EXPERIMENTAL STUDY ON THE CORRELATION OF SUBCOOLED BOILING FLOW IN HORIZONTAL TUBES

by

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Subcooled boiling is the most effective form of heat exchange in the water jacket of the cylinder head. Chen's model is the most widely used correlation for predicting boiling heat transfer, but the selection of the correlation for the nucleate boiling is controversial. The work of this paper is to simulate the heat transfer process in the water jacket of the cylinder head with a horizontal rectangular channel that is heated on one side. Using the coolant flow velocity, inlet temperature and system pressure as variables, the heat flux and heat transfer coefficient were obtained. The results show that the increase of the coolant flow velocity can effectively promote the convection heat transfer, and the change of inlet temperature and system pressure will affect the occurrence of nucleate boiling. However, the Chen's model predictions does not fit well with the experimental data. Four nucleate boiling correlations were selected to replace Chen's model nucleate boiling correlation. The correlation proposed by Pioro coincides best with the experimental data. The mean error after correction is 18.2%.

Key words: *subcooled boiling flow, Chen's model, engine cooling, nucleate boiling correlation*

Introduction

In recent years, with the development of advanced technologies such as turbocharging technology and high pressure common rail technology, miniaturization and high power density are the future development trends, resulting in the problem of excessively high overall engine thermal load [1]. As a part of the combustion chamber, the engine cylinder head is easy to deform under continuous high temperature, and improving its heat transfer ability can effectively alleviate the impact of heat load. Nucleate boiling can greatly improve the heat transfer ability of the wall, but due to local overheating or bubble accumulation, the boiling state can easily develop into transitional boiling or even film boiling, resulting in the occurrence of wall ablation [2, 3]. Therefore, the researchers hope to find the best position in forced convection heat transfer and nucleate boiling heat transfer. Using the subcooled boiling phenomenon in the cooling water chamber can improve the heat transfer capacity while ensuring the safety of the wall surface [4].

Chen correlation was proposed based on six data sources, which provided a relatively simple interaction form between nucleate boiling and convective heat transfer [5]. Dittus-Boelter [6] correlation was used in convective heat transfer, Foster-Zuber's [7] pool boiling correlation was used in nucleate boiling, and the enhancement factor F of boiling on convection

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and suppression factor S of fluid-flow on boiling were proposed. Later researchers, including Jallouk [8] and Chaddock and Noerager [9], found in the experimental verification of the Chen model that the correlation would overestimate the impact of nucleate boiling in the heat transfer process, leading to higher prediction results of the correlation equation. Therefore, Rohsenow's pool boiling correlation [10] was incorporated into Chen's model by Jallouk, replacing the original Foster-Zuber's correlation. Gungor and Winterton [11] incorporated Cooper's pool boiling correlation into Chen's model, and also correlated the enhancement factor F and suppression factor S with the boiling number and Martinelli parameter. Shah [12] proposed a new correlation in graphical form, and 3000 experimental data points were selected to confirm its validity. It was proposed to replace the Martinelli parameter with the convection number, Co, and add the boiling number, Bo, to the correlation. The ratio, ψ, of the two-phase heat transfer coefficient to the liquid surface heat transfer coefficient was related to the boiling number. The experimental results show that the fluid viscosity has little effect on the correlation formula [13]. After considering the bubble dynamics of wall growth, Sarma [14] introduced a new π-parameter into the pool boiling correlation, and the new correlation was in good agreement with the experimental results of water and ethyl alcohol. Pioro conducted an exhaustive investigation, studied the important boiling surface parameters affecting pool boiling heat transfer, and compared six previous pool boiling correlations. Based on the Rohsenow correlation, a new pool boiling correlation was proposed. The advantage is that the corresponding dimensionless constants can be determined according to different combinations of wall characteristics and fluids. This has a great advantage compared with other correlations, and the surface medium combination coefficients are corrected to make it more consistent with the experimental results [15]. Kandlikar [16] constructed a two-phase flow heat transfer correlation for saturated boiling of horizontal and vertical tubes with boiling number, convection number, and Froude number. Its research showed that the heat transfer is dominated by convection at lower value of Bo, and Bo has relatively little effect on heat transfer. When Bo increases with the value of Co, the convection term remains constant. The initial growth rate of the nucleate boiling portion is slow, and then increases rapidly. Fang *et al*. [17-19] summarized the 45 boiling correlations established by the previous researchers, and included nine non-dimensional numbers with a higher frequency into his new correlation. Least squares method and error analysis method were used in the experimental database to reduce the mean absolute deviation between the predicted value and the experimental value, and the accuracy of the correlation was verified in the inspection database. The results showed the average absolute deviation of the correlation in the inspection database 4.4%. The correlation has a wide application range and can be applied to various channel sizes and different fluids. Kim and Mudawar [20] constructed a new correlation by superimposing the effects of nucleate boiling and convective heat transfer. The correlation had a good prediction effect on the previous experimental database. The overall average absolute error was 20.3%, with 79.9%, and 95.5% of the data falling within ±30% and ±50% error bands, respectively. This correlation could be extended to different working fluids.

