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Original Article

Research on heat transfer coefficient of supercritical water based on factorial and correspondence analysis

Feng Xiang [a, b, c, *], Zhou Tao [a, b, c, **], Zhang Jialei [a, b, c], Zhang Boya [a, b, c], Ma Dongliang [a, b, c]

[a] School of Nuclear Science and Engineering, North China Electric Power University, Beijing, 102206, China
[b] Institute of Nuclear Thermal-hydraulic Safety and Standardization, North China Electric PowerUniversity, Beijing, 102206, China
[c] Beijing Key Laboratory of Passive Safety Technology for Nuclear Energy, North China Electric Power University, Beijing, 102206, China

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ABSTRACT

The study of heat transfer coefficient of supercritical water plays an important role in improving the heat transfer efficiency of the reactor. Taking the supercritical natural circulation experimental bench as the research object, the effects of power, flow, pipe diameter and mainstream temperature on the heat transfer coefficient of supercritical water were studied. At the same time, the experimental data of Chen Yuzhou's supercritical water heat transfer coefficient was collected. Through the factorial design method, the influence of different factors and their interactions on the heat transfer coefficient of supercritical water is analyzed. Through the corresponding analysis method, the influencing factors of different levels of heat transfer coefficient are analyzed. It can be found: Except for the effects of flow rate, power, power-temperature and temperature, the influence of other factors on the natural circulation heat transfer coefficient of supercritical water is negligible. When the heat transfer coefficient is low, it is mainly affected by the pipe diameter. As the heat transfer coefficient is further increased, it is mainly affected by temperature and power. When the heat transfer coefficient is at a large level, the influence of the flow rate is the largest at this time.

1. Introduction

The Supercritical Water Cooled Reactor (SCWR) is the only water-cooled reactor of the six four-generation reactors selected internationally, with many advantages such as economy, continuity and sustainability. Usually in the event of an accident, the supercritical water reactor will generate huge waste heat. The rate at which residual heat is removed from the core is related to the safety and stability of the reactor. The natural circulation can continuously derive the residual heat in the core and improve the inherent safety of the reactor. It is a main cooling method for the passive natural circulation reactor. In view of the heat transfer characteristics [1] of supercritical water reactors, researchers from various countries have conducted extensive and in-depth research in various aspects in the past 50 years. They carried out experimental research on heat transfer of supercritical water under various parameters. Mokry et al. [2] summarized the existing formulas related to supercritical hydrothermal transfer. He proposed a new dimensionless formula for supercritical hydrothermal transfer, and verified its accuracy. Wang Han et al. [3,4] experimentally studied the heat transfer coefficient and flow resistance in the supercritical water reactor subchannel, and he found that the test conditions of heat transfer deterioration are close to the Ogata relational prediction value. The lift force plays an important role in the occurrence of heat transfer deterioration. Manish Sharma et al. [5] built a closed supercritical pressure natural circulation experimental bench. The natural convection flow and heat transfer characteristics of supercritical water in a rectangular natural circulation loop were studied through experiments. The experimental parameters obtained were compared with the existing supercritical water flow heat transfer correlation calculation results. Ma Dongliang et al. [6] collected and analyzed the experimental data of supercritical water heat transfer coefficient. Based on the experimental data, a prediction model of supercritical water heat transfer coefficient based on BP neural network was established. The influence of changes in parameters such as pipe diameter, flow, power and pressure on the heat transfer coefficient of supercritical water was predicted and analyzed. At present, a single factor analysis method is used when studying the heat transfer coefficient of natural circulation of

* Corresponding author. School of Nuclear Science and Engineering, North China Electric Power University, Beijing, 102206, China.
** Corresponding author. School of Nuclear Science and Engineering, North China Electric Power University, Beijing, 102206, China.
E-mail addresses: 619085654@qq.com (F. Xiang), zhoutao@ncepu.edu.cn (Z. Tao).

