Experiments on Heat Transfer of Supercritical Pressure Kerosene in Mini Tube under Ultra-High Heat Fluxes

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Abstract: Heat transfer of supercritical-pressure kerosene is crucial for regenerative cooling systems in rocket engines. In this study, experiments were devoted to measure the heat transfer of supercritical-pressure kerosene under ultra-high heat fluxes. The kerosene flowed horizontally in a mini circular tube with a 1.0 mm inner diameter and was heated uniformly under pressures of 10–25 MPa, mass fluxes of 8600–51,600 kg/m²/s, and a maximum heat flux of up to 33.6 MW/m². The effects of the operating parameters on the heat transfer of supercritical-pressure kerosene were discussed. It was observed that the heat transfer coefficient of kerosene increases at a higher mass flux and inlet bulk temperature, but is little affected by pressure. The heat transfer of supercritical-pressure kerosene is classified into two regions: normal heat transfer and enhanced heat transfer. When the wall temperature exceeds a certain value, heat transfer is enhanced, which could be attributed to pseudo boiling. This phenomenon is more likely to occur under higher heat flux and lower mass flux conditions. In addition, the experimental data were compared with several existing heat transfer correlations, in which one of these correlations can relatively well predict the heat transfer of supercritical-pressure kerosene. The results drawn from this study could be beneficial to the regenerative cooling technology for rocket engines.

Keywords: heat transfer; supercritical kerosene; supercritical fluids; regenerative cooling

1. Introduction

Supercritical fluids have been extensively studied since the 1960s, because of the urgent demand from a number of new technologies, such as supercritical water-cooled reactors, supercritical CO₂ Brayton cycles, and supercritical organic Rankine cycles [1–3]. In particular, thermal management technology is urgently required for advanced aerospace vehicles, including supersonic combustion ramjet (scramjet) and rocket engines. These vehicles are designed to sustain high heat fluxes, and require a regenerative cooling system to dissipate the huge heat load [4–6]. In regenerative cooling systems, supercritical hydrocarbon fuel is employed as a coolant, prior to use as a propellant. The low-temperature fuel flows in mini cooling channels, removing a large amount of heat from the combustion chamber. After that, the outflow high-temperature fuel is injected into the combustor as a propellant. As the pressure in the combustion chamber is higher than the fuel’s critical pressure, the heat transfer of hydrocarbon fuel in regenerative cooling channels is conducted under supercritical pressures [7–9].

Kerosene, a kind of hydrocarbon fuel, is often used for liquid rocket engine cooling [10,11]. The working pressure of kerosene in the regenerative cooling system of a rocket engine is typically 20–25 MPa (far higher than its critical pressure, which is approximately 2 MPa), and its velocity can reach 40–60 m/s in order to remove heat flux with a 10-MW/m² level. To sum it up, the heat transfer of
kerosene for rocket engine cooling is under ultra-high heat flux, high pressure, high mass flux, and in mini channel.

The heat transfer of supercritical-pressure kerosene for rocket engine cooling is a challenging issue due to its complex thermo-physical properties, multi-chemical composition and high operating parameters. At supercritical pressures, there is a so-called pseudo-critical temperature, at which there are strong nonlinear distributions in the thermo-physical properties with temperature for supercritical fluids, including supercritical kerosene. Due to the above-mentioned factors, the heat transfer of supercritical kerosene is notably distinguished from that of conventional fluids [12,13].

A number of investigations have been devoted to the supercritical heat transfer for various fluids [14–17]. However, while most of these studies were aimed at supercritical water and CO2 [18–21], few studies have been devoted to the heat transfer of supercritical kerosene. Edwards [6] and Powell et al. [22] carried out a series of experiments on the heat transfer and thermal stability of aviation kerosene for hypersonic propulsion. Yang et al. [23] observed the heat transfer enhancement phenomenon of supercritical-pressure aviation kerosene. They considered the reasons as being thermo-physical property variation, thermo-acoustic oscillation, and endothermic chemical reaction. Pan et al. [24] analyzed the correlated characteristics between heat transfer with thermo-acoustic instability from their experiments for supercritical-pressure aviation kerosene. Huang et al. [25] separated the heat transfer of aviation kerosene RP-3 into three regions: normal, improved, and deteriorated heat transfer. Li et al. [26] observed the heat transfer enhancement of aviation kerosene RP-3 when the wall temperature was close to the pseudo-critical value. While in similar experiments [27,28], heat transfer deterioration was observed by several researchers. Except for compound hydrocarbon fuel, the heat transfer of pure hydrocarbon fuels at supercritical pressures was also investigated. Urbano and Nasuti [29] numerically discussed supercritical heat transfer for methane, ethane and propane. They observed heat transfer deterioration for the three kinds of light hydrocarbons at high q/G ratio. Wang et al. [30] numerically studied the heat transfer of supercritical n-decane, and pointed out two kinds of heat transfer deterioration while the wall and bulk fluid temperatures were close to the pseudo-critical value.