The objective of this paper is to provide a calculation basis for the subcooled boiling flow behavior in the engine cylinder head, and to prove the validity of applying the Chen model in subcooled boiling. Through the subcooled boiling experiment of two-phase flow in the horizontal tube, the prediction effects of different boiling correlations were compared. Based on the Chen model, the experimental parameters are used to modify the correlation parameters of the convection and boiling heat transfer terms. In addition, the effects of different inlet temperature, flow rate and system pressure on boiling heat transfer are also compared.

Experimental methods

Experimental facility

In order to simulate the subcooled boiling phenomenon of the cylinder head water jacket, the experimental system was set up. The schematic diagram of the experimental facility is shown in fig. 1.

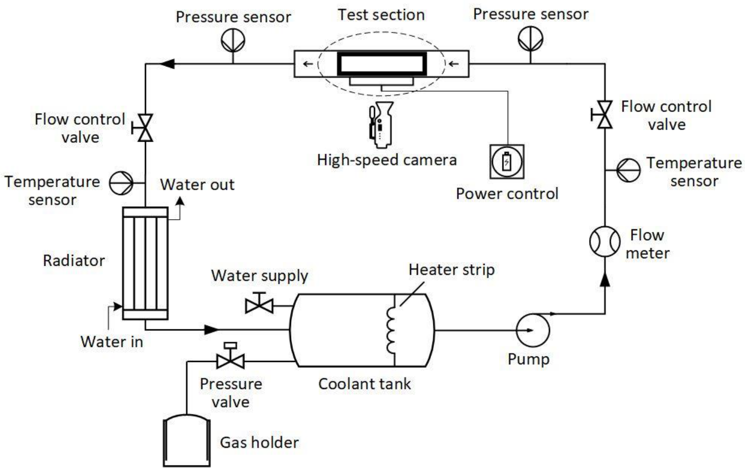

Figure 1. Schematic diagram of the experimental facility

The system is composed of a coolant circulation loop, which mainly includes a coolant tank, a gas holder, a circulating water pump, a test section, a radiator, and measurement and control devices. A heating strip is installed in the coolant tank to preheat the working fluid. The coolant tank is connected to the gas holder through a pressure valve, and the gas holder is filled with high pressure nitrogen to stabilize the inlet pressure of the test section at the specified pressure. The working fluid-flow is adjusted by pumps and flow control valves, and measured by electromagnetic-flowmeter (relative error 0.5%) before the fluid-flow to the test section. Temperature and pressure sensors are located near the test section monitor the temperature and pressure of the working fluid. The working fluid that is heated in the test section flows to the radiator to reduce the temperature, and then returns to the coolant tank.

The test section is shown in fig. 2. The fluid passage is designed as a horizontal rectangular channel whose dimensions are 30 mm long, 16 mm wide. In order to consistent with the cylinder head water jacket, the material of the heating block in the test was selected as vermicular iron and embedded in the bottom of the test section. The heating surface is 100 mm long and 20 mm wide. Heat is generated by high frequency induction. Two thermocouples are arranged 2 mm below the top of the heating block, and three thermocouples are arranged at 6 mm. In order to observe the growth process of bubbles during the boiling process, quartz glass is embedded in the middle of the test sec-

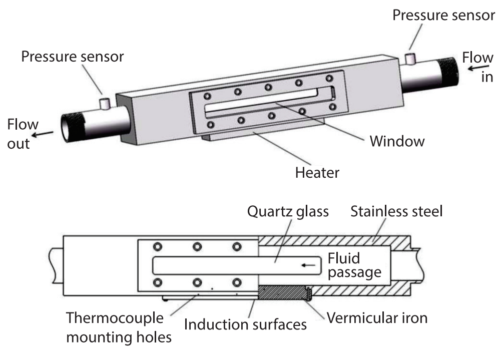

Figure 2. Schematic diagram of the experimental facility

tion form a visualization window, and a high speed camera is provided to capture the bubble pictures.