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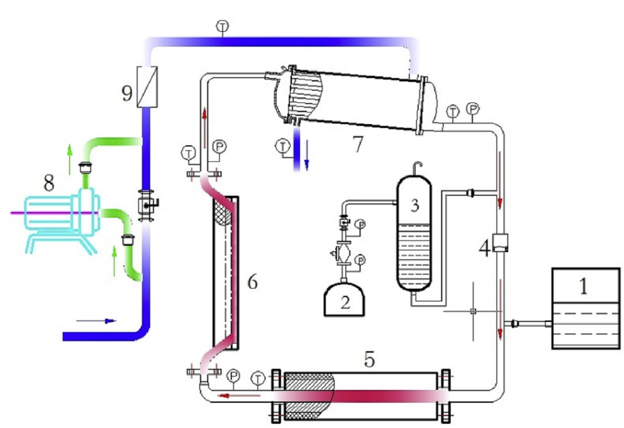
supercritical water. This method can only analyze the influence of individual factors on the experimental results, and cannot analyze the influence of interaction between various factors. However, interaction [7] may have an impact on the system in practical engineering. Factorial design [8] is a kind of experimental design. It refers to multiple factors (two or more) as the research object, and explores the main effects of various factors and the interaction between factors. If two or more factors interact, it means that the factors are not independent, the effect of one or more factors changes accordingly when the level of one factor changes; otherwise, if there is no interaction, it means that each factor is independent. When the number of factors and the number of levels are not too many, and the relationship between effects and factors is complex, factorial design is often recommended. Li Jingjing et al. [9] used the factorial analysis method to study the flow stability of supercritical water natural circulation, and obtained the influence of different factors on steady flow and pulsation period. Qi Shi et al. [10] studied the location of the ONB point of the narrow circular channel of the natural circulation based on the factorial analysis, and found that the inlet subcooling had the greatest influence on the position of the ONB point. In addition, the influence of each factor on the heat transfer coefficient is often only studied as a whole when studying the heat transfer coefficient of natural circulation of supercritical water. In actual engineering, the influence degree of each factor on the heat transfer coefficient is different at different stages. By studying the heat transfer coefficient of the natural circulation of supercritical water by the corresponding analysis method, the main factors that influence the heat transfer coefficient at each level can be obtained. Correspondence analysis method [11], also known as association analysis method, is a new multi-dependent variable statistical analysis technique developed in recent years. It reveals the relationship between variables by analyzing the interaction summary table composed of qualitative variables. It is possible to reveal the differences between the various categories of the same variable and the correspondence between the various categories of different variables. It is able to display several sets of data that have no visible connection, through visually acceptable positioning maps. The basic idea [12] of the corresponding analysis is to represent the proportional structure of each element in the row and column of a contingency table in the form of points in a lower dimensional space. Traditional factor analysis can only study the relationship between samples (Q-factor analysis) or between variables (R-factor analysis). In fact, there is often a relationship between samples and variables. Correspondence analysis can analyze samples and variables at the same time, which has become an important method to study the internal relations of multivariate. The advantage of the corresponding analysis method is that it can present simple and clear graphics when studying multiple categories of categorical variables, or a large number of categorical variables. The more the categories of qualitative variables are divided, the more obvious the advantages of this method are, and the way they are used is easy to grasp, and the interpretation of the data is relatively easy. Factorial and corresponding analysis can study the interaction and influence degree of factors affecting heat transfer coefficient, which is of great significance for understanding the heat transfer mechanism of supercritical water natural circulation.

2. Research object

2.1. Experimental device

The supercritical water natural circulation experimental device built by the team of the Institute of Nuclear Thermal Safety and Standardization of North China Electric Power University, where the author worked, is shown in Fig. 1.

It can be seen from Fig. 1 that the supercritical water natural circulation experimental device is composed of a preheating section, an experimental section, a condenser, a flow meter, a surge tank and related pipes, valves and measuring instruments. The test bench is 2.5 m high and 3.5 m wide, and the design pressure is 30 MPa. The secondary circuit has an outer diameter of 32 mm and an inner diameter of 22 mm. The length of the experimental section is 2 m, the outer diameter of the pipe is 12 mm, and the inner diameter is 4 mm. The experimental section is the main part of the whole experimental power source, which can heat the water to above 400 °C. In the experimental section, a total of nine K-type armored thermocouples were used for temperature measurement, which were placed on the wall of the experimental section, and the inlet and outlet of the test section, it was used to measure the wall temperature and the fluid temperature at the inlet and outlet of the experimental section with an accuracy of 0.1 °C. There are two pressure measuring points at the exit and entrance of the experimental section, which can measure the pressure value at the exit and the inlet with an accuracy of 0.01 MPa, and can calculate the pressure difference between the inlet and outlet. The heating power is 0kW–30kW, the accuracy is 0.1 kW, and the heating power is continuously adjustable. The preheating section can provide a part of the experimental power source, which uses parallel three-stage heating to heat the ultrapure water to above 280 °C. The natural circulation experimental device condenser is a shell-and-tube condenser, which is used to discharge the heat of the primary circuit fluid. The heat exchange area is 2 m^2, and the whole body adopts countercurrent cooling, which can cool the water from 400 °C to below 70 °C. The secondary circuit cooling water pump mainly supplies cooling water to the condenser, the protection grade is IP42, the cooling flow is 6 m^3/h, and the maximum indenter is 13 m. The cooling water tank mainly supplies cooling water to the secondary circuit system, and the cooling water tank has a diameter of 1.04 m and a height of 1.15 m. The regulator tank volume is 5L in the voltage regulator system. When the system pressure is increased, the nitrogen gas is discharged from the surge tank. When the system pressure is reduced, the booster pump is added with nitrogen to the surge tank to maintain the pressure stability. The tap water is treated by an ultrapure water machine to remove the salt and suspended matter, and it is fed into a storage



1. Deionized water tank 2. Nitrogen bottle 3. voltage stabilizer
4. Turbine flowmeter 5. Preheating section6. Experimental section
7. Condenser 8. Cooling water pump 9. Float flowmeter

Fig. 1. Supercritical water natural circulation experimental device.

tank. The working fluid enters the primary circuit through the feed pump during the experiment. The electrical system is mainly used for data monitoring and control of various systems, and it is an important part of the entire natural circulation experimental device, including parameter display instrument and parameter control button. The instrument data acquisition system collects data every second, and the data is displayed and recorded in real time through the instrument control cabinet.

