Effects of Different Influencing Factors on Temperature Distributions and Cooling Performance of Turbocharger Bearing Casing

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Abstract: In order to study temperature distributions under different influencing factors and evaluate the cooling performance of the turbocharger bearing casing, water-cooling system experiments regarding the turbocharger bearing casing are carried out, and an improved fuzzy analytic hierarchy process (FAHP) evaluation method for evaluating its design performance is proposed firstly. Then, the effects of various factors such as cooling-water inlet flow velocity, cooling-water inlet temperature, cooling-water pressure and exhaust temperature on the cooling performance of the bearing casing are investigated according to the experimental results. Finally, the design performance of the water-cooling system in the turbocharger bearing casing is evaluated based on the FAHP evaluation method. The results show that the turbocharger bearing casing temperature and the temperature drop rate show a decreasing trend with the increase of inlet cooling-water velocity, but that the temperature and temperature rise rate increase with the increase of the inlet temperature of cooling-water and exhaust temperature; the temperatures under the inlet velocities of 4 m/s, 5 m/s and 6 m/s are reduced by 4.1%, 5.9% and 6.7% compared with that under 3 m/s, respectively. In addition, the bearing casing temperatures firstly reduce then increase with the increase of cooling-water pressure, where the boiling heat transfer plays an important role; points 1, 2 and 3 have relatively higher temperatures than other points under all working conditions; the bearing casing temperature of six measuring points also increases under a cooling-water pressure between 0.1 MPa and 0.25 MPa. Moreover, the performance evaluation value based on the FAHP method for the turbocharger bearing casing is 87.7620, and the performance evaluation level is good, which indicates that the water-cooling system in the turbocharger bearing casing has desirable design performance. This work provides reference for the turbocharger’s design and its cooling performance enhancement.

Keywords: turbocharger; bearing casing; cooling performance; influencing factors; boiling heat transfer

1. Introduction

As an important energy consumer and polluter, the energy conservation and automobile emission reduction of vehicles have become the focus of attention [1]. Thus, they have become some of the most important issues that technicians need to solve urgently [2]. In order to effectively improve the engine power, reduce fuel consumption and meet increasingly stringent emission standards, turbochargers have been widely used in the automotive industry [3,4]. However, the bearing casing of a turbocharger is considered as an important part [5] and usually works in a harsh environment of high temperature [6]. Due to the disadvantages of water cooling [7,8], there is a large temperature gradient which results in uneven temperature distribution and a great thermal stress on the water-cooled bearing-casing of the turbocharger [9,10]. Thus, it is significant to obtain the correct tem-
perature field and flow field to better evaluate the thermal stress and thermal state of the bearing-casing [11–13].

Heat transfer in the narrow space of the turbocharger is very important to obtain an accurate temperature distribution [14]. However, there is a boiling phenomenon in the hot spots in the turbocharger because of the increased cooling-water temperature [15]. In general, the boiling includes subcooled boiling and saturated boiling [16], and the cooling-water temperature in the supercooling zone is lower than its saturation temperature [17]. Because bubbles produced by moving from the surface are condensed upward [18], when the surface temperature rises further, the bubbles increase. Then, the bubble area forms a vapor layer and generates film boiling, resulting in a great reduction in the heat transfer from the surface to the cooling water [19]. Finally, the surface temperature increases greatly, which is a very dangerous phenomenon for mechanical equipment [20]. Many researchers have carried out relevant research on boiling heat transfer [21]. For instance, Zhang et al. [22] developed a water jacket bearing model for a gasoline engine turbocharger and evaluated the effect of the boiling heat transfer state on the surface temperature. They found that the mean void fraction could evaluate accurately the nucleate boiling state. In addition, an improved self-assembly surface was developed by Zhou et al. [23], and the results showed that the critical heat flux and heat transfer coefficient are increased by 104% and 73%, respectively, compared with those of a conventional copper surface. Cai et al. [24] carried out experiments in mini-channels and found that different refrigerants have different flow boiling heat transfer characteristics. A two-phase boiling model was developed and validated by Podowske et al. [25]; the results showed that boiling heat transfer could be accurately predicted by this boiling model. Similarly, Mohummadi et al. [26] investigated boiling heat transfer by a two-phase boiling model and a single-phase boiling model and reached a similar conclusion. Therefore, in order to improve the calculation accuracy for heat transfer and cooling performance evaluation in the water-cooling system of a turbocharger, the effect of boiling heat transfer on the bearing casing should be considered [27]. The bearing of the turbocharger is generally cooled with lubricating oil, and there has been little research on cooling water jackets in the bearing casing’s cooling system, where boiling heat transfer in the cooling system has not often been considered. Therefore, it is significant to investigate the water-cooling performance in the bearing casing in this paper.

