Optimization of phase change heat exchanger based on RSM

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Abstract. A tube phase change heat storage unit with fins was designed and optimized by multi-objective optimization method based on response surface method. Taking the temperature of phase change material (PCM) at a certain time as the optimization index, the effect of the relative position between the outer wall of the inner tube and the inner wall of the intermediate tube on the heat exchanger performance is mainly considered. The angle of the inner tube outer wall fin, the angle between the two fins on the outer wall of the inner tube and the angle of the fin on the inner wall of the outer tube are the three influencing factors. The optimum parameters are as follows: angle A = 7.09 °, angle B = 40.06 ° and angle C = 45 ° and the best result is obtained when the relative position of inner and outer fins is about 40 °and the optimization result is increased by 6.4%. The results show that the fitting accuracy of the regression model is as high as 97%, which shows that the results are reliable.

1. Introduction

CO₂ heat pump water heater is a very effective method to preheat domestic water in advance. Since sensible heat storage requires a lot of energy storage materials and space, the latent heat storage of PCM is now commonly used.

MAT S et al. [1] studied the effects of three different fin placement positions, namely: internal fins, external fins and internal-external fins. The results show that when the PCM is heated from the internal and external at the same time, the rate has increased by 43% compared to the non-fins. LI G [2] mentioned that the design parameters and structural parameters will affect the performance of the latent heat storage heat exchanger.

Common phase-change heat exchanger documents have improved the angle of the fins on the outer wall of the inner tube, and the influence of the length, thickness, and number of the fins on the phase change process. However, the relative position and angle between the fins on the outer wall of the inner tube and the inner wall of the outer tube have little research on the phase change process. When designing a heat exchanger with fins, the influence of the relative position of the two fins on the heat exchange rate and heat exchange effect of the phase change unit should also be considered. This paper it is mainly to study the influence of the relative position of the internal and external fins and optimize its structure.
2. Numerical simulation of phase change thermal storage unit

2.1. Physical model and numerical model

At present, there are few theoretical calculation studies on the multi-inner tube-in-tube heat exchanger in the existing research. Therefore, the traditional heat exchanger method cannot be used to design and calculate the phase change heat exchanger. For most of the existing simulation and experimental studies, non-standard sizes are used. When considering practical applications, the specified standard sizes should be used [3]. According to the reference standard and actual manufacturing requirements and considering that the experimental environment is under transcritical pressure conditions. Therefore, the American standard copper tube size method [4] is adopted, and the TYPE-K type is selected. The inner diameter of the inner tube is 49.76 mm, the outer diameter is 53.98 mm, and the thickness is 2.11 mm. The inner diameter of the middle tube is 145.82 mm, the outer diameter is 155.58 mm, and the thickness is 4.88 mm. The length of the fins is 30mm and the thickness is 2mm. The inner tube, middle tube and fins are all made of copper.

Considering that the actual application of heat pumps is usually to heat water from room temperature to the temperature used in households, RT42 is selected as the phase change material, and the thermophysical properties are shown in Table 1.

| Properties                  | Symbol | Value        |
|-----------------------------|--------|--------------|
| Melting temperature         | $T_l$  | 311 K        |
| Freezing temperature        | $T_s$  | 310 K        |
| Latent heat of melting      | $L$    | 174000 J·kg⁻¹|
| Specific heat capacity      | $C_p$  | 2000 J·kg⁻¹K⁻¹|
| Thermal conductivity        | $k$    | 0.2 W·m⁻¹K⁻¹|
| Density                     | $\rho$ | 760 Kg·m⁻³   |
| Coefficient of expansion    | $\beta$| 0.0006 1·K⁻¹|

According to the calculation formula (1) of the heat storage capacity of the heat exchanger, and mentioned in the previous research by LIU F et al. [5], the maximum heat storage capacity of this experimental platform is 22.157 MJ. The calculation can be obtained, under the same initial conditions, it can be calculated that the heat storage phase change material is 110 L. The phase change heat storage volume is 62.4% of the heat exchanger of the traditional transcritical CO₂ heat pump system, and the volume is reduced by 37.6%.

