frontiers | Frontiers in Energy Research

TYPE Original Research
PUBLISHED 29 July 2024
DOI 10.3389/fenrg.2024.1340675

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RECEIVED 18 November 2023
ACCEPTED 30 April 2024
PUBLISHED 29 July 2024

CITATION
Duan M, Zhao M, Wei J and Xu Y (2024), An experimental research of the influence on critical heat flux of a rod bundle under certain inlet temperatures.
Front. Energy Res. 12:1340675.
doi: 10.3389/fenrg.2024.1340675

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An experimental research of the influence on critical heat flux of a rod bundle under certain inlet temperatures

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Critical heat flux (CHF) is one of the most concerned thermal hydraulic phenomena in reactor safety analysis. It involves complex two-phase flow heat transfer mechanism, and has not been fully understood, so the prediction of critical heat flux mainly depends on CHF correlations obtained under limited experimental conditions. At present, CHF correlations are generally developed with pressure, mass flux and quality as key independent variables. And correspondingly, the test matrix of a CHF test consists of the above parameters. However, it is impossible to perform CHF tests accurately according to the predetermined quality. In CIAE, a CHF experimental research of a 5 × 5 uniformly heated rod bundle has been carried out. In the experiment, the inlet temperature of the test section was directly taken as a parameter in the test matrix. The CHF data were achieved by stepwise increasing the heating power. The test conditions covered the pressure of 2.8–15.5 MPa, the mass flux of 845–3533 kg/(m^2·s), and the inlet temperature of 100°C–300°C. The test data have been analyzed to obtain the thermal-hydraulic parameter influences on CHF by taking the inlet temperature as a variable. The results indicated that, within the test condition range, under the same inlet temperatures, CHF was hardly affected by pressure, and linearly increased with the increasing mass flux. With the increase of inlet temperature, the enhancement of CHF with the increasing mass flux gradually weakens. And CHF was linearly decreased with the increasing inlet temperature under the same mass flux. By contrast, the parameter influences on CHF were more complex by taking the local quality as a variable. According to the research, it can be concluded that, it has an advantage of simplifying the CHF correlation form to take the inlet temperature of the test section as a variable parameter. The research can provide new ideas for CHF experiment, data analysis and correlation development.

KEYWORDS

critical heat flux, reactor safety, CHF experiment, uniformly heated rod bundle, parameter influence

1 Introduction

Critical heat flux (CHF) is an important thermo-hydraulic phenomenon in reactor safety analysis. It is a phenomenon where the boiling heat transfer mechanism changes, resulting in a sudden deterioration of heat transfer, and the corresponding heat flux is called CHF. For heating surfaces with controlled heat flux, such as fuel elements, when CHF occurs, the wall temperature of the heating surface suddenly increases, even causing the wall burnout. Therefore, CHF phenomenon should be avoided. In the design and operation of nuclear power plants, CHF is one of the most important parameters limiting the operation of nuclear power plants, and has a significant impact on the safety and economy of the reactor (Herer et al., 2005).

There are two types of CHF mechanisms, including Departure From Nucleate Boiling (DNB) and Dryout (DO). For high heat flux condition, when the local heat flux of the fuel element reaches CHF, the cladding surface is covered by steam film, and the heat transfer mechanism changes from nucleate boiling to film boiling. This phenomenon is called DNB. For low heat flux and high-quality condition, when CHF happens, the liquid film on the fuel surface dries out, and the flow regime changes from annular flow into dispersed flow. This phenomenon is called DO (Hao et al., 2016). Usually, DNB is more likely to occur in pressurized water reactors (PWRs) while DO in boiling water reactors (Yang et al., 2021).

In PWRs, departure from nucleate boiling design criterion is important in reactor thermal hydraulic design (Yang et al., 2013). In order to quantitatively evaluate the distance from DNB during the reactor operation, the concept of departure from nucleate boiling ratio (DNBR) has been introduced, which is the ratio of CHF to the local heat flux of the fuel element (Hao and Xie, 1993). In the nuclear power plants operation, it is very important to monitor or predict the minimum DNBR of the core to prevent the fuel rod burning. In order to obtain DNBR, subchannel analysis codes are usually used to calculate the distribution of coolant pressure, mass flux and temperature (or quality), then the corresponding CHF is calculated according to CHF correlations, so as to obtain the distribution of DNBR in the core, and finally determine the minimum DNBR (Zhao et al., 2020).

In order to accurately calculate the DNBR of the core, an accurate CHF correlation is required. As CHF involves complex two-phase flow heat transfer mechanism, many researches on CHF have been conducted all over the world, including mechanism researches, empirical correlation developments and applications, numerical simulations and so on (Bruder et al., 2016).