In this complex water-cooling system considering boiling heat transfer, the heat transfer performance evaluation is a multi-criterion coupling analytic hierarchy process [28], where some important data are difficult to obtain in the experiment [29]. However, the fuzzy analytical hierarchy process (FAHP) that integrates objective fuzziness and objective randomness [30,31] can be considered an effective evaluation method and can be used to solve these problems with uncertain criteria quantification and qualitative description [32]. For this evaluation method, a linguistic comparison matrix is often employed to compile experts’ opinions [33], and the expressions are converted into fuzzy triangular numbers according to the proposed language level standard. For instance, Alarcin et al. [34] developed an FAHP model and investigated the auxiliary system failures of a main engine. After expert consultation and a comprehensive investigation, six fault types were determined as high-priority [35]. From the above discussions, it is significant to evaluate the cooling performance of a turbocharger bearing casing with boiling heat transfer based on the FAHP model.

Therefore, an improved fuzzy analytic hierarchy process evaluation method for the performance evaluation of the water-cooling system in a turbocharger bearing casing is proposed. Firstly, water-cooling experiments [36–39] regarding the turbocharger bearing casing are carried out, and an accurate temperature field of the bearing casing is obtained by temperature sensors at the corresponding test positions. Considering the boiling heat transfer, the effects of various factors on the water-cooling performance are studied. Then, a triangular membership function is used to construct the fuzzy consistency judgment matrix of the water-cooling performance index, and the analytic hierarchy process is
employed to calculate the performance index weight of the water-cooling system. Finally, the performance evaluation value, grade and most influential factor of the cooling-water system in the turbocharger bearing casing are investigated.

2. Investigative Methods
2.1. Experimental Method
2.1.1. Experimental Apparatus

According to the turbocharger test method of Mechanical Industry Standard JB-T9752.2-2005 of the People’s Republic of China, the overall structure of the test bench was determined as shown in Figure 1.

![Figure 1. Schematic diagram of the test bench.](image)

This test bench is a multi-purpose test platform suitable for a turbocharger which can also be used for gas turbine test. The main components include an electric regulating valve, air compressor, pipeline system, fuel supply system, combustion chamber, supercharger, sensor, etc. As shown in Figure 2, a JK45 turbocharger (JK45, Hunan Tyen Machinery Co., Ltd, Hengyang, China, 2015) is employed to carry out the experiment, the highest speed of which is 230,000 r/min and the volume of which ranges from 0.8 to 2.5 L. Six Kistler pressure sensors (9136B, Kistler, Winterthur, Switzerland, 2020) are employed to measure the pressure. In addition, a corresponding speed sensor, five temperature sensors (WRTK-112, Senxte, Tianjin, China, 2020) and two flow mass sensors (CMF010, Emerson, St. Louis, Missouri, US, 2019) are employed to measure the speed, temperature and flow mass, respectively. An FCMM-2 fuel flowmeter is employed to measure the fuel flow mass. More specifically, the measurement range and error of each instrument are shown in Table 1.
Figure 2. Main equipment in the test bench.

Table 1. The measurement range and error of each instrument.

| Measurements     | Instrument Type and Manufacturer | Measuring Range | Accuracy | Uncertainty (%) |
|------------------|----------------------------------|-----------------|----------|-----------------|
| Engine speed     | JC3A/Xiangyi                      | 1–250,000 rpm   | ±10 rpm  | ±0.5            |
| Fuel consumption | S8005C/Gregory                    | 0–1000 g        | ±5 g/kW-h| ±1.5            |
| Temperature      | WRTK-112/Senxte                   | 0–1000 °C       | ±1 °C    | ±0.25           |
| Air flow mass    | CMF010/Emerson                    | 0–33.3 kg/min   | ±1%      | ±0.5            |
| Pressure         | PCI-6238/NI                       | 1–25 MPa        | ±10 kPa  | ±0.5            |

In the experimental process, regulating valve 1 is closed. External air can enter through regulating valve 3 when the turbine is started and accelerated. After the turbine speed reaches a certain value, fuel is injected into the combustion chamber and burnt, resulting in high-temperature gas. Meanwhile, the turbine drives the compressor impeller to rotate through the turbine shaft. In this test bench, regulating valve 2 is connected to the atmosphere through an exhaust device, and the outlet flow of the compressor can be controlled by adjusting its opening ratio to realize different working conditions. In addition, the air flow into the combustion chamber can be regulated by controlling regulating valve 3. There are oil pressure test points, oil gauges and oil quantity regulating devices which can control the injection quantity between the oil pump and the combustion chamber. By adjusting the air flow and fuel quantity, parameters such as intake temperature and turbine speed can be controlled. Moreover, the cooling water enters from the high-temperature end and passes through the entire turbine bearing with the water jacket; it then outflows from the low-temperature end, finally flowing into the engine-cooling system through a hosepipe for temperature reduction, resulting in cooling water’s constant circulation in the water jacket and bearing cooling.

2.1.2. Data Acquisition and Processing

In the actual experimental environment, the accuracy of the data acquisition system will be affected by the noise, electromagnetic radiation, ground ring and common-mode voltage. Thus, a data acquisition card with a current signal of 4–20 mA is used for measurement, considering these factors in the experimental process. The isolation can isolate the common-mode voltage from the earth ring and prevent the signal attenuation caused by the resistance of the wire during long-distance transmission. At this time, the range of
current signals output by the temperature and pressure sensors is also 4~20 mA, and there is the same current signal range for the frequency converters. In addition, the sensors of the PCI-6238 data acquisition device produced by NI are selected to measure the temperature and pressure. The rotational speed is measured by a JC3A rotational speed sensor produced by the Xiangyi Power Testing Instrument Co., Ltd. The Siemens PLC is adopted to control the switching value.