Experimental procedure

In this experiment, water is used as the working fluid. Water is heated to boiling in order to separate the dissolved gases. The purpose of this is to reduce the influence of the dissolved gas on the heat transfer process. The experiment mainly investigated the influence of coolant flow parameters on the heat transfer characteristics. The experimental conditions are shown in tab. 1.

Table 1. Experimental conditions

Serial number	Pressure [kPa]	Inlet temperature [°C]	Flow velocity [ms^{-1}]
1	200	95	0.6, 0.8, 1, 1.2, 2, 3, 4, 5, 6
2	200	60, 70, 80, 90	1
3	100, 150, 250	95	1

Since the heat flux and surface temperature cannot be directly measured, it is obtained by indirect calculation. The heat flux is calculated by Fourier's equation of heat conduction, and the wall temperature of the heating block top is calculated by interpolation:

$$q = \lambda \frac{T_{\mathrm{lower}} - T_{\mathrm{upper}}}{h_{\mathrm{l,u}}} \tag{1}$$

$$T_{\mathrm{top}} = T_{\mathrm{upper}} - \frac{q h_{\mathrm{u,t}}}{\lambda} \tag{2}$$

where T_{lower} and T_{upper} are the average measured temperature of the thermocouple at 6 mm and 2 mm from the top of the heating block, respectively, T_{top} – the surface temperature at the top of the heating block, $h_{\mathrm{l,u}}$ – the vertical distance between the lower thermocouple and the upper thermocouple (4 mm), $h_{\mathrm{u,t}}$ – the vertical distance (2 mm) between the top of the heating block and the upper thermocouple, λ – the thermal conductivity of the heating block, and q – the heat flux.

The uncertainties of the measurement parameters in the experiment is obtained by the test accuracy of the measuring instrument. The measurement accuracy of the temperature sensor is ±0.5%, the measurement accuracy of the pressure sensor is ±0.4%, the measurement accuracy of the flowmeter is ±0.5%, the distance measurement accuracy is 0.15 mm. The uncertainties of heat flux and wall temperature are calculated by the error propagation equation proposed by [21]:

$$\delta R = \sqrt{\left(\frac{\partial R}{\partial x_1}\delta x_1\right)^2 + \left(\frac{\partial R}{\partial x_2}\delta x_2\right)^2 + \cdots + \left(\frac{\partial R}{\partial x_n}\delta x_n\right)^2} \tag{3}$$

where δx_1, $\delta x_2 \ldots \delta x_n$ are the uncertainty of the direct measurement parameters x_1, $x_2 \ldots x_n$, and R is the uncertainty of the indirect measurement parameter. The uncertainties of measurement parameters are shown in tab. 2.

Experimental results and discussions

In the subcooled boiling process, there are many factors that affect the heat transfer characteristics, mainly including the flow velocity of the working fluid, the inlet temperature and the system pressure. In the experiment, keeping the remaining variables constant, and analyzing the influence of single variables on heat transfer characteristics is the focus of this section.

Table 2. Uncertainties of measurement parameters

Parameter	Uncertainty
Bulk temperature [°C]	±0.5%
Flow velocity [ms⁻1]	±0.5%
System pressure [kPa]	±0.5%
Thermocouple position [mm]	0.15 mm
Thermocouple temperature [°C]	±0.5%
Wall temperature [°C]	±2%
Heat flux [Wm^{-2}]	8.2~15.5%

Effect of flow velocity

Figure 3 shows the effect of working fluid-flow velocity on heat flux. The system pressure is constant at 200 kPa, the working fluid inlet temperature is 95 °C, and the flow velocity are 0.6 m/s, 0.8 m/s, 1.0 m/s, 1.2 m/s, and 2 m/s. As the wall temperature increases, the heat flux shows an upward trend and the slope of the curve gradually increases. It shows that the heat transfer process is changing from forced convection nucleate boiling. During this process, the heat transfer coefficient is rising. Comparing the curves at various flow velocity reveals that when the wall temperature remains constant, the flow velocity is positively correlated with the heat flux. However, when the wall temperature reaches a higher point, the curves are converging, indicating that the change in flow velocity at this time has a low influence on the heat flux. It is clear that the increase in velocity can greatly affect the change of heat flux at low wall temperature, and the degree of influence on heat flux decreases at high wall temperature. In other words, flow velocity has a significant promotion effect on forced convective, and has a less effect on nucleate boiling.

