Thermal design and heat transfer numerical research of kerosene heat exchanger

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Abstract. Design of a cryogenic heat exchanger for kerosene rapid cooling is carried out, and the heat transfer mode and structural form of the heat exchanger are preliminarily designed by theoretical calculation. The corresponding physical and numerical models are established, and the cooling characteristics of aerospace kerosene were studied by numerical calculation method. By comparison with experimental data, the validity and accuracy of the numerical simulation results are verified, which provide theoretical guidance for further research.

1. Introduction

Kerosene has good characteristics such as high energy density and good combustion performance, and it is widely used for aerospace and aircraft engine. The kerosene engine has become the main power of the core stage, booster and non-toxic upper stage of the launch vehicle and reusable carrier. So far, the Soviet Union/Russia and the United States have successfully developed a variety of historically significant kerosene engines. Before filling, kerosene must meet the requirements of service temperature. The temperature of kerosene stored on ground is generally slightly higher, so it must be cooled. On the premise of ensuring the temperature index, how to increase the cooling rate and shorten the cooling time has become the focus of engineering implementation and theoretical research [1].

There are many types of heat exchangers for cooling kerosene. According to the heat exchange method of cold and hot fluids, heat exchangers can be divided into partition type, direct contact type and regenerative type.

In direct contact heat exchangers, cold and hot fluids blends, and heat transfer is often accompanied by mass transfer. The process mechanism is different from pure heat transfer, and the application is also limited by process requirements. The disadvantage of regenerative heat exchangers is that the equipment is large in size, and the heat exchange process is in unsteady alternating condition. The doping of the two fluids cannot be completely avoided, so this type of equipment is less used. The characteristic of the partition wall heat exchanger is that the cold and hot fluids are separated by a metal wall, so that the two fluids can transfer heat without mixing[2].

The liquid nitrogen bath heat transfer cooling method uses cryogenic liquid nitrogen (77K) as the cold source (kerosene in tube side, liquid nitrogen in shell side). Controlling the kerosene cooling rate can be achieved by adjusting the kerosene flow rate and liquid nitrogen liquid level height. Small heat
transfer exchange area can be achieved due to large temperature difference between inside and outside the heat exchange tube, which makes heat exchanger compact. Comparing with other type heat exchanger, the cold kerosene temperature at the outlet of the cryogenic liquid nitrogen heat exchanger is lower, and the amount of cold energy storage is larger, which improves the cooling rate.

![Figure 1. Cooling system](image)

As shown in Fig.1, the liquid nitrogen cooling system mainly includes kerosene storage tank, heat exchanger, cryogenic pipelines and valves.

2. Heat exchanger preliminary design
Stainless steel(0Cr18Ni9)is used as the raw material for heat exchange tubes. The initial temperature of kerosene is set to 33°C, and final temperature is set to 3°C. Thermal properties calculations of kerosene are based on average temperature 18°C and pressure 0.5MPa. Properties of liquid nitrogen are calculated at a standard boiling point of -196°C and a pressure of 0.3MPa. Specific parameters are shown in Table 1.

|                   | Kerosene(inside tube) | Liquid nitrogen(outside tube) |
|-------------------|-----------------------|------------------------------|
| Inlet temperature(℃) | +33                   | Inlet temperature(℃)         | -196                          |
| Outlet temperature(℃) | +3                   | Latent heat of vaporization(kcal/kg) | 47.68                        |
| Average temperature(℃) | 18                   | Operating pressure(MPa)      | 0.1~0.3                       |
| Flow rate(m³/h)     | 67.5                  | Density(kg/m³)               | 807.3                         |
| Operating pressure(MPa) | 0.5                   | Specific heat capacity(kcal/kg·K) | 0.49                         |
| Density(kg/m³)      | 839.49                | Viscosity(kg/m·h)            | 0.5688                        |
| Specific heat capacity(kcal/kg·K) | 0.47              | Thermal conductivity(kcal/m·h·K) | 0.12                         |
| Viscosity(kg/m·h)   | 7.48                  | Prandtl number               | 2.32                          |
| Thermal conductivity (kcal/m·h·K) | 0.1193              | Surface tension(kg/m)        | 9.08×10⁻⁴                     |
| Prandtl number      | 29.74                 | Gas density(kg/m³)           | 146.24                        |

2.1. Logarithmic mean temperature difference calculation

\[ \Delta T_m = \frac{|T_1 - t_2| - |T_2 - t_1|}{\ln\left(\frac{T_1 - t_2}{T_2 - t_1}\right)} \] (1)

\( \Delta T_m \) —— Logarithmic mean temperature difference, °C
\( T_1 \) —— Kerosene inlet temperature of heat exchanger, °C
\( T_2 \) —— Kerosene outlet temperature of heat exchanger, °C
t\textsubscript{1} —— Liquid nitrogen inlet temperature of heat exchanger, °C

\( t\textsubscript{2} \) —— Liquid nitrogen outlet temperature of heat exchanger, °C

Substitute each parameter value into the formula, \( \Delta T\textsubscript{m} = 213.44°C \)

### 2.2. Heat transfer calculation

Ignoring the heat loss, the heat released by kerosene will be absorbed by liquid nitrogen, which vaporizes the liquid nitrogen. The heat released by kerosene is calculated as follows:

\[
Q = C \cdot M \cdot \Delta t
\]  

(2)

- \( Q \) —— Heat transfer by kerosene, kcal/h;
- \( C \) —— Average specific heat capacity of kerosene, kcal/kg·°C;
- \( M \) —— Flow rate of kerosene, kg/h;
- \( \Delta t \) —— Inlet and outlet temperature difference of kerosene, °C.