The measurement and control system of the turbocharger test bench is shown in Figure 3, where an electric control cabinet in the figure is used to control various electrical systems, such as the manual adjustment of valves, the cooling-water and lubrication system, and the total stopping of the air compressor and whole test system. In the experimental process, the signals from various sensors are collected and analyzed by the computer through the instrument interface and data acquisition card, and the control signals are sent to various actuators after processing the data. Similarly, the driver software DAQx and Labview produced by NI were used to develop the program of the measurement and control system, which makes the program complete many functions such as information collection, processing, control, result display and printing [40].

![Figure 3. Structure diagram of measurement and control system for turbocharger test bench.](image)

2.1.3. Temperature Measurement of Water-Cooled Bearing Casing in the Turbocharger

Boiling heat transfer is very important for the turbocharger when it works. In order to obtain the actual temperature distribution of a turbocharger water-cooled bearing, it is necessary to conduct temperature testing for the turbocharger. The turbocharger turbine is affected by the high-temperature exhaust gas, which makes the bearing casing gather a large amount of heat load near the turbine end. Thus, the temperature distribution of the turbine varies with the heat load. Due to the limitation of measurement conditions, it is difficult to directly measure the actual temperature of the bearing casing at the turbine end and the compressor end in the experimental process. Thus, an indirect measurement method (non-contact measurement) is used to test the temperature of the bearing casing at the turbine end and the compressor end. For the indirect measurement method, non-contact thermometry mostly uses advanced optical technology or infrared technology to measure the surface temperature by data conversion. The pixel count of the thermal imaging camera
in the test is $640 \times 480$, the frame frequency is $8.5$ Hz, the spectral response is $8$–$14$ $\mu$m, and the heat sensitivity is $0.02$ °C.

In the temperature measurement process, except for the bearing casing at the turbine end and the compressor end, contact temperature measurement with thermocouples can meet the temperature measurement requirements of the parts of the turbocharger. Therefore, six industrial armored thermocouples (type: WRTK-112, measuring range: $-40$–$1100$ °C, diameter: $0.25$ mm, reaction time: $0.5$ s) are located in six measuring points in Figure 4 to collect the corresponding heat loads. The full turbocharger’s section can be seen in [41]. In order to ensure measurement accuracy, the position of the thermocouple hole should be accurate, which can be drilled from the outside to the inside. When a measuring hole is drilled in the wall near the floating bearing of the bearing casing [42], its radius should be $0.5$ mm, and the distance between the bottom of the measuring point and the sealing ring and the floating bearing wall should be less than $1.0$ mm.

![Figure 4. Temperature measuring point distribution for the turbocharger.](image)

2.2. Evaluation Method

The increased temperature caused by the unit volume loss in the operation process is the main factor that limits the design capacity of the turbocharger bearing casing [43,44]. However, good water-cooling performance can effectively reduce the heat load and improve the operating reliability and power density of the turbocharger bearing casing [45]. Therefore, it is very important to conduct a reasonable and effective comprehensive evaluation of the design performance of the water-cooling system for a turbocharger [46,47].

The analytic hierarchy process [48] is considered as a good option for a reasonable and effective comprehensive evaluation. It can achieve a qualitative and quantitative analysis of the water-cooling performance for the turbocharger bearing casing. However, the analytic hierarchy process is subjective and non-fuzzy. In this paper, a triangular membership function is used to construct the fuzzy consistency judgment matrix of a turbocharger bearing water-cooling system performance index. Then, the AHP is used to calculate the weight index of water-cooling system performance, and an improved fuzzy analytic hierarchy process is constructed. Thus, a fuzzy analytic hierarchy process evaluation method for the design of a turbocharger bearing water-cooling system is proposed, which can provide strong support for the effective evaluation of the designed turbocharger bearing’s reliability and other performance indexes. The improved FAHP is used to evaluate the water-cooling system performance, and its main steps are as follows:

1. Firstly, determine the performance evaluation indexes of the water-cooling system.
2. Design a questionnaire for the water-cooling system’s performance.
3. Carry out the fuzzy evaluation of the performance evaluation index of the water-cooling system.
4. Calculate the fuzzy evaluation average value of the water-cooling system performance.
index. (5) Calculate the correlation of fuzzy evaluation values of the water-cooling system performance. (6) Obtain the performance evaluation value of the water-cooling system.

2.2.1. Performance Evaluation Index System

The performance evaluation of the water-cooling system of the turbocharger bearing casing mainly includes three aspects: structural design evaluation of the water-cooling pipeline, resistance design evaluation of the water-cooling pipeline and heat transfer design evaluation of the turbocharger bearing.