To sum up, the existing studies on supercritical heat transfer have mainly concentrated on pure inorganic substances, in which supercritical water and CO2 are extensively used. The heat transfer of supercritical-pressure kerosene, composed of multi-component organic compounds, is still insufficiently studied. In this study, heat-transfer experiments are conducted for supercritical-pressure kerosene in a mini tube under high operating parameters. The channel size and operating parameters are close to those for the regenerative cooling of rocket engines. The heat transfer coefficients of kerosene are measured under ultra-high heat flux (0–33.6 MW/m²), high pressure (10–25 MPa), and high mass flux (8600–51,600 kg/m² s), and the influence factors are discussed in detail.

The objective of this study is to obtain the heat transfer characteristics of supercritical-pressure kerosene under high operating parameters. The results of this study could be beneficial for designing regenerative cooling systems for rocket engines. The structure of the present study is arranged as follows: the descriptions of the experiments are shown in Section 2; the thermo-physical properties of tested kerosene are given in Section 3.1; heat transfer data are presented in Section 3.2; the parameter effects of pressure, mass flux, and inlet bulk temperature on heat transfer are discussed in Section 3.3; and heat transfer correlations are compared with the data in Section 3.4.

2. Experimental Descriptions

2.1. Test Facility and Test Section

Figure 1 presents the diagrammatic drawing of the heat transfer test facility for supercritical kerosene. A plunger pump was employed to drive kerosene from a fuel tank. The maximum operating pressure for the pump was 40 MPa, which can cover the operating pressure range for this test. As the volume flow rate of pumped kerosene was constant, a bypass loop was used to guide the
redundant fluid flowing back to the fuel tank, while the desired flow entered into the main loop. A preheater was used to heat up the kerosene to the desired temperature by a transformer (maximum AC power capacity was 150 kW). A filter was installed at the downstream of the test tube to block potential coke particles produced from kerosene under high temperatures. The filter had a filtering accuracy of 40 μm and can withstand a high temperature and high pressure. After the filter, the kerosene flowed through a condenser, where high-temperature kerosene was cooled down by water. At the downstream of the condenser, a back-pressure valve was used to regulate the system pressure. Finally, the tested kerosene with normal pressure and temperature flowed back to the fuel tank to complete a closed circulation.

![Diagrammatic drawing of the test facility.](image)

**Figure 1.** Diagrammatic drawing of the test facility.

Figure 2 presents the structural details of the test section. The test section was a circular tube ($d_i = 1$ mm and $d_o = 2$ mm), and the tube material was 1Cr18Ni9Ti stainless steel. The tube was installed in a horizontal position. Two copper electrodes were used to connect the tube with an electric power source. The maximum capacity and current for the power was 250 kW and 10,000 A. The length of the effectively heated tube was 100 mm. The kerosene flowed horizontally through the tube, and the local wall temperatures were measured along the flow direction. In order to strengthen the stability of the wall temperature measurement, as well as for heat preservation, the tube was covered by heat insulation cotton.

![Structural details of the test section.](image)

**Figure 2.** Structural details of the test section.

2.2. Parameter Measurement
The measured parameters mainly contained pressure $p$, mass flow $m$, bulk fluid temperatures $T_b$, outer wall temperatures $T_{w,o}$ and heating power $P$ for the test section. The operating ranges for these parameters were as follows: $p = 10–25$ MPa, $m = 6–42$ g/s, $T_b = 20–386$ °C, $T_{w,o} = 20–843$ °C and $P = 0–12$ kW.

As presented in Figure 2, the pressure $p$ was measured at the entrance and exit of the test tube using pressure transmitters (Rosemount 3051 type). The accuracies of the pressure transmitters were ±0.075% and the measuring ranges were set as 0–30 MPa. The mass flow of the kerosene was obtained using a mass flow meter (Siemens), which had an accuracy of ±0.05% and a maximum range of 0.1 kg/s. The inlet and outlet fluid temperatures, $T_b$, were obtained using K-type sheathed thermocouples. There were ten temperature measurement sections with a 10 mm uniform space along the axial tube. On each section, one K-type thermocouple was spot-welded on the outer wall surface to detect the outer wall temperature $T_{w,o}$. The heating power $P$ imposed on the test tube was equal to heating current $I$ times heating voltage $U$ through the tube, which were obtained from transducers for current and voltage, respectively. All of the measurement parameters were recorded synchronously using a data acquisition and processing program (IMP 3595, manufactured by the Solartron, UK).