Though DO type CHF can be predicted relatively accurate by analytical model as significant portion of mechanism for DO has been identified (Weisman, 1992; International Atomic Energy Agency, 2001; Todreas and Kazimi, 2012; Park et al., 2013), DNB type CHF prediction is still challenging. Different mechanistic models have been developed to predict CHF, such as single nucleation (Le Corre et al., 2010), interfacial lift-off (Galloway and Mudawar, 1993a; 1993b), liquid sublayer dryout models (Haramura and Katto, 1983; Katto, 1990), vapor blanket (Lee and Mudawar, 1988), and bubble coalescence models (Weisman and Pei, 1983). However, there is still no consensus on causal mechanism for DNB (Lyons et al., 2020). Most of the mechanistic models are primarily studied from simple geometries, and still require experimental data to improve the accuracy. In PWRs, fuel assemblies have complicated geometry, non-uniform power distribution, strong open subchannel interactions, and mixing effects from mixing vane grids, so it is more difficult to understand and predict the CHF phenomena in reactor core subchannel systems (Yang et al., 2021).

In design and safety analysis of PWRs, uncertainties of CHF prediction by mechanistic models or analytical methods are unacceptable. Therefore, experiment researches are an important way to obtain CHF data and correlations (Qin et al., 2016). CHF experimental studies developed from simple channels (Dittus and Boelter, 1930; Bishop et al., 1964; Groeneveld et al., 1986; Zhang et al., 2004) to 2 × 2 or 3 × 3 small bundles (Moon and Chun, 2005). In order to minimize cold wall effect, larger bundle CHF experiments, such as 5 × 5 and 6 × 6, were performed for fuel assemblies, including experiments on Heat Transfer Research Facility (Fighetti and Reddy, 1982), OMEGA loop of the French C.E.A. (Clément, 2013), Karlstein Thermal Hydraulic Facility (KATHY) loop of Framatome-ANP (Wieckhorst, 2014), ODEN loop of the Westinghouse Thermal-Hydraulic Test Facility (Smith, 2011). In these experiments, direct heating rods are recommended to simulate fuel rods for well controlled heat flux. The radial power distributions are non-uniform to avoid CHF occurring near the non-typical wall (Park et al., 2013). The power ratios of central rods to peripheral rods are usually 0.76–0.93. In test procedures, some experiments achieved the CHF value by increasing the inlet temperature continuously with a constant temporal slope while the other fluid conditions are kept stable (Clément, 2013; Park et al., 2013), while some by increasing the heating power continuously (Fighetti and Reddy, 1982).

Based on experiment data, look-up tables and empirical correlations were developed for CHF prediction, such as the1995 and 2006 CHF look-up tables (Groeneveld et al., 1995; Groeneveld et al., 2007), BAW-2 (Wilson et al., 1969), W-3 (Tong, 1972), EPRI (Reddy and Fighetti, 1983), FC 2000, FC 2002r (Zhang et al., 2016), etc. CHF correlations can be mainly divided into two types (Hejzlar and Todreas, 1996; Siman-Tov, 1996). One type is to directly take the local quality as one of the parameters, and the other type is to take the inlet subcooling (or inlet enthalpy) and heating length instead of the local quality through energy balance (Lu et al., 2016). In the previous method, CHF value is not affected by the heating length, so as to reduce the independent variable. Furthermore, the simple use of the inlet parameters cannot reflect the mixing effect of the spacer grid in the subchannel of the rod bundle. Therefore, for a rod bundle with specific structure, the CHF correlation is usually developed with the local pressure, mass flux and quality at the critical point as independent variables, and necessary corrections are made to the correlation in consideration of cold wall effect, grid effect and non-uniform axial heat flux effect. Correspondingly, pressure, mass flux and quality are taken as test parameters in the test matrix. However, in the data analysis of critical heat flux tests, since the local quality is a non-independent variable affected by pressure, when the quality is taken as the independent variable, the influence of pressure, mass flux and quality on CHF becomes relatively complex, which leads to complex forms of CHF correlations.

In this research, a CHF test of a 5 × 5 uniformly heated rod bundle has been performed, which simulated a developing fuel assembly. In the experiment, the inlet temperature of the test section was directly taken as a parameter in the test matrix. The CHF data were achieved by stepwise increasing the heating power. By test result analysis, the influences of thermal-hydraulic parameters on CHF have been obtained, taking inlet temperature as independent variable.

2 CHF experiment

A CHF experimental research of 5 × 5 uniformly heated rod bundle with full-length, which simulated a developing fuel assembly,

TABLE 1 The design parameters of the main loop of TCTF.

Parameter	Design value
Pressure	20 MPa
Flow rate of the main pump	180 m^3/h
Temperature	366°C
Heat exchanger power	3MW × 2+6 MW
Power supply	13.5 MW

was carried out on Thermal hydraulic Comprehensive Test Facility (TCTF) in China Institute of Atomic Energy (CIAE).