The evaluation value of the water-cooled pipeline structure design $S_1$ includes water pump loss $S_{11}$, cooling-water flow $S_{12}$, cross-sectional area of the water-cooled pipeline $S_{13}$, absorbed heat of cooling water $S_{14}$, radiating area of the water-cooled pipeline $S_{15}$, length of the water-cooled pipeline $S_{16}$, channel number of the water-cooled pipeline $S_{17}$ and width of the water isolation platform $S_{18}$. Evaluation value of the water-cooling pipeline resistance design $S_2$ includes: resistance along the way $S_{21}$, local resistance $S_{22}$ and water pump loss $S_{23}$. The evaluation value of the bearing heat transfer design $S_3$ includes: bearing casing temperature drop $S_{31}$, bearing casing lower temperature drop $S_{32}$, bearing casing upper temperature drop $S_{33}$, bearing casing and water jacket assembly gap temperature drop $S_{34}$, water jacket temperature drop $S_{35}$, bearing casing total temperature drop $S_{36}$, engine oil temperature drop $S_{37}$, water jacket total temperature drop $S_{38}$ and water jacket surface average temperature $S_{39}$.

Thus, the performance evaluation index system parameters of the turbocharger bearing water-cooling system can be expressed as: $S = (S_1, S_2, S_3)$, $S_1 = (S_{11}, S_{12}, S_{13}, S_{14}, S_{15}, S_{16}, S_{17}, S_{18})$, $S_2 = (S_{21}, S_{22}, S_{23})$, $S_3 = (S_{31}, S_{32}, S_{33}, S_{34}, S_{35}, S_{36}, S_{37}, S_{38}, S_{39})$.

As shown in Table 2, the performance evaluation data of the water-cooling system are sent to selected experts in the thermal control field of turbocharger bearings. Then, the questions are answered anonymously by them. Half of these experts come from academia, and the other half come from industry. After the test, the questionnaire on performance evaluation of the turbocharger bearing water-cooling system is collected. Table 3 is used to score the performance index parameters of the turbocharger bearing water-cooling system, and the scoring interval is (0.5–0.9).

| Evaluation Factors | Performance Index Scoring Range of Water-Cooling System of the Turbocharger |
|--------------------|--------------------------------------------------------------------------------|
|                    | Excellent | Good | Fair | Fairly Bad | Bad |
| Evaluation value of water-cooled pipeline structure design $S_1$ | $S_{11}$ | $S_{12}$ | $S_{13}$ | $S_{14}$ | $S_{15}$ | $S_{16}$ | $S_{17}$ | $S_{18}$ |
| Evaluation value of water-cooling pipeline resistance design $S_2$ | $S_{21}$ | $S_{22}$ | $S_{23}$ |
| Evaluation value of bearing heat transfer design $S_3$ | $S_{31}$ | $S_{32}$ | $S_{33}$ | $S_{34}$ | $S_{35}$ | $S_{36}$ | $S_{37}$ | $S_{38}$ | $S_{39}$ |

Table 2. Data collection table for performance evaluation.
Table 3. Performance index scoring range of the water-cooling system of the turbocharger.

| Level     | Excellent | Good       | Fair | Fairly Bad | Bad   |
|-----------|-----------|------------|------|------------|-------|
| Evaluation score | 0.90~1.0  | 0.80~0.89  | 0.70~0.79 | 0.60~0.69 | 0~0.59 |

2.2.2. Fuzzy Judgment Matrix for Performance Evaluation

The fuzzy judgment matrix construction of the water-cooling system performance evaluation was conducted as follows:

Step 1: If the evaluation value of the performance index parameters is not given by any evaluation experts, the evaluation value is considered to be 0.

Step 2: If the evaluation value of the performance index parameters is only given by one evaluation expert, the evaluation value will be recognized.

Step 3: If the evaluation value of the performance index parameter of the turbocharger bearing water-cooling system is given by \( K \) evaluation experts, the membership degree of the evaluation value \( x_{ijk} \) is determined by Formula (1):

\[
\mu_{ijk}(x) = \begin{cases} 
0 & \left| x_{ijk} - u_{ij} \right| > t_{ij} \\
1 - \frac{\left| x_{ijk} - u_{ij} \right|}{t_{ij}} & \left| x_{ijk} - u_{ij} \right| < t_{ij}
\end{cases}
\]  

(1)

where \( 1 \leq k \leq K \leq n \), \( u_{ij} \) is the average value of the evaluation values of performance index factors in item \( j \) of class \( i \), \( m_{ij} \) is the fuzzy subset boundary of performance index factor evaluation, and \( m_{ij} = 2\sigma_{ij} \); \( \sigma_{ij} \) is the standard deviation of the evaluation values, which is determined by Formula (2):

\[
\sigma_{ij} = \sqrt{\frac{(x_{ij1} - u_{ij})^2 + (x_{ij2} - u_{ij})^2 + \cdots + (x_{ijk} - u_{ij})^2}{K}}
\]  

(2)

If the number of evaluation experts excluded in Formula (1) is \( k_0 \), then the membership degree calculation formula of the evaluation value \( x_{ij} \) of the performance index factor of the turbocharger bearing casing water-cooling system in item \( j \) of category \( i \) is determined by Formula (3):

\[
\mu_{ijk}(x) = \frac{\sum_{k=1}^{K-k_0} \mu_{ijk}(x)}{K - k_0}
\]  

(3)

According to the above method, the fuzzy judgment matrix of the performance index is shown as follows:

\[
R_i = \begin{bmatrix} 
\mu_{11} & \mu_{12} & \cdots & \mu_{1n} \\
\mu_{21} & \mu_{22} & \cdots & \mu_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
\mu_{m1} & \mu_{m2} & \cdots & \mu_{mn} 
\end{bmatrix}
\]  

(4)

where \( 0 \leq i \leq m \), and \( 0 \leq j \leq n \).