2.3. Experimental Procedure

First, it is necessary to determine the thermal efficiency $\eta$ in order to calculate the heat flux imposed on the test tube. In this experiment, thermal efficiency $\eta$ is determined from a heat loss perspective. The tube was heated at various heat fluxes without fluid flowing through it. According to heat balance, the imposed power was equal to the heat loss at steady conditions. The heat loss $Q_{loss}$ is mainly determined by outer wall temperature, and thus the function $Q_{loss} = f(\Delta T)$ can be correlated, in which the temperature difference $\Delta T$ is equal to the average outer wall temperature minus the ambient temperature. Therefore, in the heat-transfer experiments of kerosene, the thermal efficiency can be calculated as:

$$\eta = (1 - \frac{Q_{loss}}{UI}) \times 100\%$$ (1)

Second, the experiment loop was validated using a single-phase heat transfer of deionized water. The validation range was as follows: $p = 12$ MPa, $G = 5000–40,000$ kg/m²s, $q = 1.68–16.8$ kW/m² and $Re = 1.7 \times 10^4–4.6 \times 10^5$. The data were validated using the modified Dittus–Boelter correlation Equation 2. As shown in Figure 3, the experimental data fit well with the classic correlation, and the majority of the data were predicted within the error lines of ±15%. According to the results from validation experiments, it was verified that this experimental facility was reliable.

$$Nu_b=0.023Re_b^{0.8}Pr_b^{0.4} \left( \frac{\mu_b}{\mu_w} \right)^{0.11}$$ (2)
Last, the heat transfer experiments of kerosene were performed at the desired conditions. Under each working condition, the inlet parameters ($p$, $G$ and $T_{b,i}$) were fixed, while the heat flux varied from a low level to a high level. After each adjustment in heat flux, data were recorded for approximately 100 seconds after all parameters had achieved a steady state.

2.4. Data Reduction

The mass flux $G$ is obtained as:

$$ G = \frac{4m}{\pi d_i^2} $$  \hspace{1cm} (3)

where $m$ is the mass flow of kerosene (kg/s), and $d_i$ is the inner diameter (m). The heat flux $q$ is calculated as:

$$ q = \frac{U \cdot I \cdot \eta}{\pi d_i L} $$  \hspace{1cm} (4)

where $\eta$ is the thermal efficiency, and $L$ is the heated length of the test tube. The heat transfer coefficient $h$ is obtained from:

$$ h = \frac{q}{T_{w,i} - T_b} $$  \hspace{1cm} (5)

where $T_b$ is the bulk fluid temperature, and $T_{w,i}$ is the inner wall temperature. It should be pointed out that it is inconvenient to directly measure the inner wall temperature; instead, a heat conduction model is developed to calculate it from outer wall temperature (see [31] for detailed descriptions). Table 1 presents the uncertainties for the main parameters, which are calculated according to Equation 6 [32].

$$ \frac{\delta Y}{Y} = \frac{1}{Y} \left[ \sum_{i=1}^{N} \left( \frac{\partial Y}{\partial X_i} \right)^2 \right]^{1/2} $$  \hspace{1cm} (6)

where $Y$ is the dependent variable (indirectly measured), and $X_i$ is the independent variable (directly measured).

| Parameters | Uncertainties |
|------------|---------------|
|             |               |

Table 1. Parameter uncertainties.
| Parameter                        | ± Percentage | Unit            |
|---------------------------------|--------------|-----------------|
| Bulk temperature $T_b$          | ±0.5%        | °C              |
| Heat flux $q$                   | ±4.9%        | MW/m²          |
| Heat transfer coefficient $h$   | ±7.0%        | kW/m² K        |
| Mass flux $G$                   | ±0.9%        | kg/m² s        |
| Outer wall temperature $T_{w,o}$| ±0.4%        | °C              |
| Pressure $p$                    | ±0.2%        | MPa            |

3. Results and Discussion

3.1. Thermo-Physical Properties of Kerosene at Supercritical Pressure

The tested kerosene is a multi-component hydrocarbon mixture mainly consisting of alkanes and aromatics. Its critical pressure is 2.2 MPa and its critical temperature is 400 °C approximately. For supercritical fluids, the heat transfer performance is closely related with their thermophysical properties. Due to the complex chemical composition, the thermophysical properties of the supercritical-pressure kerosene are distinguished from conventional fluids, which exert an influence on heat transfer directly.

