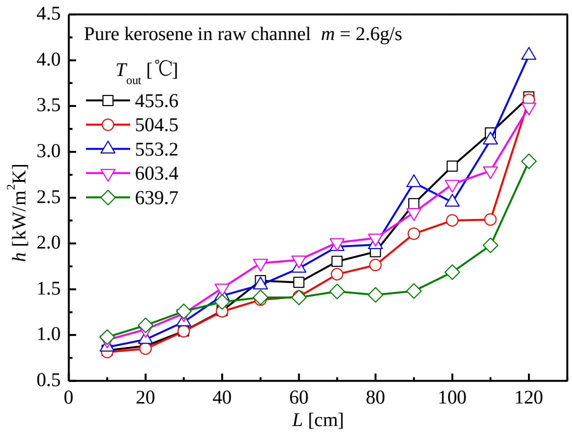

Figure 3 The heat transfer coefficient of pure kerosene at different outlet temperature

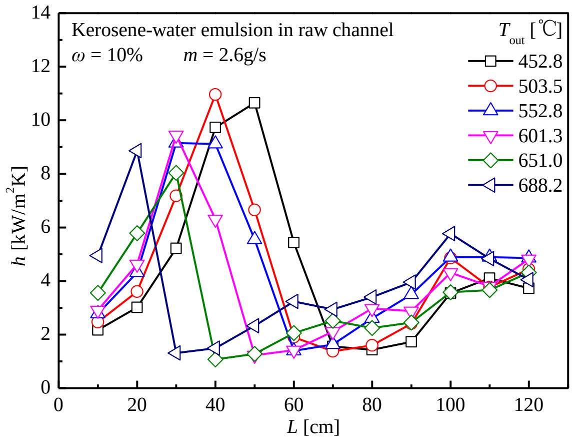

Figure 4 The heat transfer coefficient of kerosene-water emulsion at different outlet temperature

However, obvious heat transfer deterioration occurred at the middle section of the channel while the kerosene was emulsified with 10 wt.% water. This phenomenon wasn't reported in Hou's numerical research[14]. As the outlet fuel temperature increased, the deterioration point moved to the inlet direction of the channel. At the outlet temperature of 453℃ and 688℃, the inner wall and the fuel temperature distributions along the channel are plotted in Figure 5. When the bulk fuel temperature was slight higher than the saturation temperature of water at the pressure of 3.0MPa, a significant increase in the inner wall temperature could be noticed. It could be inferred that the heat transfer deterioration was induced by the dryout of the water in the emulsion. When the bulk fuel temperature was higher than the saturation temperature, the water transferred from liquid state to steam which would restrain the heat transfer. At the outlet temperature of 688℃, the increase of the inner wall temperature was as high as 400℃. Before the dryout point, significant heat was absorbed by the evaporation of the water. As a result, the inner wall temperature increased gently along the flow direction and the heat transfer coefficient reached a peak. After the dryout point, the velocity of the fuel increased as the density decreased, and the reforming reaction promoted the heat absorption. The heat transfer coefficient showed slightly rise along the channel.

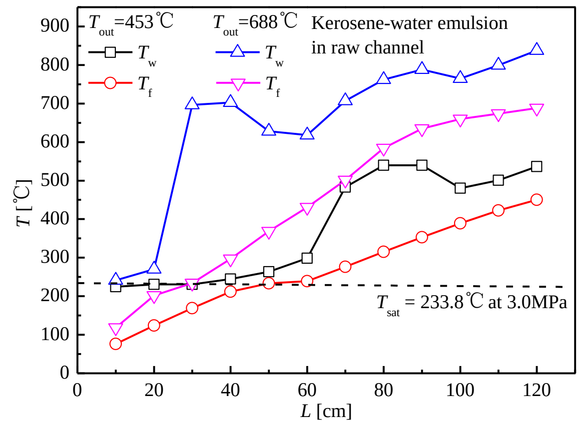

Figure 5 The wall and fuel temperature distribution of kerosene-water emulsion at different outlet temperature

Effect of the catalyst

In this study, a special catalyst was plasma sprayed on the inner surface of the channel to promote the reforming of kerosene with water. The heat sink of the emulsion with water content of 10 wt.% at different temperature in the raw channel and the catalyst channel are presented in Figure 6. The heat sink reached 3.65MJ/kg at the temperature of 752℃ in catalytic channel. It was found that the catalyst had little influence on the heat sink of the emulsion. The flow area of the raw channel and the catalytic channel was 6mm^2 and 3.36mm^2 respectively, so the residence time of the emulsion in the raw channel was 1.78 times longer than that in catalytic channel. On one side, the catalyst promoted the reforming of kerosene with water, but on the other side the residence time was short in the catalytic channel. Consequently, the heat sink of the emulsified kerosene in the raw channel was close to that in the catalytic channel.