2.2. Physical device

The supercritical water natural circulation experimental device and corresponding components are shown in Fig. 2.

2.3. Experimental parameters

The experimental data of the supercritical water natural circulation obtained by this experiment,and the collected experimental data of Chen Yuzhou [13,14] are shown in Table 1 below.

Wherein, the arithmetic mean of the inlet and outlet fluid temperatures of the experimental section is taken as the qualitative temperature of the fluid. For the convenience of analysis, the power, mainstream temperature, flow rate, and tube diameter effects are represented by letters A, B, C, and D, respectively. Then, the effect of interaction between power and mainstream temperature is AB; the effect of interaction between power and flow is AC; the effect of interaction between power and pipe diameter is AD; the effect of interaction between mainstream temperature and flow is BC; and the effect of interaction between mainstream temperature and pipe diameter is BD; the effect of interaction between flow and pipe diameter is CD. The effect of interaction between power, mainstream temperature and flow is ABC; the interaction of power, mainstream temperature and pipe diameter is ABD; the effect of interaction between power, flow and pipe diameter is ACD; the effect of interaction between mainstream temperature, flow and pipe diameter is BCD. The effect of total interaction of power, mainstream temperature, flow and pipe diameter is ABCD.

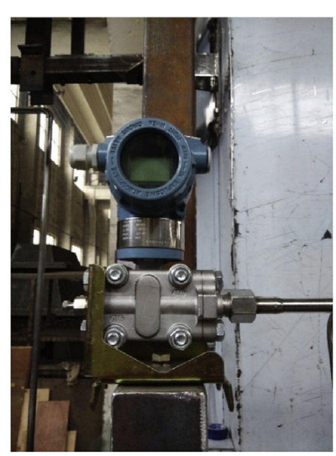
Table 1
Range of parameters.

Technical Parameters	This experiment	Chen Yuzhou
Pressure (Mpa)	25	25
Pipe diameter (mm)	4	10.89
Power (kW)	0–25	0–25
Mainstream temperature (°C)	150–400	120–380
Flow rate (g/s)	0–15	0–20
Heat transfer coefficient (W/m^{2}K)	2300–8900	1200–4500

a Supercritical water natural circulation physical device

b Supercritical water natural circulation control instrument cabinet

c Voltage Regulator System



d Differential pressure measurement system

Fig. 2. Experimental device physical map. **a** Supercritical water natural circulation physical device, **b** Supercritical water natural circulation control instrument cabinet, **c** Voltage Regulator System, **d** Differential pressure measurement system.

3. Calculation model

3.1. Factorial design

Factorial analysis refers to multiple factors (two or more) as the research object. The experimental factors are comprehensively combined to form different experimental conditions, and two or more independent experiments are performed under each experimental condition. The factorial analysis method can not only test the difference between the various levels of each factor, but also the interaction between the factors. A two-level test of k factors is recorded as 2^k factorial analysis (representing k factors, each with 2 levels). It is the most important design method, which can obtain more information with relatively small samples especially the interaction effect analysis. So the 2^k factorial analysis [9] is used to study the natural circulation heat transfer coefficient of supercritical water. The comparison of effect *AB…K* can be obtained by expanding equation (1).

$$(\text{Contrast})_{AB\ldots K}=(a\pm1)(b\pm1)\cdots(k\pm1) \tag{1}$$

In formula (1), $(\text{Contrast})_{AB\ldots K}$ represents a comparison of effects; a, b, and k represent respective factors. In expansion (1), it is calculated according to the elementary algebra method. In the last representation [1], is substituted for "1", which means that all factors take their low level. The symbols in the parentheses are selected by taking a negative sign when the factor is included in the effect and a positive sign when not. Once the effects are calculated, their estimated effects and their sum of squares can be calculated separately.

$$AB\cdots K=\frac{2}{2^k n}(\text{Contrast}_{AB\cdots K}) \tag{2}$$

$$SS_{AB\cdots K}=\frac{1}{2^k n}(\text{Contrast}_{AB\cdots K})^2 \tag{3}$$

Among them, *AB…K* represents the effect estimate, $SS_{AB\ldots K}$ represents the sum of squares of effects, n is the number of repeated experiments.

Taking the natural circulation heat transfer coefficient as the response value, the heat transfer coefficient (y) can be fitted as shown in formula (4).

$$y=\alpha_0+\sum\alpha_i x_i+\sum\alpha_{ij}x_i x_j+\sum\alpha_{ijk}x_i x_j x_k+\alpha_{1234}x_1x_2x_3x_4 \tag{4}$$

Among them, $\alpha0$、αi、αij、αijk、$\alpha1234$are respectively the mean, the effect of factor i, the effect of the interaction of factors i and j, the effect of the interaction of factor i and j and k, the effect of the interaction of four factors, *x* is the encoded value of the factor.