2.1 Test facility

TCTF consists of a main loop, a test section, a cooling system, a pressure system, and other auxiliary systems. It can provide the test section with needed thermal-hydraulics parameters, including the outlet pressure, inlet temperature, mass flux and heating power. Its design parameters are shown in Table 1. Its main flow chart is shown in Figure 1.

The working medium in the main loop is driven into the preheater by the main pump, and preheated to a certain temperature before entering the test section. Then it enters the mixer after being heated by the test section. In the mixer, the working medium in the branch of the test section and that in the bypass of the test section are mixed into the working medium with a lower temperature, which flows into the 3# heat exchanger for further cooling, and finally returns to the inlet of the main pump. The mass flux into the test section can be controlled by adjusting the valve group and changing the frequency of the main pump. The inlet temperature of the test section can be controlled by changing the power of the preheater, which has an automatic control program to achieve stable and accurately control of the inlet temperature of the test section. The pressurizer provides stable pressure for the main loop. The system pressure can be increased by adding nitrogen or deionized water to the pressurizer, and reduced by actively discharging water through the pressure relief line. The test section and preheater are both powered by a silicon-controlled rectifier power supply.

The key measurement parameters of the facility include outlet pressure, inlet flow rate, inlet temperature, voltage and current of the test section, etc. Table 2 shows the locations, instruments, measuring ranges and accuracies of these parameters.

2.2 Test section

Previous researches have suggested that a 5 × 5 or larger bundle should be used for the PWR rod bundle CHF (Kaizer and Anzalone, 2019; Yang et al., 2021). In this experiment, the test section uses 25 electric heating elements to simulate the fuel assembly. The geometric dimension and arrangement of the electric heating elements are consistent with the prototype, and the effective heating length is 3657 mm, and the ratio of Pitch to Diameter is 1.08. A square ceramic shround is adopted to maintain the square flow cross-section, which area is 2,311 mm^2. The 16 peripheral rods are cold rods, and 9 center rods are hot rods. The power ratio of hot rods to cold rods is 1:0.85, as shown in Figure 2. As there are cold ceramic walls surrounding the heating rods, the cold rods are used to avoid CHF occurring near the non-typical wall (Park et al., 2013). The axial power of the rod bundle is uniformly distributed. Three types of spacer grids are arranged along the axial height. The height of grid A and grid B is 33 mm, and the simple support grid includes heights of 33 mm and 18 mm. Since the critical phenomenon of a uniformly heated rod bundle occurs at the end of the heating section, three thermocouples are arranged at the end of the heating section and upstream of the last spacer grid to monitor the wall temperature

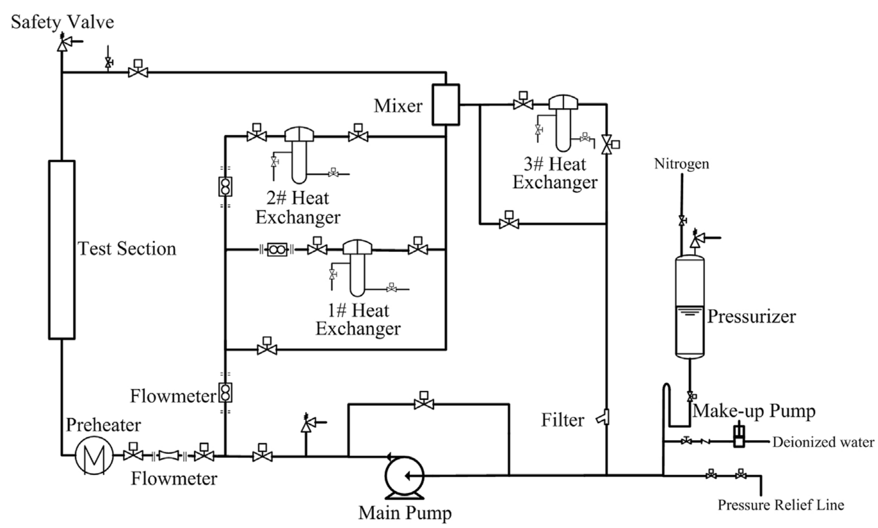

FIGURE 1
The flow chart of Thermal hydraulic Comprehensive Test Facility.

TABLE 2 The key instruments of TCTF.