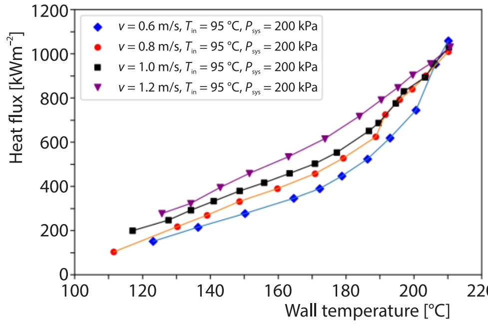

Figure 3. Effect of flow velocity on heat flux

Effect of inlet temperature

Figure 4 shows the effect of working fluid inlet temperature on the heat flux. The system pressure is constant at 200 kPa, the flow velocity is 1.0 m/s, and the inlet temperature are 60 °C, 70 °C, 80 °C, and 90 °C. It can be seen from the curve that when the wall temperature is low, forced convection plays a dominated role in the heat exchange process, and the curves of different inlet temperatures are basically parallel. As the wall temperature gradually increases, the heat transfer condition gradually shifts to the heat transfer mode dominated by nucleate boiling. The slope of the curve with an inlet temperature of 90 °C increases first, indicating that the higher inlet temperature (the lower the degree of subcooling) will cause the nuleate boiling to come earlier. When the heat transfer state of the fluid is dominated by nucleate boiling, the effect of inlet temperature on heat flux is significantly reduced, which means that the curves are merged in the figure. Therefore, in the heat transfer of the engine cylinder head, the coolant inlet temperature should be kept low. Although the higher

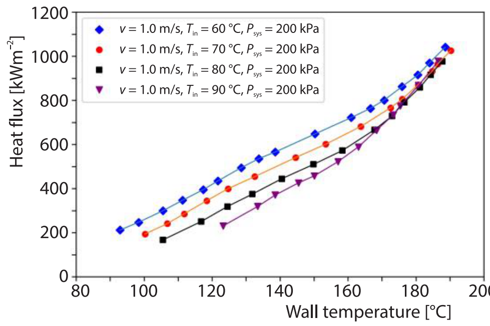

Figure 4. Effect of inlet temperature on heat flux

coolant temperature will cause the nucleate boiling to occur as soon as possible (increased heat transfer coefficient), the heat flux at the same time is affected by the difference between the wall temperature and the fluid temperature, maintaining a high degree of subcooling will make the product of the two higher and avoid overheating of the engine.

Effect of system pressure

Figure 5 shows the effect of system pressure on heat flux. The working fluid inlet temperature is constant at 95 °C, the flow velocity is 1.0 m/s, and the system pressures are 100 kPa, 150 kPa, 200 kPa, and 250 kPa. When the wall temperature is low, the coolant is dominated by forced convection, and the curves of different system pressures almost overlap. It shows that the system pressure has little effect on the convection state. The coolant flow is dominated by nucleate boiling when the wall temperature rises. The curves are separated and the slope of the curve with lower system pressure increases first. This is because when the system pressure decreases, the saturation temperature of the working fluid decreases (the degree of supercooling decreases). Under the same wall temperature condition, the low degree of supercooling is more likely to produce nucleate boiling.