Figure 4 shows the thermophysical properties of kerosene under pressure of 15 MPa. As it demonstrated, the following particularities in thermophysical properties of kerosene can be observed. First, there is no obvious peak in specific heat at the pseudo-critical point, which is considerably different from that of near-supercritical fluids. Since pressure is far away from the critical value, the specific heat of the supercritical kerosene varies insignificantly with temperature. Second, there is a remarkable peak of thermal conductivity $\lambda$ when temperature exceeds the pseudo-critical point. Last, the viscosity of kerosene decreased rapidly with increasing temperature at low temperatures, while the variation of viscosity with temperature was mild in the high temperature range ($> 400$ °C).

![Figure 4. Thermophysical properties of the tested kerosene. (Relative value to the data at 20 °C).](image)

(Solid line: density; Dash line: viscosity; Short dot line: Prandtl number; Dash dot line: thermal conductivity; Dash dot dot line: specific heat)

3.2. Heat Transfer Characteristics of the Tested Supercritical-Pressure Kerosene

Figure 5 describes the typical heat transfer features of supercritical-pressure kerosene at the operating parameters of $p = 10$ MPa, $G = 8600$ kg/m² s, $T_{b,i} = 50$ °C, and maximum $q = 12.5$ MW/m². The data in Figure 5 a,b are averaged values for all measuring sections, while the data in Figure 5 c,d are local values at each measuring section.
Figure 5. Heat transfer characteristics of the supercritical-pressure kerosene ($p = 10$ MPa). (a) Average parameters; (b) $h$ vs. $T_{w,i}$; (c) local wall temperature; (d) local heat transfer coefficient.

Figure 5a shows the variations of $T_b$, $T_{w,i}$, and $h$, with $q$ increased from 2.5 to 12.5 MW/m². For better understanding, the relationship between $h$ and $T_{w,i}$ is displayed in Figure 5b. From the variation tendency of $T_{w,i}$ and $h$, we divided the heat transfer of the supercritical-pressure kerosene into two regions: the normal heat transfer region and enhanced heat transfer region.

In the former heat transfer region, the $T_b$ and $T_{w,i}$ can be regarded as being in a linear growth with increasing $q$, and thus a linear growth in $h$. In this region, the heat transfer regularities of the supercritical-pressure kerosene are similar to those of single-phase fluids. In the latter region, the wall temperature is typically high (exceeding 650 °C, approximately), and heat transfer enhancement is observed from the decelerating trend in wall temperature, and accelerating growth in heat transfer coefficient. The reason for heat transfer enhancement could be attributed to the occurrence of pseudo boiling. The concept of “pseudo boiling”, which is analogous to the boiling phenomenon for subcritical fluids, is proposed to elaborate heat transfer mechanisms for the supercritical fluids [33,34]. When pseudo boiling occurs, a vapor-like fluid is generated continuously on the heating wall and enters into bulk flow, while the liquid-like fluid flows towards the heating wall in succession. With this approach, the energy transportation between the wall and bulk is promoted effectively, and thus heat transfer is enhanced.

Figure 5c presents the local wall temperatures along the axial tube. With the augmentation of heat flux, the local wall temperature increases monotonously. Under lower heat fluxes, heat transfer situates in the normal region, and the wall temperature slightly decreases along the tube. Under higher heat fluxes, the wall temperature tends to be even along the tube. In addition, the temperature difference is remarkable between the wall and bulk fluid under high heat fluxes. Taking
\( q = 12.5 \text{ MW/m}^2 \) as an example, the average wall temperature is 721 °C, while the outlet bulk temperature and average bulk temperature are 337 and 191 °C respectively. Due to the large temperature difference, there are significant variations of thermophysical properties in a radical direction, affecting the heat transfer of kerosene.

Figure 5d shows the local heat transfer curves at three measuring sections (Section 2, 5, and 8). It finds that when the inner wall temperatures exceed approximately 650 °C, heat transfer is enhanced almost at the same time. This suggests that pseudo boiling would occur simultaneously in the test tube, rather than occurring first at the tube outlet.

3.3. Parameter Effects on Heat Transfer of Supercritical-Pressure Kerosene

The influence of pressure on the heat transfer of kerosene is shown in Figure 6. As it shows, the heat transfer curves basically coincide with each other from 10 to 25 MPa, indicating a limited effect of pressure on heat transfer. This could be attributed to the fact that the thermophysical properties are little affected by pressure because fluid is far from its critical point. When the wall temperatures are high enough, heat transfer enhancement occurs under all pressures, which is considered to be caused by pseudo boiling.