2.2.3. Weight Determination of Performance Index Factors

If there are \( t \) evaluation index factors \( u_1, u_2, \ldots, u_t \) in a certain layer of the performance evaluation system of the turbocharger bearing water-cooling system, the analytic hierarchy process can be used to construct the judgment matrix \( C = (c_{ij})_{t \times t} \), so as to determine the weight of the performance index factors of the turbocharger bearing water-cooling system. Professionals compare the relative importance of each element in pairs and judge the scale values 1–9 and their reciprocal of the elements in the matrix \( C = (c_{ij})_{t \times t} \), and they select the values according to the following methods:
Step 1: If $u_i$ meets the following requirements compared with $u_j$: [equally important, slightly important, obviously important, especially important, absolutely important], then $c_{ij} = \{1, 3, 5, 7, 9\}$.

Step 2: If the importance of $u_i$ and $u_j$ is between their levels, it can be scaled by 2, 4, 6, 8, 1/2, 1/4, 1/6 or 1/8.

Step 3: The element $c_{ij}$ in the judgment matrix $C = (c_{ij})_{n \times t}$ also has the following properties: (1) $c_{ij} > 0$, (2) $c_{ij} = 1/c_{ji}$, (3) $c_{ii} = 1$.

The weight $W_i$ of that performance index factor of the water-cooling system of the turbocharger bearing casing can be expressed as:

$$W_i = \frac{\sum_{j=1}^{n} c_{ij}}{\sum_{j=1}^{n} \sum_{i=1}^{n} c_{ij}}$$  \hspace{1cm} (5)

By applying the analytic hierarchy process twice, the weights $W_1$, $W_2$ and $W_3$ of some index factors in the performance evaluation system of the turbocharger bearing water-cooling system can be finally obtained, and $\sum W_i = 1$. The weight set $W = (W_1, W_2, W_3)$. For example, the weight of the water-cooled pipeline structure design evaluation is $W_1$, $W_1 = (W_{11}, W_{12}, W_{13}, W_{14}, W_{15}, W_{16}, W_{17}, W_{18})$. The weight of the water-cooling resistance design evaluation is $W_2$, $W_2 = (W_{21}, W_{22}, W_{23})$. The evaluation weight of the turbocharger bearing heat transfer design is $W_3$, $W_3 = (W_{31}, W_{32}, W_{33}, W_{34}, W_{35}, W_{36}, W_{37}, W_{38}, W_{39})$.

2.2.4. Performance Evaluation Steps of Water-Cooling System

The performance evaluation steps of water-cooling system can be expressed as follows:

Step 1: Find the evaluation matrix $b_i = w_{ij} r_i$ ($0 \leq i \leq m$) of each factor of the performance index, and normalize it.

Step 2: Establish the target price matrix $B = (B_1^T, B_2^T, \ldots, B_i^T)^T$ of the performance index, where “$T$” means matrix transposition.

Step 3: The fuzzy comprehensive evaluation of the performance index is carried out to obtain the fuzzy comprehensive evaluation result set of the water-cooling system performance index, that is, the fuzzy subset $F$ obtained by combining the weight vector $W$ and the fuzzy matrix $B$ is as follows:

$$F = WB$$  \hspace{1cm} (6)

The performance evaluation value of the water-cooling system can be obtained from Equation (6), and thus the performance evaluation value of the water-cooling system can be determined.

Step 4: The performance evaluation value of the water-cooling system of the turbocharger bearing casing can be expressed as follows:

$$f = FY^T$$  \hspace{1cm} (7)

where $y$ is the corresponding score vector in the performance evaluation set of the turbocharger bearing water-cooling system, and its score table is shown in Table 4.

Table 4. Performance scoring table of the water-cooling system of the turbocharger bearing casing.

| Score Y | 95 | 80 | 65 | 50 | 35 |
|---------|----|----|----|----|----|
| Evaluation grade | Excellent | Good | Fair | Fairly bad | Bad |
| Score | $>90$ | 80–90 | 60–79 | 50–59 | $<50$ |

3. Results and Discussion

In the test, the gas heated by the combustion chamber is used to simulate the engine exhaust to drive the turbocharger. The temperatures of the turbocharger floating bearing casing are measured after the turbocharger runs at a steady state for 20 min. The turbine
rotor speed is kept at 90,000 r/min by adjusting the control equipment, the inlet temperature of the turbine is 750 °C, the inlet temperature of the cooling water is 95 °C, the inlet flow velocity is 4 m/s, the inlet temperature of the engine oil is 112 °C, and the inlet pressure is 0.21 MPa. In order to ensure steady state measurement, the results are recorded under each operating condition after running for 20 min. The experiments are carried out three times, and the average results are recorded. In addition, the design performance of the water-cooling system of the turbocharger bearing casing is evaluated by the improved fuzzy analytic hierarchy process method.