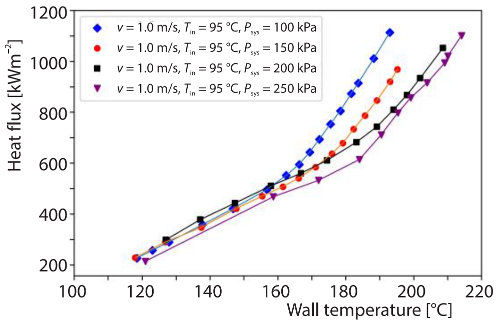

Figure 5. Effect of system temperature on heat flux

Comparison of experimental data and subcooled boiling correlation

Description of Chen's correlation

The superposition method was first proposed by Chen *et al.* [3]. This method is based on a large amount of experimental data and regards the flow boiling heat transfer as a linear superposition of forced convection and nucleate boiling:

$$q_{\mathrm{tp}} = Fq_{\mathrm{fc}} + Sq_{\mathrm{nb}} = Fh_{\mathrm{fc}}\left(T_w - T_b\right) + Sh_{\mathrm{nb}}\left(T_{\mathrm{w}} - T_{\mathrm{sat}}\right) \tag{4}$$

where q_{tp} is the total heat flux, q_{fc} and q_{nb} represent the forced convection heat flux and the nucleate boiling heat flux, respectively, F – the dimensionless enhancement factor of forced convection, S – the suppresion factor of nucleate boiling, h_{fc} and h_{nb} are the forced convection heat transfer coefficient and the nucleate boiling heat transfer coefficient, respectively, T_{w}, T_{b}, and T_{sat} – the wall temperature, the bulk temperature, and the saturation temperature of fluid, respectively.

For the forced convection heat transfer coefficient in flow boiling, Chen's model adopts the forced convection correlation based on smooth pipe proposed by Dittus-Boelter, which has a wide range of applications and is well fitted to the verification experiment:

$$h_{\mathrm{fc}} = 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4}\left(\frac{k_{\mathrm{l}}}{D_{\mathrm{h}}}\right)\left(\frac{\mu_{\mathrm{b}}}{\mu_{\mathrm{w}}}\right)^{0.14} \tag{5}$$

where Re and Pr denote the Reynolds number and the Prandtl number of fluid, respectively, k_{l} – the thermal conductivity of the fluid, D_{h} – the hydraulic diameter, μ_{b} and μ_{w} represent the dynamic viscosity evaluated at the bulk and wall temperatures, respectively:

$$\mathrm{Re} = \frac{\rho_\mathrm{l} u_\mathrm{b} D_\mathrm{h}}{\mu_\mathrm{l}}, \quad \mathrm{Pr} = \frac{\mu_\mathrm{l} c_{p,\mathrm{l}}}{k_\mathrm{l}} \tag{6}$$

where ρ_l and μ_l are the density of fluid and the dynamic viscocity of fluid, respectively, u_b – the bulk velocity, and $c_{p,\mathrm{l}}$ – the specific heat capacity of fluid.

The experimental data were compared with Dittus-Boelter correlation prediction results to verify the accuracy of correlation. In order to ensure that the working fluid is in the forced convection state and exclude the influence of nucleate boiling on the heat flux, the data points of the wall temperature below the saturation temperature in the experiment are compared with the predicted results. The comparison between the predicted and experimental results is shown in fig. 6.

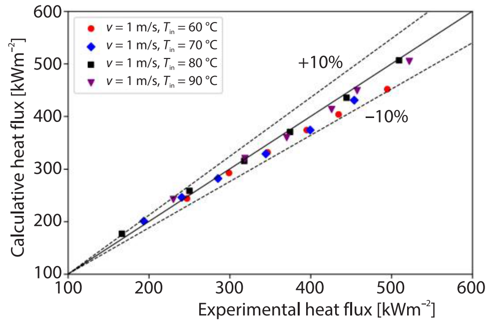

Figure 6. Comparison of experimental data with convective heat transfer correlation

Figure 6 shows that the experimental values are in good agreement with the predicted values. All data points are within ±10% error line with an average error of 6.2%.

Researchers proposed different correlations based on experimental data in previous studies on nucleate boiling heat transfer coefficient. There are basically two types:

– The first type uses constants to represent the coefficients and power exponents in the correlation. This method has a wide range of applications, but ignores the effects of fluid types and surface materials on boiling. It makes prediction accuracy insufficient.
– The second type is to select the appropriate correlation coefficient according to the combination of fluid and surface material, or determine the value of the correlation coefficient to which the fluid belongs based on representative factors such as Prandtl number and Reynolds number.