Parameter	Location	Instrument	Range	Accuracy	Absolute error
Outlet pressure	Outlet of the test section	EJX pressure transmitter	0–20 MPa	±0.05% F.S.	±0.01 MPa
Inlet flow rate	Inlet of the preheater	Venturi flow meter	0–65 m^3/h	±0.5% F.S.	±0.325 m^3/h
Inlet temperature	Inlet of the test section	Pt100 thermal resistance	0–600°C	A Class	±0.15@0°C
Voltage	The copper busbar of the test section	Isolation DC voltage transmitter	0–300 V	±0.1% F.S.	0.3 V
Current	The copper busbar of the test section	Hall DC sensor	0–50000 A	±0.1% F.S.	50 A

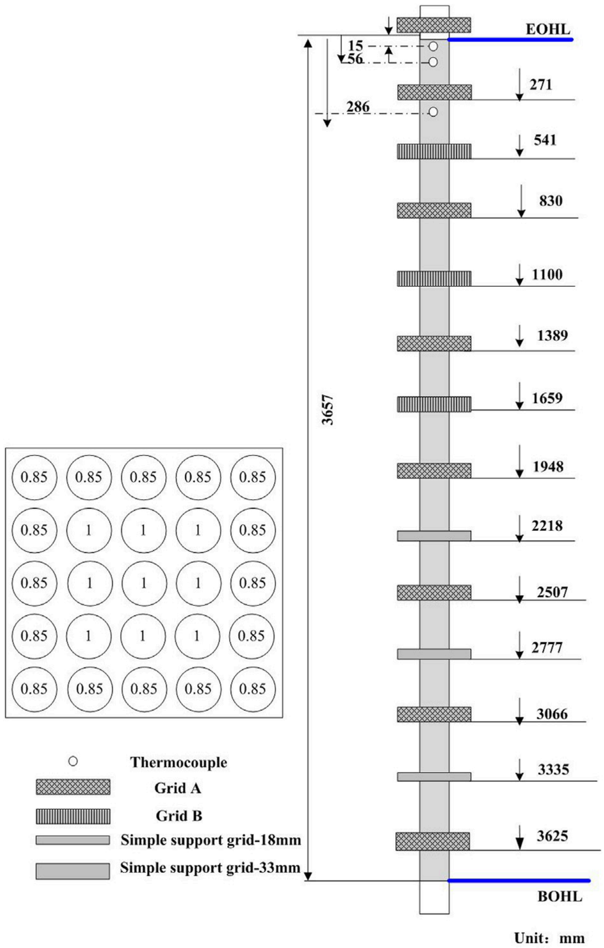

FIGURE 2
The schematic diagram of the test section.

of each heating rod. The locations of the grids and thermocouples are shown in Figure 2.

2.3 Test conditions

According to the CHF correlation development demands, a CHF test usually uses pressure, mass flux and quality as test controlling parameters. However, the local quality is not an independent parameter that can be directly measured and controlled. It is still necessary to convert the local quality into the inlet temperature of the test section for control. However, the inlet temperature cannot be calculated directly from the quality. It can only be obtained by iterative calculation with a subchannel code: under a certain pressure and mass flux, assuming an inlet temperature and heating power, the subchannel code is used to calculate the distribution of the quality, critical heat flux and the minimum departure from nucleate boiling ratio (MDNBR). It is generally impossible to be exactly critical. Then, according to the value of MDNBR, the heating power is adjusted. Through multiple iterations. The critical condition at the given inlet temperature is obtained. However, the quality under this critical condition cannot be exactly the predetermined quality in the test matrix. Therefore, it is necessary to change the inlet temperature to repeat the above iterative process until the quality reaches the predetermined value. This process not only requires a large amount of calculation, but also the calculated inlet temperature is very dispersed, and the inlet temperature is different under almost every condition. As a result, the inlet temperature needs to be adjusted once for each test condition during the test, which increases the workload and time of the test. In addition, the CHF correlation used in the pre-calculation has some error, so the local quality at the critical position during a CHF test condition actually cannot be exactly the predetermined quality. It means that it is practically impossible to carry out the CHF test accurately according to the predetermined quality.

In fact, the development of a CHF correlation requires not the critical heat flux under some certain exact quality, but within a certain quality range at appropriate intervals. Therefore, it is not necessary to pursue accurate control of quality. Under a certain pressure and mass flux, as long as the inlet temperature interval is appropriate, the interval of quality will be appropriate. Therefore, the inlet temperature can be directly used in the test matrix, which can greatly simplify the pre-calculation.

Therefore, in this research, the test matrix is a combination of different pressures, mass flux and inlet temperatures. In order to cover a wide quality range, the inlet temperature should cover 100°C–300°C with an interval of 50°C. According to the pre-calculation, when the interval of the inlet temperature is 50°C, the interval of the outlet quality will be nearly 0.03.

Finally, the range of test conditions in the research covered the outlet pressure of 2.8–15.5 MPa, the inlet mass flux of 845–3533 kg/(m^2·s), and the inlet temperature of 100–300°C, as shown in Figure 3.