3.1. Effect of Cooling-Water Inlet Flow Velocity on Cooling Performance

In order to study the effect of cooling-water inlet flow velocity on the cooling performance of the bearing casing, the experiments were carried out with different inlet flow velocities of cooling water under stable working conditions. The bearing casing temperatures of the corresponding six measuring points under different flow velocities are shown in Figure 5.

As shown in Figure 5, the temperature of the measuring point decreases with the increase of the inlet flow velocity of cooling water, especially at point 1 and point 2, which indicates that a larger inlet flow velocity enhances the heat transfer effect between the cooling liquid and the wall. The reason is that there are a gradient change of flow velocity along the normal direction of the wall and a laminar layer near the wall bottom layer of the water chamber which moves smoothly and linearly along the direction parallel to the wall. When the fluid flow velocity increases, the laminar layer becomes thinner, and the turbulent flow layer is enhanced. However, when the flow velocity of the cooling water increases continuously to a certain extent, the temperature decline rate is reduced. For point 1, compared with the temperature under the inlet cooling-water velocity of 3 m/s, those under 4 m/s, 5 m/s and 6 m/s are reduced by 4.1%, 5.9% and 6.7%, respectively. This may be mainly due to the fact that turbulent flow exists in the cooling cavity. Similarly, the temperature of each measuring point is reduced due to the improved cooling performance. As the cooling-water inlet flow velocity increases, the bubbles easily flow away from the water cavity, resulting in smoother fluid flow; the heat transfer intensity increases due to the increased flow velocity of the gas and liquid phases in the boiling region and the increased turbulent kinetic energy. However, with the further increase of the inlet velocity of the cooling water, the flow loss increases. Due to the viscosity of the liquid, the thickness of the laminar bottom layer on the water chamber wall does not change much, the gas–liquid
disturbance does not increase significantly, the heat transfer intensity does not increase much, and the heat transfer performance tends to be stable.

3.2. Effect of Inlet Temperature of Cooling Water on Cooling Performance

The cooling-water temperature is also an important factor. Figure 6 shows the bearing casing temperatures of the corresponding six measuring points at different inlet cooling-water temperatures. It can be found that the temperature increases with the increase of the inlet temperature of cooling water, and point 2 has the highest temperature. When the inlet temperature is 100 °C, the temperature of each measuring point reaches its maximum. More specifically, compared with the temperature of measuring point 1 at an inlet cooling-water temperature of 85 °C, those under the inlet cooling-water temperatures of 90 °C, 95 °C and 100 °C are increased by 6.2 °C, 12.3 °C and 20.7 °C, respectively. This is due to the fact that the temperature difference between the fluid and solid decreases with the increase of the inlet cooling-water temperature. Similarly, boiling heat transfer may occur in the water cavity when the water temperature increases, and bubbles will be generated and gradually increase. The increased volume of the vapor phase makes the fluid flow not smooth and reduces the disturbance between the two phases, resulting in a reduction of the heat exchange intensity of the cooling water. Thus, the increased ratio of the bearing casing temperature is reduced with the increase of the inlet temperature of cooling water. Boiling heat transfer has great influence on the bearing casing temperature.

![Figure 6. Effects of cooling-water inlet temperature on the temperature.](image)

3.3. Effect of Exhaust Temperature on Cooling Performance

When the exhaust temperature is only changed under stable working conditions, the bearing casing temperatures of the corresponding six measuring points at different exhaust temperatures are shown in Figure 7.

As can be seen from Figure 7, with the increase of the exhaust temperature, the temperature of each measuring point increases, but the increase rates are different. The temperature variation of point 2 near the turbine end is the most obvious, and those of point 1 and point 3 are also larger, while those of other points are smaller. More specifically, compared with the temperature of measuring point 2 when the exhaust temperature is 650 °C, the temperatures of measuring point 2 at the exhaust temperatures of 700 °C, 750 °C and 800 °C are increased by 16.2 °C, 42.3 °C and 72.5 °C, respectively. This is due to the increased heat load caused by the increase of the exhaust temperature. Therefore, the exhaust temperature has its largest effect on the measuring point near the turbine end, and temperature of the bearing casing near the turbine end will increase. The measuring points near the cooling water cavity and far away from the hot end face will see little direct impact, where the temperature increases a little.
3.4. Effect of Cooling-Water Pressure on Cooling Performance

Bubbles are continuously produced and destroyed, resulting in severe disturbances in the nucleate boiling state. In order to improve the heat exchange efficiency, it is very important to study the influence of different inlet pressures on heat transfer. At the single-phase convection heat transfer stage, the influence of pressure on the cooling performance of the bearing casing can be neglected. When boiling occurs, the pressure change will directly affect the boiling heat transfer efficiency. This is due to the variable saturation temperature of the cooling water with its variable pressure.