![Figure 6. Effect of pressure on heat transfer. (a) Wall temperature; (b) Heat transfer coefficient.](image)

(Square symbol: \( p = 10 \text{ MPa} \); circular symbol: \( p = 15 \text{ MPa} \); Up triangle symbol: \( p = 25 \text{ MPa} \))

Figure 7 presents the effect of mass flux on the heat transfer of supercritical-pressure kerosene. In order to sustain ultra-high heat flux with a 10-MW/m² level, it is necessary to adopt a high mass flux of coolants, otherwise the wall temperature may be overheated. Higher heat flux can be sustained by supercritical kerosene at a higher mass flux. Taking \( G = 34,400 \text{ kg/m}^2 \text{s} \) as an example, when heat flux is increased to 26.7 MW/m², the inner wall temperature is lower than 650 °C, and it is still in the normal heat transfer region.
Figure 7. Effect of mass flux on heat transfer. (a) Wall temperature; (b) heat transfer coefficient. (Square symbol: $G = 8600$ kg/m$^2$ s; circular symbol: $G = 17,200$ kg/m$^2$ s; Up triangle symbol: $G = 34,400$ kg/m$^2$ s)

Figure 8 a and b display the effect of inlet fluid temperature on the heat transfer of supercritical-pressure kerosene. It is presented that the heat transfer performs better at higher inlet fluid temperatures. In normal heat transfer regions, the dominant mode of heat transfer is forced convection. A higher bulk temperature indicates a lower fluid viscosity and a larger Re number, which is beneficial to heat transfer. As shown in Figure 8b, when the inner wall temperature reaches about 650 °C with $T_{b,i} = 50$ °C, heat transfer is enhanced obviously, indicating a notable effect of pseudo boiling. However, heat transfer enhancement is not apparent at the same wall temperature for $T_{b,i} = 100, 200$ °C. This suggests that a higher inlet bulk temperature may postpone the occurrence of pseudo boiling.

Figure 8. Effect of inlet fluid temperature. (a) Wall temperature; (b) heat transfer coefficient. (Square symbol: $T_{b,i} = 50$ °C; circular symbol: $T_{b,i} = 100$ °C; Up triangle symbol: $T_{b,i} = 200$ °C)

3.4. Comparisons of Experimental Data with Existing Heat Transfer Correlations

In this study, a total of 204 experimental data points for the heat transfer of supercritical-pressure kerosene are compared with several heat transfer correlations, namely, the correlations of Dittus–Boelter [35], Hess et al. [36], Hu et al. [37], and Kang–Chang [38].
The Hess et al. correlation [36] is proposed for the supercritical heat transfer of hydrogen. The correlation is based on the Dittus–Boelter correlation [35], and a correction term of density ratio is added to represent the drastic variations in thermophysical properties.

\[ \text{Nu}_b = 0.0208 \text{Re}_b^{0.8} \text{Pr}_b^{0.14} (1 + 0.01457 \rho_s / \rho_a) \] (7)

Hu et al. [37] proposed two heat transfer correlations based on their experiments for supercritical-pressure kerosene flowing in a mini circular tube \((d_i = 1.7 \text{ mm})\). Equation 8 is applied for \(T_w < T_{pc}\), while Equation 9 is developed for \(T_w > T_{pc}\), in which \(\text{Nu}_0\) is calculated from Equation 8, with the same bulk temperature and heat flux, and \(T_{pc}\) is the pseudo-critical temperature.

\[ \text{Nu}_b = 0.008 \text{Re}_b^{0.873} \text{Pr}_b^{0.451} \] (8)

\[ \frac{\text{Nu}_b}{\text{Nu}_0} = 1 + 1.67(T_{w0} - T_{pc}) / T_{pc} \] (9)

Kang and Chang [38] measured the heat transfer coefficient of supercritical R134a \((p_{cr} = 4.01 \text{ MPa})\) flowing in an upward vertical tube. They correlated the 7022 data points within the range of \(p = 4.1–4.5 \text{ MPa}, G = 600–2000 \text{ kg/m}^2\text{s}\), and developed the following equation, in which the variations in heat capacity and density are taken into account.

\[ \text{Nu}_b = 0.0244 \text{Re}_b^{0.702} \text{Pr}_b^{0.552} \left( \frac{c_p}{c_{p,b}} \right)^{0.552} \left( \frac{\rho_c}{\rho_b} \right)^{0.0293} \] (10)

Figure 9 compares the experimental \(\text{Nu}\) with the four empirical heat transfer correlations. As it shows, the correlations of Dittus–Boelter, Hess et al., and Kang–Chang overestimate the data, and the root-mean-square errors (see Equation 11) are 21.32%, 14.31%, and 36.08%, respectively. The Hu et al. correlation captures the majority of data within the error lines of ±25%, and its root-mean-square error is 12.24%. The enhanced heat transfer caused by pseudo boiling is taken into account in the Hu et al. correlation. Therefore, it can be used to predict the heat transfer of supercritical-pressure kerosene.