3.2. Correspondence analysis

Correspondence analysis method is a multivariate statistical method developed on the basis of R-type and Q-factor analysis. The basic principle of the corresponding analysis is to perform appropriate transformation on the two-dimensional data matrix. The transformed data corresponds to the row and the column, so that the row and the column can be analyzed simultaneously to find the relationship between the row and column factors. Correspondence analysis [15] uses the idea of dimensionality reduction to construct a transition matrix, and combines the covariance matrix of the original data with the similarity matrix. The eigenvectors and eigenvalues of the similar matrix are directly derived from the eigenvectors and features of the covariance matrix. Since these non-zero eigenvalues are the variances of the common factors, the same factor axis can be used to represent both the variable point and the sample point. The original data structure can be visually described by simultaneously representing the various states of the two types of attribute variables on a two-dimensional map. This is a multivariate statistical analysis method that combines R-factor analysis with Q-factor analysis.

Let the original data matrix be: $X=(x_{ij})_{n\times m}$, where x_{ij} is the ith sample, the observation of the jth quantity. i = 1,2,…,n; j = 1,2,…,m.

(1) X is summed by row and column respectively

$$T=\sum_{i=1}^{n}\sum_{j=1}^{m}x_{ij} \tag{5}$$

(2) Corresponding transformation of the original data x_{ij}, resulting in matrix $Z=(z_{ij})_{n\times m}$

$$z_{ij}=\frac{x_{ij}-x_{i.}x_{.j}/T}{\sqrt{x_{i.}x_{.j}}} \tag{6}$$

Among them, $x_{i.}=\sum_{j=1}^{m}x_{ij}, x_{.j}=\sum_{i=1}^{n}x_{ij}$(i = 1,2,…,n; j = 1,2,…,m).

(3) Perform R-factor analysis

Calculate the eigenvalue $\lambda_1\geq\lambda_2\geq\ldots\geq\lambda_m$ of the covariance matrix ZZ', according to the cumulative contribution rate ≥ 75%, 80%, 85%, etc., take the first p eigenvalues, and calculate the corresponding unit eigenvectors $U_1,U_2,\ldots,U_P$, and obtain the R-type factor load matrix:

$$F=\left(U_1\sqrt{\lambda_1},U_2\sqrt{\lambda_2},\cdot\cdot\cdot,U_p\sqrt{\lambda_p}\right) \tag{7}$$

$$\text{Expanded as: } F=\begin{bmatrix}u_{11}\sqrt{\lambda_1} & u_{12}\sqrt{\lambda_2} & \cdots & u_{1p}\sqrt{\lambda_p}\\ u_{21}\sqrt{\lambda_1} & u_{22}\sqrt{\lambda_2} & \cdots & u_{2p}\sqrt{\lambda_p}\\ \vdots & \vdots & & \vdots\\ u_{n1}\sqrt{\lambda_1} & u_{n2}\sqrt{\lambda_2} & \cdots & u_{np}\sqrt{\lambda_p}\end{bmatrix}$$

A variable scatter plot is made on the two factor axis planes.

(4) Perform Q-factor analysis

Calculate the unit eigenvector of the matrix ZZ' from p eigenvalues$\lambda_1\geq\lambda_2\geq\ldots\geq\lambda_p$, $V_1=ZU_{1(m\times1)}$,$V_2=ZU_2,\ldots,V_p=ZU_p$, and obtain the Q-factor load matrix:

$$G=\left(V_1\sqrt{\lambda_1},V_2\sqrt{\lambda_2},\cdot\cdot\cdot,V_p\sqrt{\lambda_p}\right) \tag{8}$$

$$\text{Expanded as: } G=\begin{bmatrix}v_{11}\sqrt{\lambda_1} & v_{12}\sqrt{\lambda_2} & \cdots & v_{1p}\sqrt{\lambda_p}\\ v_{21}\sqrt{\lambda_1} & v_{22}\sqrt{\lambda_2} & \cdots & v_{2p}\sqrt{\lambda_p}\\ \vdots & \vdots & & \vdots\\ v_{n1}\sqrt{\lambda_1} & v_{n2}\sqrt{\lambda_2} & \cdots & v_{np}\sqrt{\lambda_p}\end{bmatrix}$$

A sample scatter plot is made on the factor plane corresponding to the R type.

4. Experimental result

The system pressure of both experiments was maintained at around 25 Mpa, and the power was controlled in the range of 0–25 Kw. The change of mainstream temperature with power is shown

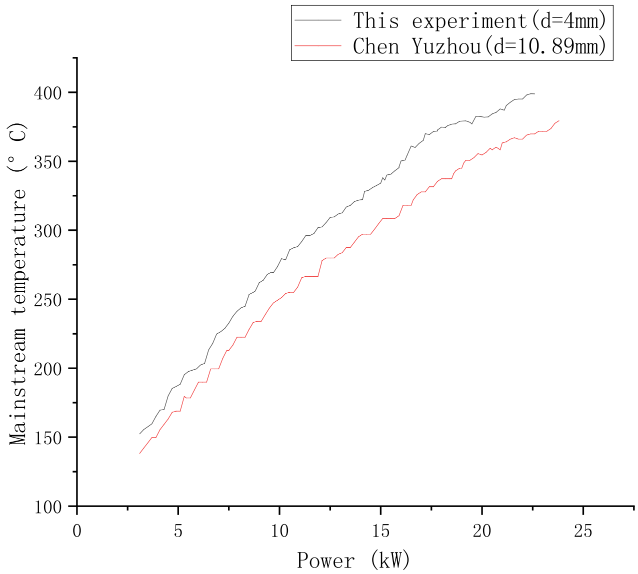


Fig. 3. The effect of power on fluid temperature.

in Fig. 3. The flow changes with power as shown in Fig. 4. The change of heat transfer coefficient with power is shown in Fig. 5.