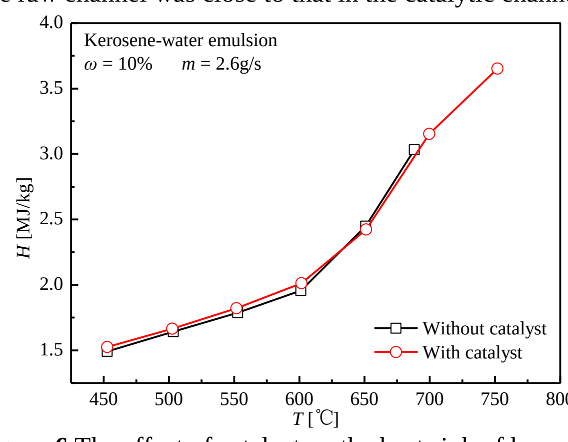

Figure 6 The effect of catalyst on the heat sink of kerosene-water emulsion

The influence of catalyst on the heat transfer performance of emulsified kerosene at the outlet temperature of 450℃ and 650℃ is presented in Figure 7. The heat transfer performance of the catalytic channel was obviously better than that of the raw channel. Although the catalyst layer acted as thermal resistance between the fuel and the channel, the velocity of the emulsified kerosene in the catalytic channel was 1.78 times of that in the raw channel. Additionally, the rugged surface formed by the catalytic could disturb the boundary layer of the emulsion and increase the turbulence intensity. As a result, heat transfer was enhanced in the catalyst channel. However, noticeable heat transfer deterioration caused by the dryout was also inevitable in the catalyst channel.

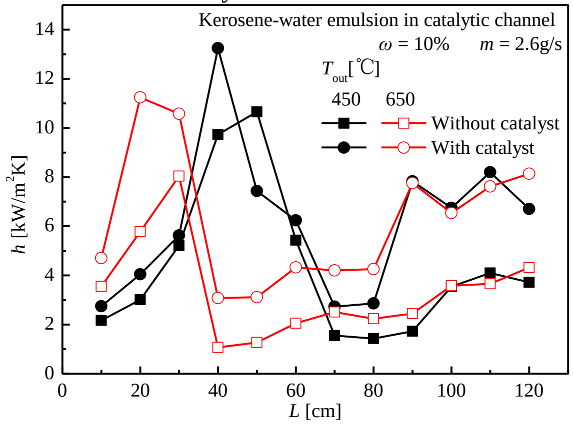

Figure 7 The effect of catalyst on the heat transfer character of kerosene-water emulsion

Effect of mass flow rate

The heat sink of the emulsion with water content of 50 wt.% at different mass flow rates is shown in Figure 8. When the outlet fuel temperature was less than 500℃, the heat sink differences between different mass flow rate could be ignored. Obvious distinguish of the heat sink could be observed when the outlet fuel temperature exceeded 500℃. It revealed that the thermal crack of the kerosene and the reforming of kerosene and water was negligible if the fuel temperature was below 500℃. The heat sink of the fuel only consisted of the physical heat sink of the kerosene and water at low temperature. When the outlet fuel temperature reached 550℃, the chemical heat sink would play an important role in the heat absorption. At lower mass flow rate, the residence time of the fuel in the channel was longer, which was beneficial to thermal cracking and catalytic reforming, so higher heat sink could be achieved at lower mass flow rate.

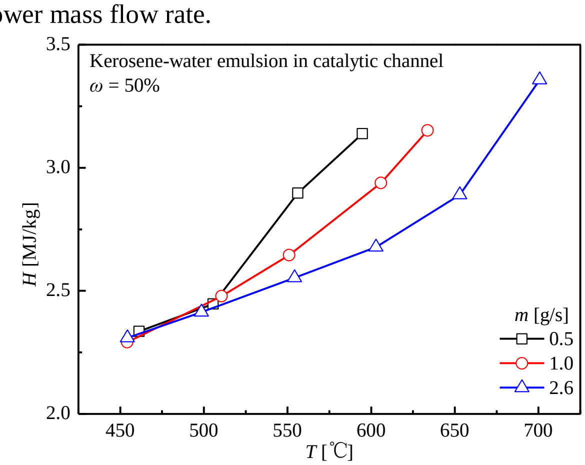

Figure 8 The effect of mass flow rate on the heat sink of kerosene-water emulsion

The heat transfer characters of the emulsified kerosene at different mass flow rate in catalytic channel are shown in Figure 9. The heat transfer coefficient increased with the mass flow rate especially at 80-120cm. The wall temperature was higher at lower mass flow rate, thus the outlet fuel temperature at low mass flow rate was restricted by the temperature endurance of the alloy. When the outlet temperature was 600℃, the heat transfer enhancement due to the evaporation of water only could be observed at the mass flow rate of 2.6g/s.