2.4 Test method

The critical process is a transient process in a very short time. The parameters such as pressure, mass flux, quality, and wall

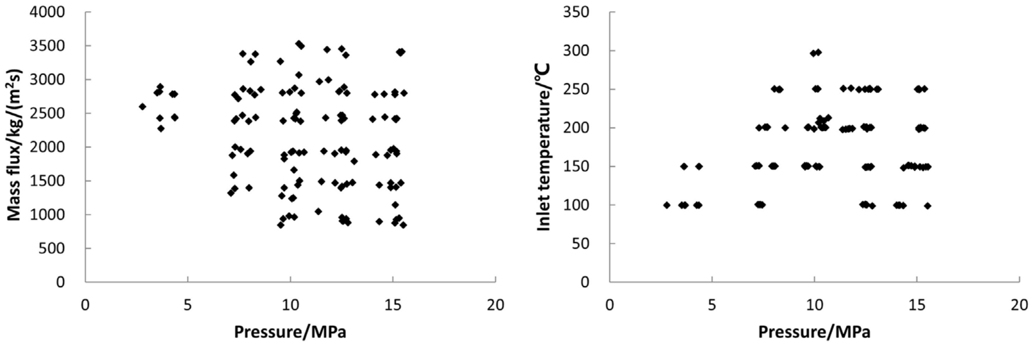

FIGURE 3
The test condition range.

temperature, cannot be stabilized in time, which leads to certain errors in the critical data. Generally, the method of continuously increasing the heating power is used to find the critical point, that is, the inlet temperature, mass flux and outlet pressure of the rod bundle are adjusted to the predetermined working condition, and remain stable as much as possible before the critical phenomenon occurs (Qin et al., 2016; Xie et al., 2018; Fighetti and Reddy, 1982). The rod bundle power starts to slowly increase from the safe value below the critical power, until a typical critical phenomenon occurs. However, in fact, after each power increase, the wall temperature, quality, and mass flux also need a period of transient change to reach a new stable state. This is because the external heat transfer state has not changed when the power is just raised, so the transferred heat is also unchanged. The increased power will cause the rod temperature to increase, and the temperature difference between rods and fluid will increase, so the transferred heat will gradually increase. Then the outlet quality increases, causing the resistance of the test section to increase slightly, so the mass flux will decrease slightly. Generally, the change of parameters will be slow down gradually, and eventually tend to be stable. Therefore, the method of continuously increasing the power makes the rod bundle always in a transient heat transfer process, and the parameters such as pressure, mass flux and quality are not stable, so the local parameter error at the critical point will relatively large.

Considering the above shortcomings, a method of stepwise rising the heating power to obtain the critical point has been adopted, that is, the heating power is slightly increased, then remain stable for a while until the wall temperatures of the rod bundle become stable. Repeat the course until critical heat flux is reached. Immediately, the heating power will be quickly reduced by 30% manually or automatically by control system to prevent the rods from burning out. The test process is shown in Figure 3. When the critical phenomenon occurs, at least one wall temperature of the rod bundle rises rapidly. Therefore, in the test, the critical criterion is that the rising rate of some wall temperature is greater than 10°C/s, or some wall temperature continuously rises above a given value, usually 500°C.

At the initial critical moment, the pressure, mass flux, quality and other parameters have not change, as shown in Figure 4, so it can be considered that they remain the value of the last stable state before the critical phenomenon happens. And the test method of stepwise rising the heating power can ensure the thermal parameter stability before CHF. Therefore, the local parameter errors at critical moment are relatively small. In this test method, the exact critical power should be between the two power levels before and after the critical occurrence, so the amplitude of the last power increase directly affects the CHF value. Therefore, when approaching critical, the amplitude of the power increase each time should be controlled within 50 kW to minimize measurement error of CHF value. For conservatism, the power flux of the last stable state before CHF is taken as the critical heat flux.

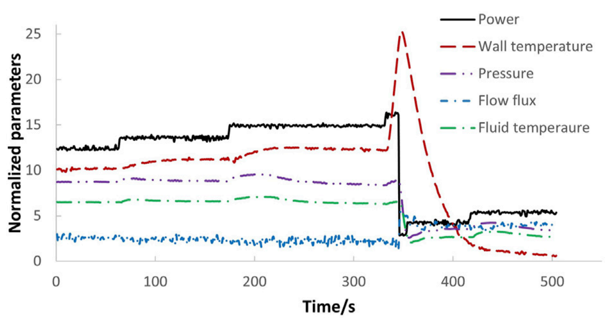

FIGURE 4
Typical curves of CHF process.

2.5 Data errors

CHF test data includes outlet pressure, inlet temperature, mass flux and critical heat flux. Among them, outlet pressure and inlet temperature of the test section are directly measured, and the measurement errors are calculated based on the instrument accuracies, as shown in Table 2. The mass flux and critical heat flux are indirectly obtained, and their errors are calculated based on error transfer function and the direct measurement quantities, including the inlet volumetric flow rate, test section voltage and current. Finally, CHF data errors are shown in Table 3.

TABLE 3 CHF data errors.