It can be seen that the fluid temperature increases with increasing power, and the fluid temperature of the small pipe diameter is higher than the fluid temperature of the large pipe diameter. The flow increases first and then decreases as the power increases. For a 4 mm pipe diameter, the flow has an oscillating region as the power changes. There is a threshold in the effect of power on the heat transfer coefficient. Under the current experimental conditions, the power of the 4 mm pipe diameter has a threshold of about 14.8 Kw. At the same power, the heat transfer coefficient of the small pipe diameter is better than the large pipe diameter, which indicates that the reduction in size enhances the heat exchange process in the channel.

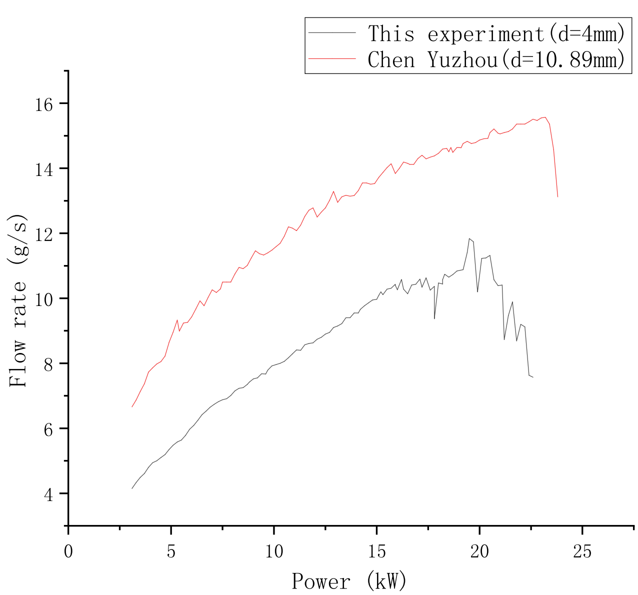


Fig. 4. The effect of power on flow rate.

5. Factorial analysis results

5.1. Factor impact

Through formula (1) - (3), the estimated effects of each factor and the interaction between the effects can be derived. The semi-normal probability distribution of the effect estimates is shown in Fig. 6.

In Fig. 6, the negligible effects are normally distributed, and they roughly fall near a line on the graph. Significant effects will not fall near this line. In addition to the effects of effect C, effect A, effect AB and effect B, other effects can be ignored in the influence of the natural circulation heat transfer coefficient of supercritical water. Effect C deviates the farthest from the straight line, Effect C deviates the farthest from the straight line, which indicates that it has the greatest impact. The percentage contribution rate is obtained by the ratio of the sum of the squares of the effects to the total sum of squares. It represents the degree of dependence between the influencing factors and the response. The contribution rate of different influencing factors can be calculated by equation (3). It can be obtained that the effect C has the largest contribution rate to the heat transfer coefficient, which is about 43.6%. The contribution rate of the effect A to the heat transfer coefficient is about 21.9%. The contribution rate of the effect AB to the heat transfer coefficient is about 17.5%. The contribution rate of the effect B to the heat transfer coefficient is about 11.7%. This is because the size of the circulating flow can significantly affect the heat transfer between the medium and the pipe wall, so the flow rate becomes the most closely related parameter to the heat transfer coefficient in the natural circulation of the supercritical water. In the natural circulation of supercritical water, there is no boiling state in which the working fluid changes from liquid to vapor. The power has a threshold. When the power is less than the threshold, increasing the power will obviously improve the heat exchange effect; otherwise, the heat exchange tends to deteriorate. Compared with subcritical, the effect of power in supercritical is weakened, which becomes the second largest factor affecting heat transfer coefficient. The physical properties of the working fluid are hardly affected by the pipe diameter, so the influence of the pipe diameter on the heat transfer coefficient is weak.

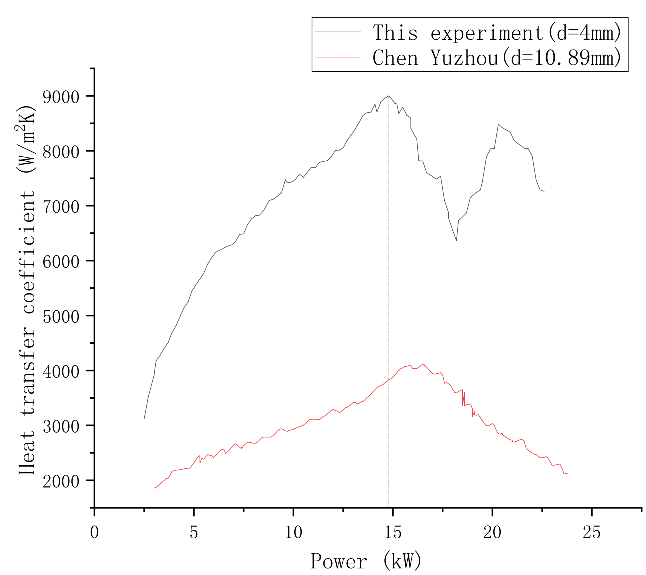


Fig. 5. The effect of power on heat transfer coefficient.