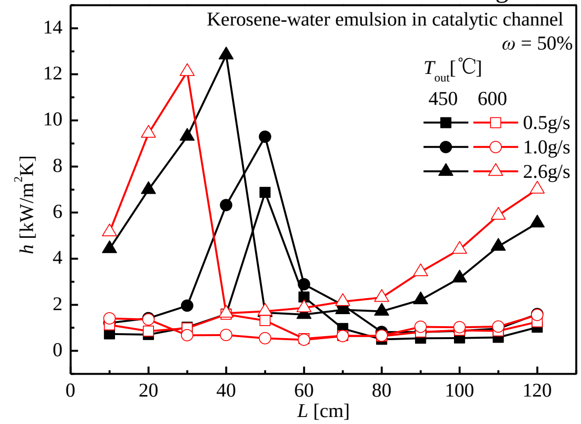

Figure 9 The effect of mass flow rate on the heat transfer character of kerosene-water emulsion

Effect of water content

In this study, heat sink and heat transfer characters of the emulsion with different water content in catalytic channel were investigated at the mass flow rate of 2.6g/s. The effect of water content on the heat sink of the emulsion is shown in Figure 10. As the sensible and latent heat of water was higher than those of kerosene, the heat sink of the emulsion increased with the water content, and the heat sink differences between different water content kept the same when the outlet fuel temperature was lower than 600℃. When the temperature was higher than 600℃, the thermal cracking of the kerosene would play an important role in the heat absorption. More kerosene would participate in thermal cracking at lower water content, so the heat sink differences began to decrease and finally vanished when the fuel temperature reached 700℃.

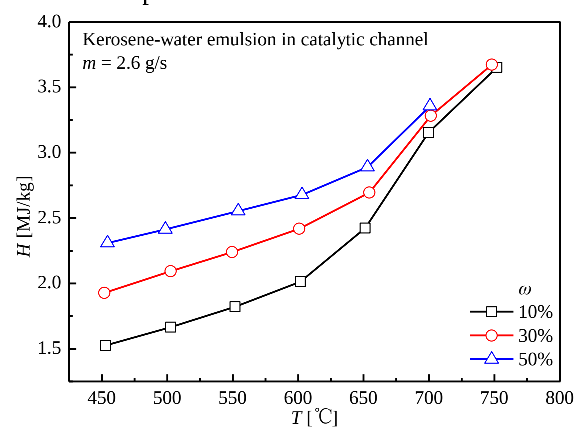

Figure 10 The effect of water content on the heat sink of kerosene-water emulsion

The heat transfer coefficients of the emulsion at different water content along the channel are shown in Figure 11. When the outlet fuel temperature was 450 ℃, the heat transfer coefficient increased with the water content at the 10-40cm region, as more heat would be absorbed by the evaporation of water at higher water content. However, the heat transfer performance of the emulsion at lower water content was better than that at higher water content after the heat transfer deterioration point. All the water in the emulsion evaporated to steam in this region, and the thermal conductivity as well as the heat capacity of steam was lower than those of kerosene. As a consequence, the heat transfer coefficient decreased with the increase of the water content at 50-120cm.

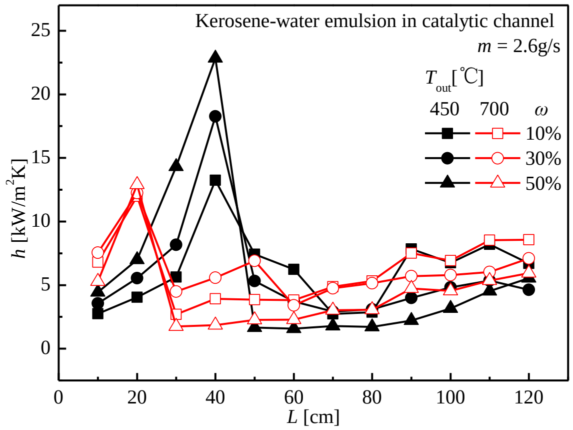

Figure 11 The effect of water content on the heat transfer character of kerosene-water emulsion

CONCLUSION

The heat sink and heat transfer peculiarities of emulsified kerosene in a rectangular channel were experimentally investigated at the pressure of 3.0MPa. The influences of the catalyst, the mass flow rate and the water content were discussed. The main conclusions are summarized as follows:

(1) The water in the emulsion could lead to heat transfer deterioration when the bulk fuel temperature was slightly higher than the saturation temperature at 3.0MPa.

(2) The catalyst had little influence on the heat sink of the kerosene but would enhance the heat transfer coefficient as the resident time was short and the velocity of the fuel was fast in the catalytic channel.

(3) The heat transfer performance of the emulsion was positively correlated with the mass flow rate. The thermal cracking and reforming of kerosene with water could be ignored when the outlet temperature was lower than 500℃. When the outlet temperature reached 550℃, the heat sink decreased with the increase of the mass flow rate.

(4) Higher heat sink could be achieved at higher water content, however the heat sink discrepancies vanished when the outlet temperature reached 700℃, as the thermal cracking of kerosene was dramatic at low water content. After the heat transfer deterioration point, the heat transfer performance was restrained at high water content.

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