Parameter	Error (%)
Outlet pressure	0.06–0.36
Inlet temperature	0.05–0.15
Inlet mass flux	1.3–4.7
Critical Heat flux	0.24–0.42

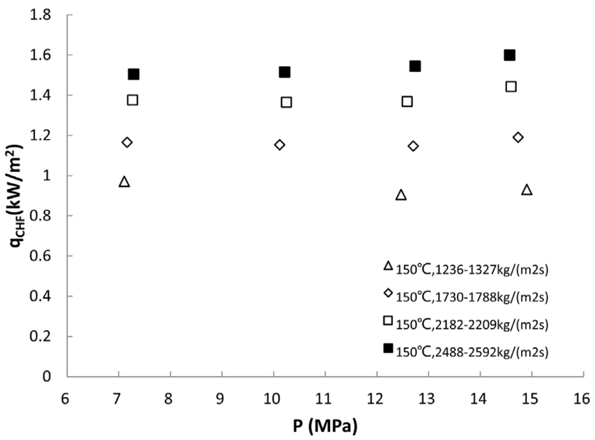

FIGURE 5
The influence of the local pressure on critical heat flux.

3 Result analysis

To analyze the thermal-hydraulic parameter influence on CHF, subchannel analysis code COBRA-EN was used to obtain the local thermal-hydraulic parameters of each test condition, including local pressure, mass flux and quality.

3.1 Pressure influence

Taking the local pressure at the critical point as the independent variable and the critical heat flux as the dependent variable, the influence of the pressure on critical heat flux can be obtained. Within the local pressure range of 7–15.5 MPa, taking the inlet temperatures of 150 ℃ as an example, the relationship between the critical heat flux and the local pressure was shown in Figure 5.

The results indicated that the deviation of CHF values at different pressures was within ±5% under the same inlet temperature and similar mass flux of the test section. Considering the control accuracy and measurement errors of parameters under different operating conditions, as well as the local parameter errors obtained by the subchannel analysis code, it could be considered that the critical heat flux values were almost the same under the same inlet temperature and mass flux within the test conditions.

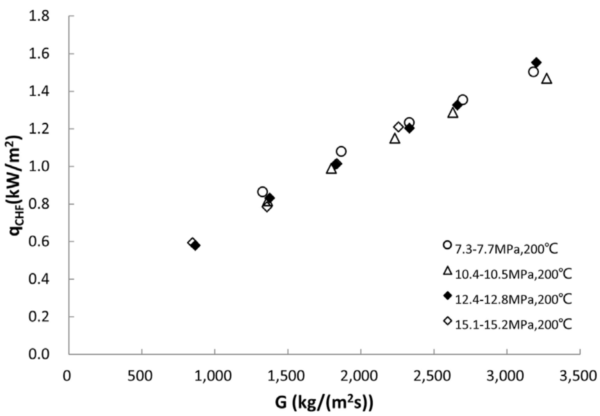

FIGURE 6
The influence of the local mass flux on critical heat flux.

3.2 Mass flux influence

The local mass flux was calculated by subchannel analysis code COBRA-EN. Take CHF values under the same inlet temperature and similar local pressure as a group data. Taking the local mass flux at the critical point as the independent variable and the critical heat flux as the dependent variable, the influence of local mass flux on the critical heat flux can be obtained. As shown in Figure 6, under similar local pressure and inlet temperature, the critical heat flux basically linearly increased with the increasing local mass flux. This was because in the nucleate boiling zone with the low quality, the increasing mass flux was more likely to take away the bubbles near the wall, and it was not easy to form a vapor film on the wall, thus the CHF value was increased.

By comparing the critical heat flux at different pressures but the same inlet temperature and mass flux in Figure 6, it can be concluded that the critical heat flux was hardly affected by the local pressure, which was the same as the conclusion in Section 3.1. Therefore, ignoring the influence of pressure, the critical heat flux value at the same inlet temperature within the range of 7–15.5 MPa can be taken as a group of data, and the relationship between local mass flux and CHF value can be obtained, as shown in Figure 7. It can be concluded that at the same inlet temperatures of the test section, ignoring the influence of pressure, the linear relationship between CHF and local mass flux was still valid.

In addition, it can be seen from Figure 7 that with the increase of mass flux, the CHF value under higher temperature conditions increased more slowly than that under lower temperature conditions. The analysis shows that with the same other inlet parameters, the higher the inlet temperature was, the higher the critical quality was. In low mass flux conditions, CHF decreased relatively slowly with the increasing quality, so the CHF value change is relatively small. While with the increasing mass flux, the quality influence on CHF became more strongly. Therefore, in large mass flux conditions, CHF value decreased relatively rapid with the increasing inlet temperature (or quality). From another perspective, with the increasing quality, the flow pattern in the rod bundle channels transited from bubbly flow to annular flow. In