\[
\text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} \left( \frac{\text{Nu}_\text{cal} - \text{Nu}_\text{exp}}{\text{Nu}_\text{exp}} \right)^2} \times 100% 
\] (11)

where \(n\) is the total number of experimental data points.
4. Conclusions

This study discusses the heat transfer of supercritical-pressure kerosene under high operating parameters with the background of regenerative cooling for rocket engines. The heat transfer coefficient of supercritical-pressure kerosene has been experimentally measured. The results are beneficial for understanding the heat transfer mechanism of supercritical-pressure kerosene, and designing regenerative cooling systems for rocket engines. The main conclusions are as follows:

1. The effects of the main parameters (including pressure, mass flux, and inlet bulk temperature) on the heat transfer of supercritical-pressure kerosene have been obtained. The heat transfer of kerosene performs better at higher mass flux and inlet bulk temperature, but is little affected by pressure.

2. The heat transfer of supercritical-pressure kerosene is divided into a normal heat transfer region and an enhanced heat transfer region. Heat transfer enhancement occurs when the wall temperature exceeds a certain value, which is considered to be attributed to pseudo boiling. In addition, pseudo boiling plays a more notable role under conditions of high heat flux and low mass flux.

3. The heat transfer data of supercritical-pressure kerosene are compared with several empirical correlations. Among these correlations, the Hu et al. correlation can predict the experimental data relatively well.

For future studies, the mechanism of pseudo boiling needs to be further explored. In addition, it is necessary to obtain more heat transfer data for supercritical-pressure kerosene in order to establish a heat transfer correlation with higher accuracy.

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Nomenclature

$c_p$ specific heat (J/kg K)
$d_i$ inner diameter (m)
$G$ mass flux (kg/m² s)
$h$ heat transfer coefficient (W/m² K)
$I$ current (A)
$L$ length (m)
$m$ mass flow (kg/s)
$p$ pressure (MPa)
$q$ heat flux (W/m²)
$T_b$ bulk temperature (°C)
$T_{w,i}$ inner wall temperature (°C)
$T_{w,o}$ outer wall temperature (°C)
$Nu_{cal}$ calculated Nusselt number (dimensionless)
$Nu_{exp}$ experimental Nusselt number (dimensionless)
$Pr$ Prandtl number (dimensionless)
$Re$ Reynolds number (dimensionless)
$Q_{loss}$ heat loss (W)
$U$ voltage (V)
$\eta$ thermal efficiency (%)\n$\lambda$ thermal conductivity (W/m K)
$\mu$ dynamic viscosity (kg/m s)
$\rho$ density (kg/m³)

References

1. Ehsan, M.M.; Guan, Z.; Klimenko, A.Y. A comprehensive review on heat transfer and pressure drop characteristics and correlations with supercritical CO2 under heating and cooling applications. Renew. Sustain. Energy Rev. 2018, 92, 658–675, doi:10.1016/j.rser.2018.04.106.
2. Koç, Y.; Yağlı, H.; Koç, A. Exergy analysis and performance improvement of a subcritical/supercritical Organic Rankine Cycle (ORC) for exhaust gas waste heat recovery in a biogas fuelled Combined Heat and Power (CHP) engine through the use of regeneration. Energies 2019, 12, 575.
3. Lazova, M.; Huisseune, H.; Kaya, A.; Lecompte, S.; Kosmadakis, G.; De Paepe, M. Performance evaluation of a helical coil heat exchanger working under supercritical conditions in a solar Organic Rankine Cycle installation. Energies 2016, 9, 432.
4. Zhu, Y.; Peng, W.; Xu, R.; Jiang, P. Review on active thermal protection and its heat transfer for airbreathing hypersonic vehicles. Chin. J. Aeronaut. 2018, 31, 1929–1935, doi:10.1016/j.cja.2018.06.011.
5. Yan, J.; Liu, Z.; Bi, Q.; Guo, Y.; Yang, Z. Heat transfer of hydrocarbon fuel under steady states and pressure-transient states. J. Propuls. Power 2016, 32, 38–45, doi:10.2514/1.b35694.
6. Edwards, T. Liquid fuels and propellants for aerospace propulsion: 1903–2003. J. Propuls. Power 2003, 19, 1089–1107, doi:10.2514/2.6946.
7. Guo, Y.; Bi, Q.; Liu, Z.; Yang, Z.; Jiang, L. Experimental investigation on thermal-hydraulic characteristics of endothermic hydrocarbon fuel in 1mm and 2mm diameter mini-channels. Appl. Therm. Eng. 2017, 122, 420–428, doi:10.1016/j.applthermaleng.2017.05.038.
8. Wen, J.; Huang, H.; Fu, Y.; Xu, G.; Zhu, K. Heat transfer performance of aviation kerosene RP-3 flowing in a vertical helical tube at supercritical pressure. Appl. Therm. Eng. 2017, 121, 853–862, doi:10.1016/j.applthermaleng.2017.04.055.
9. Sun, X.; Xu, K.; Meng, H.; Zheng, Y. Buoyancy effects on supercritical-pressure conjugate heat transfer of aviation kerosene in horizontal tubes. J. Supercrit. Fluids 2018, 139, 105–113, doi:10.1016/j.supflu.2018.05.016.
10. Zhao, W.; Song, Z.; Li, H.; Gu, H.; Tuo, X.; Zheng, Y.; Wang, H. Research on heat transfer characteristics of kerosene at supercritical pressure in circular tubes. *Exp. Therm. Fluid Sci.* 2018, 96, 507–515, doi:10.1016/j.expthermflusci.2018.03.030.