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Q = Q_{Solid\ state\ sensible\ heat} + Q_{Latent\ heat} + Q_{Liquid\ sensible\ heat} \tag{1}
\]

2.2. Structure optimization of phase change heat storage unit

Consider the relative position of the fins of the outer wall of the inner tube and the inner wall of the outer tube, and the influence of the angle between the two walls and the angle of the fins of the outer wall of the inner tube on the simulation results. The structure when A=0°, B=30°, C=0° is shown in Figure 1.

This paper uses Design-Expert professional software to carry out experimental design and data analysis. The optimization method uses the response surface method (RSM). The multiple quadratic regression equation is used to fit the functional relationship between the factors and the response value, and the regression equation is analyzed to find the best process parameters. The optimized objective function is the temperature value reached by the PCM at 1500s. The design variables are the angle of the fins on the outer wall of the inner tube, the angle between the two fins on the outer wall of the inner tube, and the angle of the fins on the inner wall of the outer tube.

BOX-Behnken Design (BBD) is the most commonly used method of experimental design in response surface methodology. The main steps are analyze the experimental design, arrange the experiment, obtain experimental data, response surface analysis (BBD adopts nonlinear fitting) to obtain the fitting
equation, use the response surface optimization method to obtain the optimal value, verify the optimal conditions through experiments.

Figure 1. Structure of heat storage unit

2.3. Establishment of optimization model

This experiment uses a 3-factor, 3-level BBD design. The three factors are the angle of the fins on the outer wall of the inner tube (A), the angle between the two fins on the outer wall of the inner tube (B), the angle of the fins on the inner wall of the outer tube (C). The design factor level is shown in Table 2, and the numerical simulation results obtained according to the experimental plan are shown in Figure 2.

Table 2. Factor levels of Box-Behnken design

| Level | A      | B      | C      |
|-------|--------|--------|--------|
| +1    | 45°    | 45°    | 90°    |
| 0     | 22.5°  | 37.5°  | 67.5°  |
| -1    | 0°     | 30°    | 45°    |

Figure 2. Numerical simulation results of test scheme

2.4. Optimization results and analysis

2.4.1. Significance analysis of the model. Perform variance analysis on the optimized model, and the analysis results are shown in Table 3. If P<0.05 is marked as significant, it can be seen from Table 3 that the optimization model is significant, that is, the fitting equation is significant. At the same time, it can be seen that the interactions of the primary and secondary terms of factor B, the quadratic term of factor A, and the interaction of factors AC are all significant, which have a greater impact on the test results. In the design of phase change thermal units with internal and external fins, it should be considered, and the significant effect of factor B is also consistent.
2.4.2. Model accuracy analysis. Whether the constructed response surface model can replace the real model for multi-objective parameter optimization can be determined by analyzing the fitting accuracy of the regression model. The coefficient $R^2$ and the correction coefficient $R_{adj}^2$ and the standard deviation S are usually used to test the fitting accuracy of the prediction model. The closer $R^2$ and $R_{adj}^2$ are to 1, the smaller the S, the higher the fitting accuracy of the regression model. The accuracy analysis of the optimized model is shown in Table 4. It can be seen that the accuracy of the quadratic equation regression model is better than the linear model and the two-factor model, and it is recommended to use it, so the established regression equation is reliable. The polynomial quadratic regression fitting is used to analyze the test data, and the actual response surface function is:

$$\text{Temperature} = +32.89125 - 0.072389 \times A + 1.21100 \times B - 0.014389 \times C - 4.14815 \times 10^{-4} \times A \times B + 2.68148 \times 10^{-3} \times A \times C - 2.96296 \times 10^{-4} \times B \times C - 2.23457 \times 10^{-3} \times A^2 - 0.014911 \times B^2 - 2.88889 \times 10^{-4} \times C^2$$