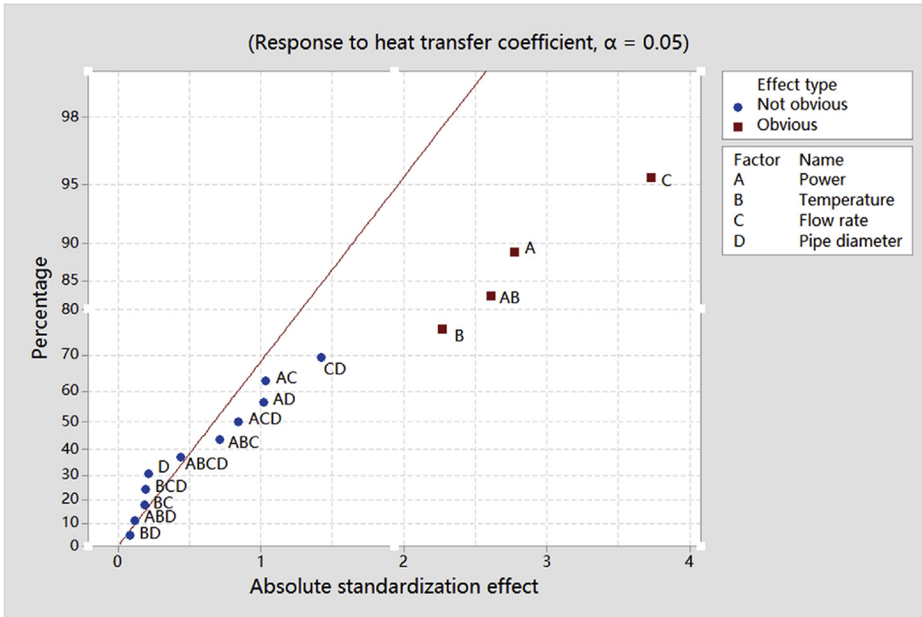


Fig. 6. Effect half-normal probability.

5.2. Factor interaction

The effect of factor interaction on the heat transfer coefficient of natural circulation of supercritical water is shown in Fig. 7.

In Fig. 7, the effect of factor interaction on the heat transfer coefficient of the natural circulation of supercritical water can be seen. When the individual effect of a factor changes with the level of another factor, and the difference between them exceeds the range of random fluctuations, there is an interaction between the two factors. In the interaction diagram, it is embodied that if two lines intersect, it means that there are interactions between the two factors; if the two lines are parallel, it means that the interaction of the two factors is small. In the AB, AC, AD, BC, BD, and CD interaction diagrams, only the two lines in the AB diagram intersect, and the other lines are approximately parallel. So it can be concluded that there is interaction between AB, and other interactions such as AC, AD, BC, BD, and CD can be ignored. Mainly because the relationship between power and temperature is more complicated, and the change in temperature will follow the change in power. At low power and high power, the effect of temperature change on the heat transfer coefficient is different, so there is a coupling between the two.

5.3. Regression analysis

The prediction model of the heat transfer coefficient can be obtained by formula (4). As can be seen from the semi-normal probability of Fig. 6, except for the effects of power, temperature, flow rate, and power-temperature, the influence of other factors on the natural circulation heat transfer coefficient of supercritical water is negligible. Therefore, formula (4) is simplified to formula (9):

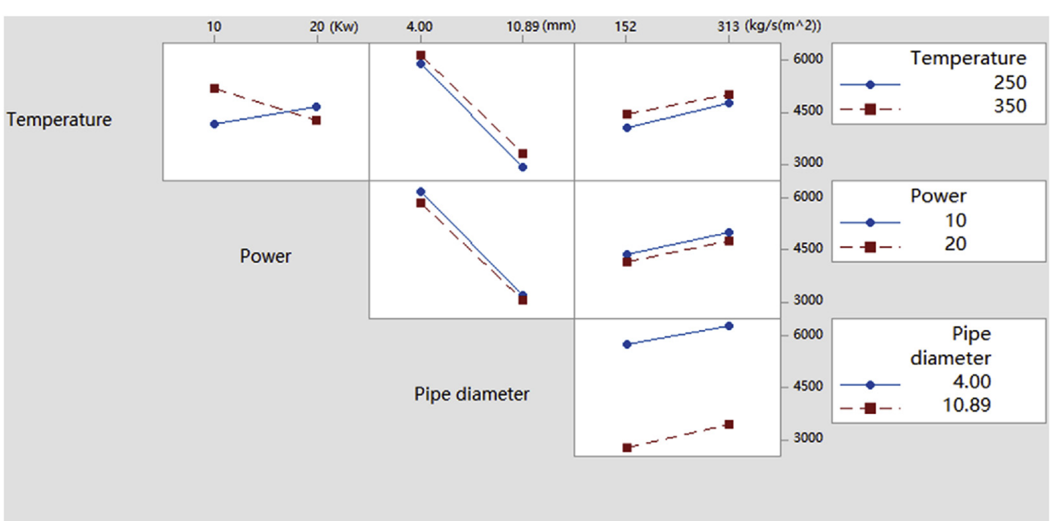


Fig. 7. Interaction of factors.