The prediction accuracy of this method is high, but the adaptability is poor. Chen chose the first type nucleate boiling correlation proposed by Foster and Zuber:

$$h_\mathrm{nb} = 0.00122 \frac{k_\mathrm{l}^{0.79} c_{p,\mathrm{l}}^{0.45} \rho_\mathrm{l}^{0.49} \mathrm{g}^{0.25}}{\sigma^{0.5} \mu_\mathrm{l}^{0.5} h_\mathrm{lg}^{0.24} \rho_\mathrm{g}^{0.24}} \Delta T^{0.24} \Delta P^{0.75} \tag{7}$$

where g is the gravity constant, σ – the surface tension, h_lg – the latent heat of vaporization, ρ_g – the vapor density, $\Delta T = T_\mathrm{w} - T_\mathrm{sat}$ – the wall superheat, and $\Delta P = P_\mathrm{w}(T_\mathrm{w}) - P_\mathrm{sat}(T_\mathrm{sat})$ – the pressure difference between wall temperature and saturation temperature.

According to Chen's model, the enhancement factor F of forced convection is expressed as a function of Martinelli parameter:

$$F = \begin{cases} 2.35\left(X_{tt}^{-1} + 0.213\right)^{0.736} & : X_{tt}^{-1} > 0.1 \\ 1 & : X_{tt}^{-1} \le 0.1 \end{cases} \tag{8}$$

$$X_{tt} = \left(\frac{1-x}{x}\right)^{0.9} \left(\frac{\rho_\mathrm{g}}{\rho_\mathrm{l}}\right)^{0.5} \left(\frac{\mu_\mathrm{l}}{\mu_\mathrm{g}}\right)^{0.5} \tag{9}$$

where X_tt is Martinelli parameter, μ_g – the gas dynamic viscosity, and x – the vapor quality, of which an effective value for subcooled boiling is computed here following [22]:

$$x = -\frac{c_{p,\mathrm{l}}\left(T_{\mathrm{sat}} - T_{\mathrm{b}}\right)}{h_{\mathrm{lg}}} \tag{10}$$

Chen's model used Butterworth's expression for suppresion factor S, which explains the decline of nucleate boiling as the flow velocity increases [23]:

$$S = \frac{1}{1 + 2.53 \cdot 10^{-6}\,\mathrm{Re}^{1.17}} \tag{11}$$

Assessment of nucleate boiling correlations

The nucleate boiling correlations are mainly divided into two types:

- The first type is to allow the correlation adapt to the combination of different fluids and surfaces, and the coefficient and power exponent are regarded as constants. Although this improves the widespread application of correlation, it sacrifices the accuracy of its prediction.
- The second type is to determine the coefficient and power exponent based on the fluid type and surface combination. This type of prediction has higher accuracy, but the disadvantage is that if the combination of surface and fluid is unknown, the application of correlation will be limited.

In order to verify the performance of different nucleate boiling correlations in Chen's model, four correlations that are well known and widely used in engineering were selected. They are, respectively, proposed by Foster-Zuber, Labuntsov, Pioro and Rohsenow [24]. The correlations of Foster-Zuber and Labuntsov belong to first type, and the correlations of Pioro and Rohsenow belong to second type. These nucleate boiling correlations are listed in tab. 3.

Table 3. Nucleate boiling correlation

Author	Correlation	Equation number
[7]	$h_{\mathrm{nb}} = 0.00122\dfrac{k_{\mathrm{l}}^{0.79} c_{p,\mathrm{l}}^{0.45} \rho_{\mathrm{l}}^{0.49} \mathrm{g}^{0.25}}{\sigma^{0.5} \mu_{\mathrm{l}}^{0.5} h_{\mathrm{lg}}^{0.24} \rho_{\mathrm{g}}^{0.24}} \Delta T^{0.24} \Delta P^{0.75}$	(7)
[10]	$\dfrac{c_{p,\mathrm{l}}\Delta T}{h_{\mathrm{lg}}} = C_{\mathrm{sf}}\left[\dfrac{q_{\mathrm{nb}}}{\mu_{\mathrm{l}} h_{\mathrm{lg}}}\sqrt{\dfrac{\sigma}{\mathrm{g}\left(\rho_{\mathrm{l}} - \rho_{\mathrm{g}}\right)}}\right]^{0.33} \mathrm{Pr}^{n}$	(12)
[15]	$\dfrac{h_{\mathrm{nb}}}{k_{\mathrm{l}}}\sqrt{\dfrac{\sigma}{\mathrm{g}\left(\rho_{\mathrm{l}} - \rho_{\mathrm{g}}\right)}} = C_{\mathrm{sf}}^{*}\left\{\dfrac{q_{\mathrm{nb}}}{h_{\mathrm{lg}}\rho_{\mathrm{g}}^{0.5}\left[\sigma \mathrm{g}\left(\rho_{\mathrm{l}} - \rho_{\mathrm{g}}\right)\right]^{0.25}}\right\}^{2/3} \mathrm{Pr}^{m}$	(13)
[24]	$h_{\mathrm{nb}} = 0.075\left[1 + 10\left(\dfrac{\rho_{\mathrm{g}}}{\rho_{\mathrm{l}} - \rho_{\mathrm{g}}}\right)^{0.67}\right]\left(\dfrac{\mu_{\mathrm{l}} k_{\mathrm{l}}^{2}}{\rho_{\mathrm{l}}\sigma\left(T_{\mathrm{sat}} + 273.15\right)}\right)^{0.33} q_{\mathrm{nb}}^{0.67}$	(14)