(2)

| Source of Variance | Sum of squares | Degree of freedom | Mean square | F Value | P Value | Significance |
|--------------------|----------------|------------------|-------------|---------|---------|-------------|
| Model              | 16.33          | 9                | 1.81        | 17.55   | 0.0028  | Significant |
| A                  | 0.23           | 1                | 0.23        | 2.2     | 0.1978  |             |
| B                  | 1.8            | 1                | 1.8         | 17.46   | 0.0087  |             |
| C                  | 0.070          | 1                | 0.070       | 0.68    | 0.4471  |             |
| AB                 | 0.020          | 1                | 0.020       | 0.19    | 0.6814  |             |
| AC                 | 7.37           | 1                | 7.37        | 71.31   | 0.0004  |             |
| BC                 | 0.010          | 1                | 0.010       | 0.097   | 0.7683  |             |
| A$^2$              | 4.73           | 1                | 4.73        | 45.71   | 0.0011  |             |
| B$^2$              | 2.6            | 1                | 2.6         | 25.13   | 0.0041  |             |
| C$^2$              | 0.079          | 1                | 0.079       | 0.76    | 0.4221  |             |
| Residual           | 0.52           | 5                | 0.1         |         |         |             |
| Sum                | 16.84          | 14               |             |         |         |             |

Table 3. Significance analysis of the regression model developed

| Standard deviation | R$^2$       | R$^2$ Correction value |
|--------------------|-------------|------------------------|
| Linear model       | 1.16        | 0.1249                 | -0.1138    |
| Two-factor         | 0.96        | 0.5642                 | 0.2374     |
| Quadratic equation | 0.32        | 0.9693                 | 0.9141     | Recommended |

Table 4. Accuracy analysis of regression model

The comparison between the test results predicted by the quadratic regression model and the actual test results is shown in Figure 3. According to the calculation, the absolute error between the true value and the predicted value of the 15 tests is less than 0.7%, indicating the predictive effect of the regression model better, the error is smaller.

2.4.3. Contour analysis of influencing factors. The response surface relationship of the three influencing factors on the melting temperature is shown in Figure 4. It can be seen from the graphs a and b that the melting temperature increases with the decrease of the angle C, and the angle B first increases and then decreases small. There is no obvious rule for the angle A, which may be because when the angle B is fixed, although there are two different angles A, they still have the same relative position relationship with the different angle C, which will produce a closer result. Figure 4-a is the interactive response surface when the angle A is around 5°, and the highest temperature can be seen at this time. Figure 4-b is the interactive response surface when the angle B is around 40°, and the highest temperature can be seen at this time temperature. Figure 4-c is the interactive response surface when the angle C is about 45°. At this time, it can be seen that the highest temperature occurs.
Figure 3. Comparison of actual and predicted values

Figure 4. Response surface graph of influence factors

2.5. Optimization and confirmatory test

The premise of using the response surface method to optimize is that the designed test points should include the best test conditions. If the test points are not selected properly, the response surface method optimization can not get good optimization results. According to the interactive response surface and data analysis between the parameters, in the range of influencing factors $0^\circ<A<45^\circ$, $30^\circ<B<45^\circ$, $45^\circ<C<90^\circ$, and use response surface software to perform design variables optimizing to determine the maximum value of the objective function, the best structural parameters are angle $A=7.09^\circ$, angle $B=40.06^\circ$, angle $C=45^\circ$, and the predicted maximum temperature is 55.82°C.
Based on the optimized parameters, the model was verified in FLUENT, and the experimental results are shown in Figure 5. At 1500 s, the temperature of PCM is 55.69 °C, and the error from the predicted value is 0.23%. Within the error range of the prediction model, the result is reliable.

3. Conclusion

The results showed that the interactions of the primary and secondary terms of factor B, the secondary term of factor A, and the interaction of factors AC are all significant.

Based on the RSM, the structure of the phase change thermal unit was optimized, and the best combination of structural parameters was obtained: angle A=7.09°, angle B=40.06°, angle C=45°, the relative position of the two fins is about 40°, and the optimization result is 6.4% higher than the lowest value in the experiment and 0.51% higher than the highest value. When the response surface method is optimized, the optimal test point can be included in the experimental design to get a better prediction effect. Therefore, the preliminary results of this test are reliable.

The optimized parameters are used to verify that the regression model is feasible. Since the temperature difference range of the phase-change energy storage heat exchanger involved in this test is relatively small, it may have a better effect on the three-tube heat exchanger with fins with high temperature difference. This study has important guiding significance for its structural design.

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