Substitute each parameter value into the formula, \( Q = 805897.29 \) (kcal/h)

### 2.3. Calculation of liquid nitrogen evaporation

According to the heat balance principle, the heat released by kerosene is equal to the heat absorbed by liquid nitrogen, from which the calculation formula for liquid nitrogen evaporation can be deduced as follows:

\[
m\textsubscript{1} = \frac{Q}{\lambda}
\]  

(3)

- \( m\textsubscript{1} \) —— Liquid nitrogen evaporation, kg/h
- \( Q \) —— Heat absorbed by liquid nitrogen, kcal/h
- \( \lambda \) —— Latent heat of liquid nitrogen vaporization, kcal/kg

Substitute each parameter value into the formula, \( m\textsubscript{1} = 16902.41 \) kg/h

The volume consumption of liquid nitrogen is calculated as follows:

\[
V\textsubscript{1} = \frac{m}{\rho\textsubscript{N}}
\]  

(4)

- \( V\textsubscript{1} \) —— Volume evaporation of liquid nitrogen, m\(^3\)/h
- \( m \) —— Mass evaporation of liquid nitrogen, kg/h
- \( \rho\textsubscript{N} \) —— Density of liquid nitrogen, kg/m\(^3\)

Substitute each parameter value into the formula, \( V\textsubscript{1} = 20.94 \) m\(^3\)/h

### 3. Physical model and mathematical model

#### 3.1. Physical model

As shown in Figure 2, the kerosene storage tank is a cylindrical container. There are hundreds of kerosene spray outlets in the container. After appropriate simplification, the nozzles are reduced to seven in physical model as shown in Figure 3.
3.2. Governing equation

The temperature of the hot kerosene in the storage tank decreases after kerosene cooling by liquid nitrogen in the heat exchanger. After that, the cold kerosene returns to the storage tank to mix and exchange heat with the left hot kerosene, and keeps looping until all the hot kerosene gets to the set temperature. The above process belongs to fluid mixing and heat exchange in a limited space. The mathematical equations describing the process include mass conservation, momentum conservation, and energy conservation differential equations.

Considering the kerosene storage tank physical model as a symmetrical cylinder, and the temperature of kerosene is basically the same on the circumference of the same height and radius along the axial direction. In the height direction, there are temperature gradients in both radial and axial directions. In the two-dimensional Cartesian coordinate system, the mass conservation, momentum conservation and energy conservation differential equations are as follows:

Mass conservation equation

$$\frac{\partial \rho}{\partial \tau} + \frac{\partial \rho u}{\partial x} + \frac{\partial \rho v}{\partial y} = 0$$  \hspace{1cm} (5)

Momentum conservation equation

$$\begin{align*}
\rho \left( \frac{\partial u}{\partial \tau} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} \right) &= F_x - \frac{\partial p}{\partial x} + \eta \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) \\
\rho \left( \frac{\partial v}{\partial \tau} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} \right) &= F_y - \frac{\partial p}{\partial y} + \eta \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right)
\end{align*}$$  \hspace{1cm} (6)

Energy conservation equation

$$\frac{\partial (\rho H)}{\partial \tau} + \frac{\partial (\rho H u)}{\partial x} + \frac{\partial (\rho H v)}{\partial y} = \frac{\partial (\rho H) u}{\partial x} + \frac{\partial (\rho H) v}{\partial y}$$
\[
\frac{\partial t}{\partial \tau} + u \frac{\partial t}{\partial x} + v \frac{\partial t}{\partial y} = \frac{\lambda}{\rho c_p} \left( \frac{\partial^2 t}{\partial x^2} + \frac{\partial^2 t}{\partial y^2} \right)
\] (7)

U: speed in x direction
V: speed in y direction
F_x: body force in x direction
F_y: body force in y direction
\(\eta\): dynamic viscosity
\(\lambda\): thermal conductivity

3.3. Comparison of calculation results and experiment data

![Figure 4](image1.png)  
**Figure 4.** Experimental and simulation comparison of kerosene temperature

![Figure 5](image2.png)  
**Figure 5.** Difference and relative error between experiment and simulation

As shown in Figure 4 and Figure 5, comparison results show that the maximum absolute value of the difference between the experimental and simulation results of the kerosene cooling process in the storage tank is less than 2K, and the absolute value of the maximum relative error is 0.7%. The calculation results are highly consistent with the experimental values. Therefore, it can be explained that the physical model established in this paper and the numerical calculation method adopted are reasonable and suitable for the calculation of the kerosene cooling process in the storage tank.
4. Conclusion
The simulation results are highly consistent with the experimental values and the numerical calculation method adopted in this paper can accurately and truly reflect the cooling process and heat transfer laws. It can be used to simulate and predict the actual process of kerosene cooling process.

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