where C_{sf}, C_{sf}^{*}, n, and m are empirical parameters, depended upon the fluid type and the surface-fluid combination, $C_{\mathrm{sf}} = 0.017$, $n = 0.76$, $C_{\mathrm{sf}}^{*} = 1.228 \cdot 10^{-3}$, $m = -1.1$.

The nucleate boiling part of Chen's model is replaced with the aforementioned four correlations, and the convection part continues to use the Dittus-Boelter correlation that has been proved by the experimental data.

Figure 7 shows the comparison between the prediction results of different nucleate boiling correlation and the experimental data. The prediction mean error is evaluated:

$$\text{Mean error} = \sum_{i=1}^{n} \frac{1}{n} \frac{\left|q_{\text{nb,pred}} - q_{\text{nb,exp}}\right|}{q_{\text{nb,exp}}} \tag{15}$$

The mean error result shows that the prediction result of Chen's model composed of Pioro nucleate boiling correlation has the minimum error with the experimental data, and the mean error is 34.8%. It can be seen from the figure that the predicted value of the Chen's model using different nucleate boiling correlation is always higher than the experimental value. This is because the aforementioned nucleate boiling correlation is not established in a single-sided heating horizontal tube, and the heating material is not vermicular iron, which will cause the microstructure of the boiling heating surface to be unknown. Compared with the four correlations, the Foster-Zuber and Labunstov correlations, fig. 7(a), represent first type because it ignores the combination type of fluid and surface, which reduce the prediction accuracy. The Rohsenow and Pioro correlations, fig. 7(b), represent second type, the mean error is smaller.