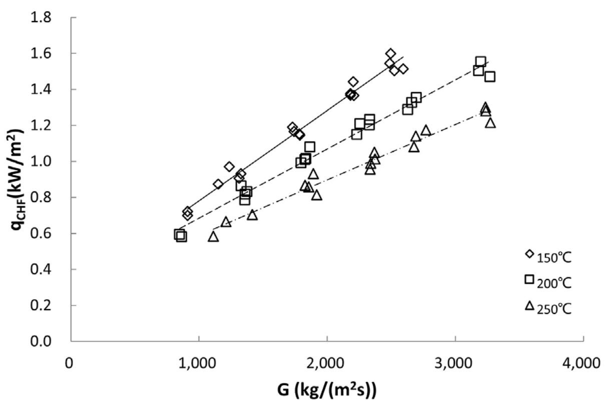

FIGURE 7
The influence of the local mass flux on critical heat flux at same inlet temperatures.

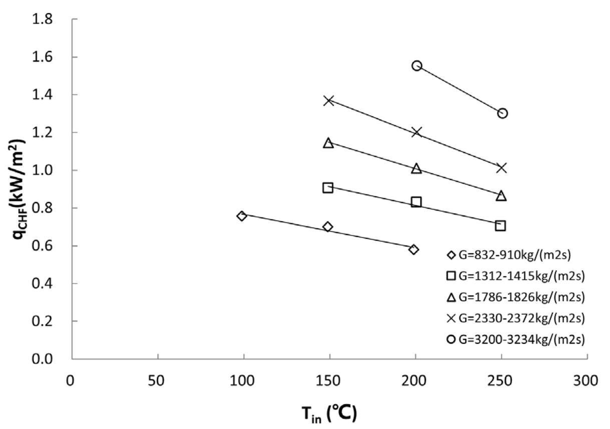

FIGURE 8
The influence of the inlet temperature on critical heat flux (p = 12.1–12.8 MPa).

bubbly flow, the increase of mass flux can enhance the flow disturbance, thereby improving CHF. In annular flow, the increase of mass flux tends to dry the liquid film on the heating wall, thus reducing CHF. Therefore, with the increase of inlet temperature, the enhancement of CHF with the increase of mass flux gradually weakens.

3.3 Inlet temperature influence

Take CHF values under similar local pressure and mass flux as a group of data. Taking the inlet temperature of the test section as the independent variable and the critical heat flux as the dependent variable, the influence of the inlet temperature on the critical heat flux can be obtained. As shown in Figure 8, under the similar local pressure and mass flux, the critical heat flux decreased linearly with the increasing inlet temperature. This was because the higher the inlet temperature was, the less heat was required to form a stable vapor film on the heating wall, resulting

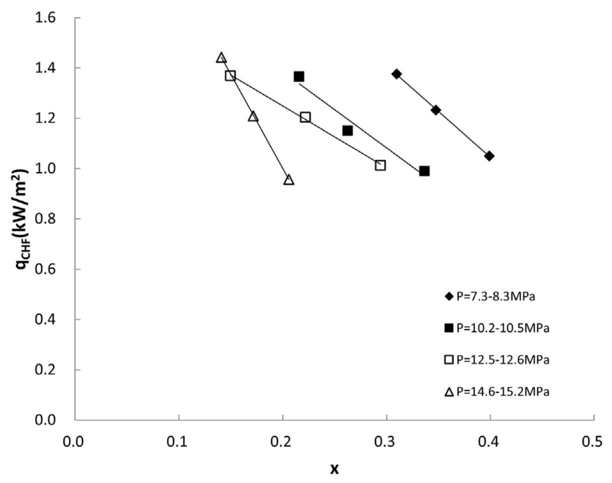

FIGURE 9
The influence of the local quality on critical heat flux (G = 2,200–2,300 kg/m^{2}s).

in a smaller CHF. And the decreasing trend became more rapidly with the increasing flow flux.

3.4 Quality influence

In the research, the local quality range covered 0.04–0.47. Take the CHF values under similar local mass flux and pressure conditions as a group of data. Taking the local quality as the independent variable, and the critical heat flux as the dependent variable, the influence of the quality on the critical heat flux can be obtained, as shown in Figure 9.

It can be seen from Figure 9 that under similar local pressure and mass flux, the critical heat flux decreased with the increasing local quality. This was because the higher the quality was, the more bubbles gathered near the rod wall, and the more likely the heat transfer deterioration will occur. Besides, in general, the higher the pressure was, the slower the CHF value decreased with the increasing quality. However, near 15 MPa, the critical heat flux value decreased rapidly with the increasing quality.

The test results also showed that the critical heat flux under high pressure was smaller than that under low pressure when the quality was the same. However, in the low-quality zone of 15 MPa, the CHF value was higher than that of 12.5 MPa. Under different mass fluxes, the qualities where the reverse trend happened were different. The analysis showed that, in the low-quality zone, with the increasing pressure, the vapor volume in the bubbly flow decreased, the contact area between the liquid phase and the wall increased, and the heat transfer was strengthened, so the CHF was improved.