Under working conditions, the bearing casing temperatures of the six measuring points when the cooling-water inlet pressure is 0.05 MPa, 0.1 MPa, 0.2 MPa and 0.25 MPa are shown in Figure 8. All points basically show an increasing trend of temperature with the increase of the inlet pressure, and points 1, 2 and 3 have relatively higher temperatures than other points. However, when the cooling system pressure drops from 0.1 MPa to 0.05 MPa, the temperatures of measuring point 1 and point 2 rise. This is due to the fact that when the pressure of the cooling system drops, the saturation temperature of the cooling water decreases, and the cooling liquid is easier to boil. Film boiling will occur in the area near the turbine end of the water jacket, leading to an overheated wall surface. This makes the heat exchange efficiency in this area drop rapidly, and the temperature rises greatly. With the increase of the cooling-water pressure, the saturation temperature of the cooling water increases, and the boiling heat transfer efficiency decreases. Therefore, the bearing casing temperature of the six measuring points also increases by between 0.1 MPa and 0.25 MPa.

3.5. Performance Evaluation of the Water-Cooling System of the Turbocharger Bearing

The analytic hierarchy process is used to determine the performance evaluation weight of the water-cooling system of the turbocharger bearing casing, and the following results can be obtained through calculation:

\[
W = (W_1, W_2, W_3) = (0.55, 0.27, 0.18), \ W_1 = (W_{11}, W_{12}, W_{13}, W_{14}, W_{15}, W_{16}, W_{17}, W_{18}) = (0.15, 0.14, 0.11, 0.12, 0.11, 0.12, 0.13, 0.14), \ W_2 = (W_{21}, W_{22}, W_{23}) = (0.36, 0.31, 0.33), \ W_3 = (W_{31}, W_{32}, W_{33}, W_{34}, W_{35}, W_{36}, W_{37}, W_{38}, W_{39}) = (0.11, 0.12, 0.11, 0.12, 0.09, 0.08, 0.13, 0.11, 0.13).
\]

According to the actual situation, the fuzzy evaluation table for the performance evaluation of the water-cooling system is shown in Table 5.
Figure 8. Effect of cooling system pressure on the temperature.

Table 5. Fuzzy evaluation table for performance evaluation of the water-cooling system of the turbocharger bearing casing.

| Judgement Factors | Index Parameter Evaluation Grade | \( W_{ij} \) | \( W_i \) |
|-------------------|----------------------------------|-------------|---------|
| \( S_1 \)        |                                  |             |         |
| \( S_{11} \)     | 0.7                              | 0.1         | 0.2     | 0.0     | 0.0     | 15.15 |
| \( S_{12} \)     | 0.6                              | 0.2         | 0.1     | 0.1     | 0.0     | 14.14 |
| \( S_{13} \)     | 0.5                              | 0.3         | 0.2     | 0.0     | 0.0     | 11.01 |
| \( S_{14} \)     | 0.7                              | 0.2         | 0.1     | 0.0     | 0.0     | 12.12 |
| \( S_{15} \)     | 0.6                              | 0.3         | 0.1     | 0.0     | 0.0     | 11.11 |
| \( S_{16} \)     | 0.5                              | 0.4         | 0.1     | 0.0     | 0.0     | 12.12 |
| \( S_{17} \)     | 0.7                              | 0.2         | 0.0     | 0.1     | 0.0     | 13.13 |
| \( S_{18} \)     | 0.8                              | 0.1         | 0.1     | 0.0     | 0.0     | 14.14 |
| \( S_2 \)        |                                  |             |         |
| \( S_{21} \)     | 0.6                              | 0.2         | 0.1     | 0.1     | 0.0     | 0.36 |
| \( S_{22} \)     | 0.5                              | 0.3         | 0.2     | 0.0     | 0.0     | 0.31 |
| \( S_{23} \)     | 0.6                              | 0.3         | 0.1     | 0.0     | 0.0     | 0.33 |
| \( S_3 \)        |                                  |             |         |
| \( S_{31} \)     | 0.6                              | 0.2         | 0.1     | 0.1     | 0.0     | 0.11 |
| \( S_{32} \)     | 0.7                              | 0.2         | 0.1     | 0.0     | 0.0     | 0.12 |
| \( S_{33} \)     | 0.7                              | 0.3         | 0.0     | 0.0     | 0.0     | 0.09 |
| \( S_{34} \)     | 0.6                              | 0.2         | 0.2     | 0.0     | 0.0     | 0.08 |
| \( S_{35} \)     | 0.8                              | 0.1         | 0.1     | 0.0     | 0.0     | 0.13 |
| \( S_{36} \)     | 0.7                              | 0.2         | 0.0     | 0.1     | 0.0     | 0.13 |
| \( S_{37} \)     | 0.6                              | 0.3         | 0.1     | 0.0     | 0.0     | 0.11 |
| \( S_{38} \)     | 0.5                              | 0.3         | 0.2     | 0.0     | 0.0     | 0.13 |
| \( S_{39} \)     | 0.6                              | 0.4         | 0.0     | 0.0     | 0.0     | 0.00 |