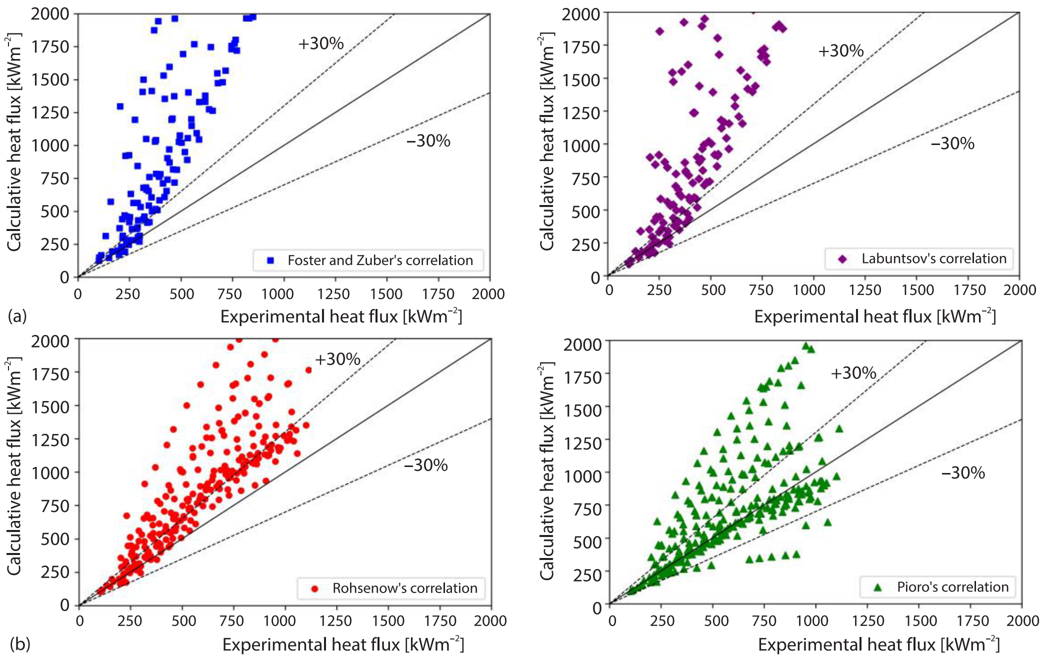

Figure 7. Comparison of experimental data with nucleate boiling correlation

Taking C_{sf}^* and m as the parameters to be fitted, using experimental data to fit the Pioro's nucleate boiling correlation, the fitting result is $C_{\text{sf}}^* = 1.538 \cdot 10^{-3}$, $m = -1.87$, using the revised Pioro's correlation prediction result and the experimental data comparison are shown in fig. 8. The error is within ±30%, and the mean error is 18.2%. This shows that the predicted results are in good agreement with the experimental data, and the boiling heat transfer law can be better explained by the reviesed Pioro's nucleate boiling correlation.

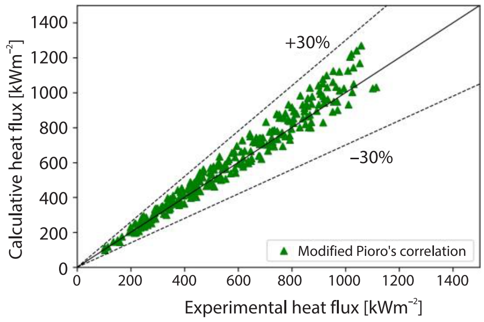

Figure 8. Comparison of experimental data with modified Pioro's correlation

Conclusions

Subcooled boiling phenomenon in the cylinder head water jacket of the engine can greatly improve its heat exchange capacity and reduce the thermal load of the cylinder head. In this paper, the horizontal tube supercooled boiling experiment was used to simulate the single-sided heating environment in the water jacket of the engine cylinder head, and a series of heat transfer laws under different conditions were obtained. The experimental data was used to compare Chen's model prediction results, and the Chen's correlation was revised according to the experimental data. Conclusions of the research are as folows.

- The velocity of the fluid promotes convective heat transfer. When the degree of superheat is low, the effect of flow velocity on the heat flux is more obvious. As the heat transfer mode shifts to nucleate boiling, the influence of flow velocity on boiling decreases. The subcooling decreases with the increase of inlet temperature, and the fluid is more likely to enter the nucleate boiling state, which promotes the heat exchange between the surface and the fluid. The system pressure does not affect the convective heat transfer, and its function is mainly to impact on the saturation temperature of the fluid. At the same surface temperature, the decrease in system pressure makes nucleate boiling easier to produce.
- The correlation of convective heat transfer in Chen's model was studied, and the experimental data of pure convective heat transfer was compared with the prediction result of the Dittus-Boelter correlation, which verified the accuracy of the correlation. The nucleate boiling correlation in Chen's model was studied. Four correlations widely used in engineering were selected to replace the original nucleate boiling correlation in Chen's model, and compared them with the experimental results. It is found that the nucleate boiling correlation proposed by Pioro has better prediction results, and the empirical parameters of the correlation are fitted to reduce the average prediction error to 18.2%.

Nomenclature

c_p – specific heat, [Jkg^{-1}K^{-1}]
D_h – equivalent diameter, [m]
F – enhancement factor
g – gravity constant, [m^{2}s^{-1}]
h – heat transfer coefficient, [Wm^{-2}K^{-1}]
h_lg – latent heat of vaporization, [Jkg^{-1}]
k – thermal conductivity, [Wm^{-1}K^{-1}]
P – pressure, [Pa]
Pr – Prandtl number
q – heat flux, [Wm^{-2}]
Re – Reynolds number
S – suppression factor
T – temperature, [°C]
v – flow velocity, [ms^{-1}]
u_b – bulk velocity

Greek symbols

μ – dynamic viscosity, [kgm^{-1}s^{-1}]
ρ – density, [kgm^{-3}]
σ – surface tension, [Nm^{-1}]

Subscripts

b – bulk flow
fc – forced convection
g – gas
l – liquid
nb – nucleate boiling
sat – saturation
tp – two-phase
w – wall

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