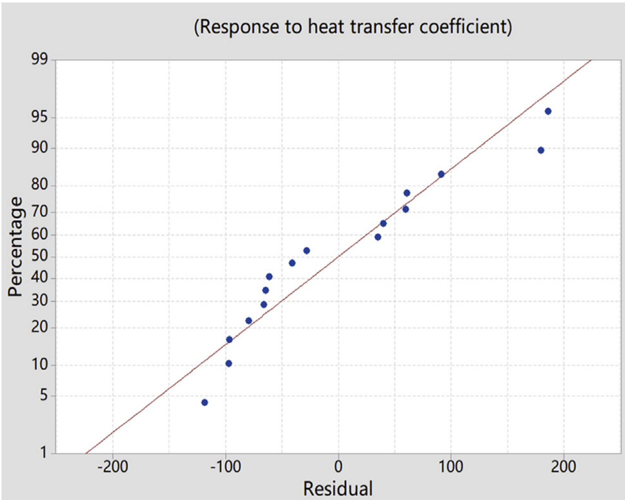


Fig. 8. Residual probability.

$$y = 2974 + 322.7x_1 + 7.391x_2 + 1805x_3 - 5.09x_1x_2 \tag{9}$$

The residual probability distribution is shown in Fig. 8, and the predicted residual distribution is shown in Fig. 9.

In Figs. 8 and 9, it can be checked whether the error obeys a normal distribution. In the analysis of variance of factorial design, the experimental results have a basic assumption of normality. The residual test is an indispensable part of any variance analysis. If the model is suitable, the residual is amorphous. It can be seen from Fig. 8 that the residual value falls on a straight line with a mean of 0 and a variance of σ^2, which conforms to the assumption of normality. According to Fig. 9, the experimental value and the predicted value are not much different, and the prediction error is 8.4%. The reliability of the factor analysis results is further proved by the two figures.

6. Correspondence analysis results

6.1. Number of components

Minitab is a statistical analysis software, which is favored by mass quality scholars and statistical experts with its unparalleled

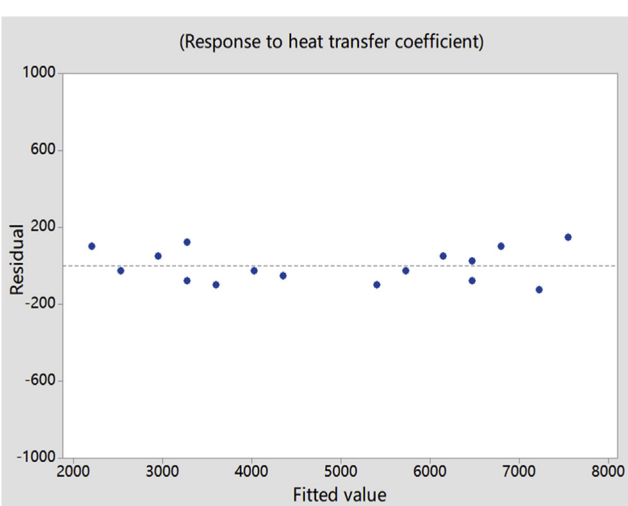


Fig. 9. Predicted values and residuals.

Table 2
Inertia and ratios for different dimensions.

Axis	Inertia	Ratio	Accumulate
Axis 1	0.1391	0.8125	0.8125
Axis 2	0.0315	0.1840	0.9965
Axis 3	0.0006	0.0035	1.0000

powerful functions and simple visual operation. Substituting the data in Table 1 into minitab, the correspondence between row and column factors can be obtained. The inertia and ratio of different dimensions are shown in Table 2.

From Table 2, we can see the decomposition of the total inertia. The contribution of each cell to the chi-square statistic is displayed as the chi-square distance, and the chi-square value in the cell is divided by the total frequency of the contingency table to obtain the cell inertia. The row inertia is the sum of the cell inertias of the rows, and the column inertia is the sum of the cell inertias of the columns. The sum of all cell inertias is the total inertia, which is the inertia. The table gives a summary that decomposes a 20 × 5 contingency table into three components. Using ratios and cumulative ratios can help determine the number of components that explain most of the total inertia. Ideally, two or three components account for most of the ratio of the total inertia. In Table 2, the heat transfer coefficient and the chi-square test of each factor are significant, which indicates that there is a correlation between the two. In the total inertia, the first dimension explains 81.15% of the amount of information, the second dimension explains 18.40% of the amount of information, the third dimension explains 0.35% of the amount of information. The first two dimensions cumulatively explain 98.6% of the total amount of information, which explains most of the information between the two, the role of the third dimension can be omitted. Therefore, a two-dimensional scatterplot can be used to reveal the relationship between heat transfer coefficient and various influencing factors.