11. Wang, H.; Luo, Y.; Gu, H.; Li, H.; Chen, T.; Chen, J.; Wu, H. Experimental investigation on heat transfer and pressure drop of kerosene at supercritical pressure in square and circular tube with artificial roughness. *Exp. Therm. Fluid Sci.* 2012, 42, 16–24, doi:10.1016/j.expthermflusci.2012.03.009.

12. Huang, D.; Wu, Z.; Sunden, B.; Li, W. A brief review on convection heat transfer of fluids at supercritical pressures in tubes and the recent progress. *Appl. Energy* 2016, 162, 494–505, doi:10.1016/j.apenergy.2015.10.080.

13. Yan, J.; Liu, S.; Guo, P.; Bai, C. Experimental investigation on convection heat transfer of supercritical hydrocarbon fuel in a long mini tube. *Exp. Therm. Fluid Sci.* 2020, 110100, doi:10.1016/j.expthermflusci.2020.110100.

14. Zhu, X.; Du, X.; Li, Q.; Qiu, Q. Study on the effects of system parameters on entropy generation behavior of supercritical water in a hexagon rod bundle. *Int. J. Heat Mass Transf.* 2018, 117, 669–681. doi: 10.1016/j.ijheatmasstransfer.2017.10.056.

15. Yang, Z.; Shan, Y. Experimental study on the onset of flow instability in small horizontal tubes at supercritical pressures. *Appl. Therm. Eng.* 2018, 135, 504–511. doi: 10.1016/j.applthermaleng.2018.02.092.

16. Li, D.X.; Zhang, S.S.; Wang, G.H. Selection of organic Rankine cycle working fluids in the low-temperature waste heat utilization. *J. Hydrodyn.* 2015, 27, 458–464. doi: 10.1016/s1001-6058(15)60504-2.

17. Suleman, M.; Ramzan, M.; Ahmad, S.; Lu, D.C.; Muhammad, T.; Chung, J.D. A numerical simulation of silver-water nanofluid flow with impacts of newtonian heating and homogeneous-heterogeneous reactions past a nonlinear stretched cylinder. *Symmetry* 2019, 11, 13. doi:10.3390/sym11020295.

18. Wang, H.; Leung, L.K.H.; Wang, W.; Bi, Q. A review on recent heat transfer studies to supercritical pressure water in channels. *Appl. Therm. Eng.* 2018, 142, 573–596. doi: 10.1016/j.applthermaleng.2018.07.007.

19. Du, X.; Lv, Z.; Yu, X.; Cao, M.; Zhou, J.; Ren, Y.; Qiu, Q.; Zhu, X. Heat transfer of supercritical CO2 in vertical round tube: A considerate turbulent Prandtl number modification. *Energy* 2020, 192, 116612, doi:10.1016/j.energy.2019.116612.

20. Cabeza, L.F.; de Gracia, A.; Fernández, A.I.; Farid, M.M. Supercritical CO2 as heat transfer fluid: A review. *Appl. Therm. Eng.* 2017, 125, 799–810. doi:10.1016/j.applthermaleng.2017.07.049.

21. Rahman, M.M.; Dongxu, J.; Beni, M.S.; Hei, H.C.; He, W.; Zhao, J. Supercritical water heat transfer for nuclear reactor applications: A review. *Ann. Nucl. Energy* 2016, 97, 53–65, doi:10.1016/j.anucene.2016.06.022.