It can be seen from Table 4 that the fuzzy judgment matrix \( R_i \) of the performance evaluation index of the water-cooling system of the turbocharger bearing casing is:

\[
R_1 = \begin{bmatrix}
0.7 & 0.1 & 0.2 & 0.0 & 0.0 \\
0.6 & 0.2 & 0.1 & 0.1 & 0.0 \\
0.5 & 0.3 & 0.2 & 0.0 & 0.0 \\
0.7 & 0.2 & 0.1 & 0.0 & 0.0 \\
0.6 & 0.3 & 0.1 & 0.0 & 0.0 \\
0.5 & 0.4 & 0.1 & 0.0 & 0.0 \\
0.7 & 0.2 & 0.0 & 0.1 & 0.0 \\
0.8 & 0.1 & 0.1 & 0.0 & 0.0
\end{bmatrix}
\]
After the normalization process, the evaluation matrix $B_i$ of each factor of the performance evaluation of the water-cooling system is as follows:

\[
B_1 = (0.6570, 0.2210, 0.1150, 0.0270, 0); 
B_2 = (0.5690, 0.2640, 0.1310, 0.0360, 0); 
B_3 = (0.6380, 0.2520, 0.0910, 0.0190, 0).
\]

The FAHP evaluation result set of the water-cooling system performance is:

\[
F = W \cdot B = (0.6298, 0.2382, 0.1150, 0.0280, 0).
\]

The performance evaluation value of the water-cooling system of the turbocharger bearing casing is:

\[
f = F \cdot Y^T = (0.2884, 0.3702, 0.2278, 0.0940, 0.0286) \times (95, 80, 65, 50, 35)^T = 87.7620.
\]

According to Table 4, the fuzzy analytic hierarchy process evaluation value of the water-cooling system performance is 87.7620. Thus, the performance evaluation level of the water-cooling system is good, which indicates that the water-cooling system in the turbocharger bearing casing has desirable design performance. Similarly, Alarcin [35] and Nezarac [40] developed the fuzzy analytic hierarchy process evaluation model and carried out similar studies. They found that this method could evaluate the water-cooling system performance effectively.

4. Conclusions

In this paper, an improved fuzzy analytic hierarchy process evaluation method for evaluating the design performance of the water-cooling system was proposed. Firstly, water-cooling system experiments for the turbocharger bearing casing were carried out based on the turbocharger test bench. According to the experimental results, the effects of various factors such as cooling-water inlet flow velocity, cooling-water inlet temperature, cooling-water pressure and exhaust temperature on the cooling performance of the bearing casing were investigated. Then, the design performance of the water-cooling system in the turbocharger bearing casing was evaluated by the fuzzy analytic hierarchy process. The main conclusions are as follows:

1. The bearing casing temperature and the temperature decline rate reduce with the increase of the inlet cooling-water velocity. Compared with that of measuring point 1 under an inlet cooling-water velocity of 3 m/s, the temperatures under the inlet velocities of 4 m/s, 5 m/s and 6 m/s are reduced by 4.1%, 5.9% and 6.7%, respectively. As the cooling-water inlet flow velocity increases, bubbles easily flow away from the water cavity, resulting in smoother fluid flow; the heat transfer intensity increases due to the increased flow velocity of the gas and liquid phases in the boiling region and the increased turbulent kinetic energy. On the contrary, the bearing casing temperature and temperature rise rate increase with the
increase of the inlet temperature of cooling water and the exhaust temperature. However, the temperature rise rates are different among measurement points.

(2) The bearing casing temperatures first reduce and then increase with the increase of the cooling-water pressure. At the reduction stage, boiling heat transfer plays an important role at the interface of the annular water channel near the turbine side and other places, which can improve the heat transfer. Under all working conditions, points 1, 2 and 3 have relatively higher temperatures than other points, where the heat transfer can be further improved. The bearing casing temperature of the six measuring points also increases under cooling-water pressures between 0.1 MPa and 0.25 MPa. Pressure changes directly affect the saturation temperature of cooling water and boiling heat transfer efficiency.

(3) The performance evaluation value of the water-cooling system of the turbocharger bearing casing is 87.7620 based on the fuzzy analytic hierarchy process method, and the performance evaluation level of the water-cooling system is good. This indicates that the water-cooling system in the turbocharger bearing casing has desirable design performance. In our future studies, heat transfer performance optimization for the water-cooling system of the turbocharger bearing casing will be further investigated by orthogonal experimental design and field synergy theory.

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Nomenclature

\( u_{ij} \) Average value of evaluation values of performance index factors in item \( j \) of class \( i \)
\( m_{ij} \) The fuzzy subset boundary of performance index factor evaluation
\( \sigma_{ij} \) The standard deviation of an evaluation value
\( R_i \) Fuzzy judgment matrix of the performance index
\( C \) The judgment matrix
\( B \) The target price matrix
\( F \) The fuzzy subset
\( W_i \) The weight of performance index factors of the water-cooling system
AHP The analytic hierarchy process
FAHP The fuzzy analytic hierarchy process

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