6.2. Two-dimensional correspondence analysis

Using the Minitab software, the two-dimensional correspondence analysis obtained by the two components is shown in Fig. 10.

A symmetry diagram is a coordinate graph of the rows and columns of a joint display. The advantage of this figure is that the profile is unfolded, so it can better see the distance between them. The line spacing and the column spacing are approximate chi-square distances (χ^2) between the corresponding profiles. Through the symmetry diagram, you can find the relationship between row categories, and the relationship between column categories. It is also possible to interpret the principal components associated with the row or column category. Each categorical variable is presented in a dimensional space in a point manner to form a corresponding analysis graph. The red circles are used to plot the row points, and the blue squares are used to plot the column points. The origin represents the center of the average distribution, and the point far from the origin indicates that the category has greater influence. The two variables are close to each other, which indicates a similar distribution. The closer the distance is, the stronger the correlation is; otherwise, the weaker the association. It can be seen from Fig. 10 that the distribution of the four types of influencing factors is relatively dispersed, which indicates that there is a significant difference in the influence of the non-factors on the heat transfer coefficient. Component 1 causes the column class flow to be opposite to the sign used by the column class power, which forms a comparison; the column class pipe diameter is furthest from the origin, and component 2 best explains the pipe diameter.

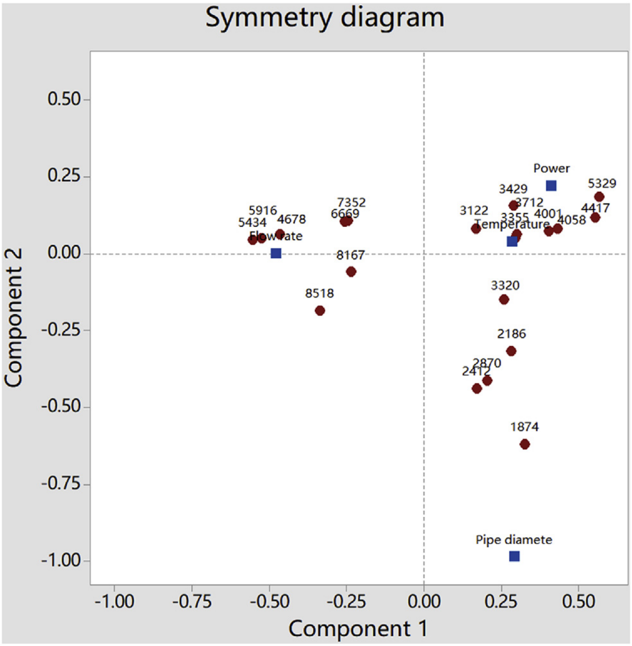


Fig. 10. Two-dimensional correspondence analysis.

The heat transfer coefficient obtained by the two sets of experiments is between 0 W/m^2K and 9000 W/m^2K, which is divided into three levels according to the range of heat transfer coefficient. Among them, the low-level heat transfer coefficient (0–3000W/m^2K) and the pipe diameter are both in the fourth quadrant, which has a relatively strong correlation. The temperature and power factors and the medium-level heat transfer coefficient (3000–6000W/m^2K) are close to each other, so they are closely related. High-level heat transfer coefficients (6000–9000W/m^2K) are almost concentrated near the flow, which shows that the relationship is significant. Therefore, when the heat transfer coefficient is low, changing the diameter of the pipe has the most significant effect on improving the heat transfer coefficient. The heat transfer effect is most beneficial by the combination of temperature and power when the heat transfer coefficient is further increased. By increasing the circulation flow rate before the heat transfer coefficient reaches the peak value, it is best to improve the heat transfer effect of the circulation loop.

7. Conclusion

Using the method of factorial and correspondence analysis, the heat transfer coefficient of supercritical water natural circulation is analyzed, and the influence of power, flow, pipe diameter and mainstream temperature on the heat transfer coefficient of supercritical water is obtained.

(1) In the influence of the natural circulation heat transfer coefficient of supercritical water, the percentage contribution of effect C(flow rate) to heat transfer coefficient is 43.6%. The percentage contribution of effect A(power) is 21.9%. Then the effect of effect AB(power-temperature) to the heat transfer coefficient is 17.5%. The contribution of effect B(temperature) is about 11.7%.
(2) In addition to the interaction AB((power-temperature) of the natural circulation heat transfer coefficient of supercritical water, the contribution of other interactions is negligible. Therefore, it is necessary to comprehensively consider the power and temperature factors when improving the heat transfer coefficient. The normality of the calculation results is tested. The residuals conform to the assumption of normality, and the prediction error is 8.4%, which further proves the reliability of the factor analysis results.
(3) Using the minitab software, two-dimensional scatter plots are used to reveal the relationship between heat transfer coefficient and various influencing factors. When the heat transfer effect is poor, it is most effective to first change the pipe diameter. Then, by the combination of power and temperature, there is a significant increase in the heat transfer coefficient. After that, the heat transfer coefficient is most affected by changing the flow rate.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.net.2019.12.017.

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