Figure 10 showed the quality influence on critical heat flux under different mass flux when the local pressure was 7 MPa. It can be seen from the figure that under the same local quality and pressure, the critical heat flux in the high-quality zone decreased with the increasing mass flux, while in the low-quality zone, the critical heat flux increased with the increasing mass flux. This was because in the high-quality zone, the increasing mass flux was easy to dry the liquid film on the heating

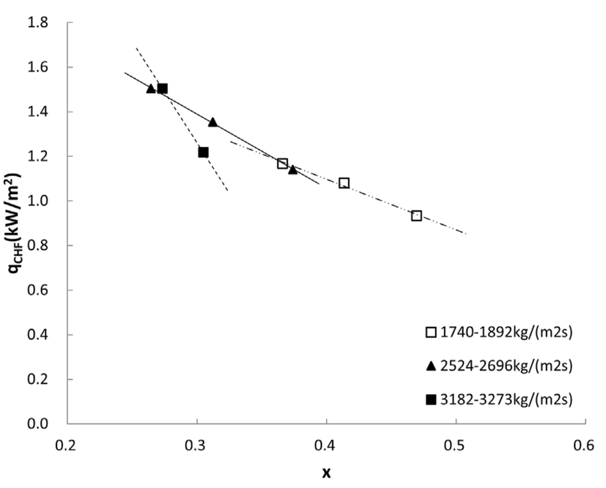

FIGURE 10
The influence of the local quality on critical heat flux (p = 7.2–8.3 MPa).

wall, thus reducing the CHF value. While in the low-quality zone, the increasing mass flux enhanced the flow disturbance, and the bubbles were easier to leave the heating surface, thus increasing the CHF.

In general, if the local quality is taken as the variable parameter, the influences of pressure and mass flux on the critical heat flux are complex. This is because the quality was not an independent variable and affected by pressure. In order to reflect such complex influences of thermal parameters, the correlation of critical heat flux with the local quality as independent variable needs to be relatively complex.

If the inlet temperature of the test section is taken as the variable parameter, the influences of the thermal parameters on CHF are simple. Compared to other thermal-hydraulic parameters, the critical heat flux is basically not affected by the pressure, and has a simple linear relationship with the mass flux and the inlet temperature. Therefore, a CHF correlation can be simplified as a function of the mass flux and the inlet temperature. Although the correlation developed in such form will be only applicable to specific test section structure and power distribution, and difficult to apply to the safety analysis of fuel assemblies, this can provide a new idea for the development of CHF correlations if we could find a way to connect inlet temperature or specific enthalpy with local quality.

4 Conclusion and future works

In the research, a 5 × 5 uniformly heated rod bundle CHF test has been performed by a test parameter control method of taking the inlet temperature of the test section as an independent variable. The test condition range was the outlet pressure of 2.8–15.5 MPa, the inlet mass flux of 845–3533 kg/(m^2·s), and the inlet temperature of 100–300°C.

The thermal-hydraulic parameter influences on critical heat flux at certain inlet temperatures have been obtained by analyzing the test results. It indicated that under the same inlet temperature of the test section, the critical heat flux was basically not affected by the pressure, and increased linearly with the increasing mass flux. Under the similar mass flux, CHF was decreased linearly with the increasing inlet temperature. With the increase of the inlet temperature, the enhancement of CHF with the increasing mass flux gradually weakened.

Compared with the local quality as the variable parameter, the influences of thermal parameters on CHF were relatively simple by taking the inlet temperature of the test section as the variable parameter. Therefore, it was conducive to simplifying the CHF correlation form to take the inlet temperature as the variable parameter instead of the local quality. Generally speaking, the research can provide new ideas for critical heat flux test, data analysis and the development of the CHF correlations.

In the future, CHF tests will be continued with different test sections for the purpose of expanding the range of quality to negative zone, and studying the axial power profile and cold wall influences on CHF. Meanwhile, a new correlation form will be studied by connecting inlet temperature or specific enthalpy with local quality.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

MD: Methodology, Project administration, Data curation, Formal Analysis, Writing–original draft. MZ: Methodology, Data curation, Formal Analysis, Writing–review and editing. JW: Data curation, Formal Analysis, Writing–review and editing. YX: Data curation, Writing–review and editing.

Funding

The authors declare that financial support was received for the research, authorship, and/or publication of this article. The research is supported by PWR Annular Fuel Pilot Assembly Development Project (CNNC[2021]251).

Acknowledgments

The authors wish to thank the CIAE CHF team who participated in the CHF test, including Kaiwen Du, Bing Yang, Wei Wang, Peng Liang, Dongxu Zhang, and Qingyuan Li.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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