22. Powell, O.A.; Edwards, J.T.; Norris, R.B.; Numbers, K.E.; Pearce, J.A. Development of hydrocarbon-fueled scramjet engines: The hypersonic technology (hyttech) program. *J. Propuls. Power* 2001, 17, 1170–1176, doi:10.2514/2.5891.

23. Yang, Z.; Bi, Q.; Liu, Z.; Guo, Y.; Yan, J. Heat transfer to supercritical pressure hydrocarbons flowing in a horizontal short tube. *Exp. Therm. Fluid Sci.* 2015, 61, 144–152, doi:10.1016/j.expthermflusci.2014.10.024.

24. Pan, H.; Bi, Q.; Liu, Z.; Feng, S.; Feng, F. Experimental investigation on thermo-acoustic instability and heat transfer of supercritical endothermic hydrocarbon fuel in a mini tube. *Exp. Therm. Fluid Sci.* 2018, 97, 109–118, doi:10.1016/j.expthermflusci.2018.03.017.

25. Huang, D.; Ruan, B.; Wu, X.; Zhang, W.; Xu, G.; Tao, Z.; Jiang, P.; Ma, L.; Li, W. Experimental study on heat transfer of aviation kerosene in a vertical upward tube at supercritical pressures. *Chem. J. Chem. Eng.* 2015, 23, 425–434, doi:10.1016/j.cjche.2014.10.016.

26. Li, W.; Huang, D.; Xu, G.Q.; Tao, Z.; Wu, Z.; Zhu, H.T. Heat transfer to aviation kerosene flowing upward in smooth tubes at supercritical pressures. *Int. J. Heat Mass Transf.* 2015, 85, 1084–1094, doi:10.1016/j.ijheatmasstransfer.2015.01.079.

27. Huang, D.; Li, W. Heat transfer deterioration of aviation kerosene flowing in mini tubes at supercritical pressures. *Int. J. Heat Mass Transf.* 2017, 111, 266–278, doi:10.1016/j.ijheatmasstransfer.2017.03.117.

28. Fu, Y.; Huang, H.; Wen, J.; Xu, G.; Zhao, W. Experimental investigation on convective heat transfer of supercritical RP-3 in vertical miniature tubes with various diameters. *Int. J. Heat Mass Transf.* 2017, 112, 814–824, doi:10.1016/j.ijheatmasstransfer.2017.05.008.

29. Urbano, A.; Nasuti, F. Conditions for the occurrence of heat transfer deterioration in light hydrocarbons flows. *Int. J. Heat Mass Transf.* 2013, 65, 599–609, doi:10.1016/j.ijheatmasstransfer.2013.06.038.
30. Wang, Y.; Li, S.; Dong, M. Numerical study on heat transfer deterioration of supercritical n-decane in horizontal circular tubes. *Energies* 2014, 7, 1–20.
31. Thom, J.R.S.; Walker, W.M.; Fallon, T.A.; Reising, G.F.S. Boiling in subcooled water during flow up heated tubes or annuli. *Proc. Inst. Mech. Eng.* 1966, 180, 226–246.
32. Coleman, H.W.; Steele, W.G. Engineering application of experimental uncertainty analysis. *AIAA J.* 1995, 33, 1888–1896, doi:10.2514/3.12742.
33. Ackerman, J.W. Pseudoboiling heat transfer to supercritical pressure water in smooth and ribbed tubes. *J. Heat Transf. Trans. ASME* 1970, 92, 490–498.
34. Zhu, B.; Xu, J.; Wu, X.; Xie, J.; Li, M. Supercritical “boiling” number, a new parameter to distinguish two regimes of carbon dioxide heat transfer in tubes. *Int. J. Therm. Sci.* 2019, 136, 254–266.
35. Dittus, F.W.; Boelter, L.M.K. Heat transfer in automobile radiators of the tubular type. *Int. Commun. Heat Mass Transf.* 1985, 12, 3–22.
36. Hess, H.L.; Kunz, H.R. A study of forced convection heat transfer to supercritical hydrogen. *J. Heat Transf.* 1965, 87, 41–46, doi:10.1115/1.3689046.
37. Hu, Z.; Chen, T.; Luo, Y.; Zheng, J.; Tang, M. Heat transfer characteristics of kerosene at supercritical pressure. *J. Xian Jiaotong Univ.* 1999, 33, 62–65.
38. Kang, K.; Chang, S. Experimental study on the heat transfer characteristics during the pressure transients under supercritical pressures. *Int. J. Heat Mass Transf.* 2009, 52, 4946–4955, doi:10.1016/j.ijheatmasstransfer.2009.06.005.

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