Simulation and optimization of steady-state heat transfer property measurement platform

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Abstract. This paper studies the measurement technology of heat transfer coefficient of building envelope, explores the main factors affecting the measurement of heat transfer coefficient, uses ANSYS Icepak software to simulate the steady-state heat transfer property measurement platform model, and establishes the virtual prototype of the product. The product design based on Icepak replaces the test on the physical prototype with the simulation on the virtual prototype. We should reduce or even cancel the manufacturing of physical prototype, shorten the R & D process, and cut R & D costs with the improvement of design quality. Through the comparison and analysis with the experimental data of the offline detection platform, the feasibility of using Icepak to simulate the equipment is proved. The software is used to simulate the thermal environment in the hot box. Through comparison and analysis, the most uniform upper wind steady-state thermal environment scheme is found.

1. Introduction
Heat transfer coefficient is an important parameter used to measure the heat transfer characteristics and thermal insulation performance of solid components. The steady-state heat transfer property measurement platform is mainly used to measure the thermal insulation performance of building components, industrial similar components, walls and glass products. The physical parameters such as thermal conductivity and heat transfer coefficient are obtained.

The metering box in the steady-state heat transfer property test system is surrounded by a protective box. Control the ambient temperature of the protective box to make the unbalanced heat flow in the test piece φ2 and heat flow through the wall of the metering tank φ3 to the minimum, as shown in Figure 1. Then the balance of air temperature inside and outside the metering box will mean the temperature balance on the surface of the test piece, and the total heat flow through the test piece will be equal to the heat input into the metering box. The measuring platform is a closed space, which is divided into cold surface and hot surface. Guide fans are set to simulate the real cold and hot environment. The experiment is a steady-state heat transfer forced convection mode, and the heat transfer modes are heat conduction, heat convection and heat radiation [1].
2. Research method

2.1. Heat transfer analysis

2.1.1. Steady state heat transfer analysis of building envelope [2]
The heat transfer process of many insulating materials and systems is a composite heat transfer process affected by conduction, convection and radiation.

2.1.2. Mathematical analysis of steady state heat transfer [3]
The energy balance equation of steady-state thermal analysis is expressed in matrix form as:

\[ [K(T)]\{T\} = \{Q(T)\} \]

Where:
- \([K]\) is the heat conduction matrix, which can be a constant or a function of temperature. For each material, the temperature related thermal conductivity can be input.
- \(\{T\}\) is the node temperature vector.
- \(\{Q\}\) is the dielectric flow rate vector, which can be a constant or a function of temperature.

2.2. Software application

Icepak software is widely used in the field of electronic and electrical appliances [8], doing heat dissipation analysis of electronic components, simulating and analyzing air and cold water cooling, natural convection and forced convection of electrical and electronic equipment. In this paper, ANSYS Icepak software will be used to model the steady-state heat transfer property measurement platform, and Fluent module will be used to simulate and calculate the platform, Explore its temperature distribution to achieve the purpose of optimization, and then improve the efficiency of R & D work [9].

3. Establishment of platform model for measuring steady-state heat transfer properties

Taking the steady-state heat transfer property measurement platform as an example, according to relevant national standards [1][7], a three-dimensional model is established by SolidWorks, including hot box, experimental frame and cold box models. The model is shown in Figure 2.
Import the model into the geometry of ANSYS software for model transformation. In order to ensure the accuracy of model transformation, select Level 3 in simplify type for transformation.

Open Icepak window, import the set model, and add hot box circulating fan, protective box heater, metering box heater, cold box circulating fan, cold box axial flow fan, cold box cooler and cold box auxiliary heater to complete its configuration.

The working parameters of the fan are set as shown in table 1 below.

| Fan  | XC(mm) | YC(mm)  | ZC(mm)  | Radius (mm) | Hub radius (mm) | Flow (m³/min) | Pressure (in water) |
|------|--------|---------|---------|-------------|-----------------|---------------|---------------------|
| Fan1 | 300    | -768.639 | 2635    | 55          | 25              | 6.56          | 0.5                 |
| Fan2 | 0      | -768.639 | 2635    | 55          | 25              | 6.55          | 0.5                 |
| Fan3 | -300   | -768.639 | 2635    | 55          | 25              | 6.56          | 0.5                 |
| Fan4 | -600   | -768.639 | 2635    | 55          | 25              | 6.56          | 0.5                 |
| Fan5 | -900   | -768.639 | 2635    | 55          | 25              | 6.56          | 0.5                 |
| Fan6 | 0      | -300    | 1870    | 120         | 50              | 20            | 1                   |
| Fan7 | -600   | -300    | 1870    | 120         | 50              | 20            | 1                   |

Set the outside ambient temperature (laboratory temperature) to 20 °C in the simulated environment. After the model is established, the calculation area is set, and the material properties and boundary conditions are defined. The experimental platform is meshed. The whole model is divided into 365254 element grids and 382796 nodes.

Reynolds number is 50647.5 and Peclet number is 35884.1. To sum up, the calculation method of the model is set as turbulence, and the enhancement realizable two equation equation is selected for operation. The number of iterations is set to 100.

4. Verification of steady state heat transfer property measurement platform

4.1. Analysis and calculation

The thermal resistance of the main part of the enclosure structure is calculated according to the following formula [6]:

$$ R = \frac{\sum_{j=1}^{n} (\theta_{lj} - \theta_{ej})}{\sum_{j=1}^{n} q_j} $$

(2)

Where

- $R$ —— Thermal resistance of main part of enclosure structure, $m^2 \cdot K/W$;
- $\theta_{lj}$ —— The j-th measured value of the inner surface temperature of the main part of the envelope, °C;
- $\theta_{ej}$ —— The j-th measured value of the external surface temperature of the main part of the enclosure structure, °C;
\( q_j \) —— The j-th measured value of heat flux density at the main part of enclosure structure, W/m²;

The heat transfer coefficient of the main part of the envelope is calculated according to the following formula [6]:

\[
K = \frac{1}{(R_i + R + R_e)}
\]

Where

\( K \) —— Heat transfer coefficient of main part of enclosure structure, W/(m²·K);
\( R_i \) —— Heat transfer resistance of inner surface, 0.11, m²·K/W;
\( R_e \) —— External surface heat transfer resistance, m²·K/W;

4.2. Analysis of measured data

The experimental data are analyzed and processed by Maple software, and the thermal resistance of the main part of the envelope is calculated \( R_1 = 1.772 \) K/W; The heat transfer coefficient of the main part of the envelope is: \( K_1 = 0.518 \) W/(m²·K)

4.3. Simulation data analysis

According to the above simulation, the temperature distribution data of hot box and cold box in table 2 are obtained. The average temperature of hot surface is 32.8122°C; The average temperature of cold noodles is -5.2117°C. The input power is 30W, and the thermal resistance of the main part of the enclosure structure calculated according to formula (2) (3) is: \( R_2 = 1.801 \) m²·K/W; The heat transfer coefficient of the main part of the envelope is: \( K_2 = 0.510 \) W/(m²·K)

| Num | Hot box | Cold box | Num | Hot box | Cold box |
|-----|---------|----------|-----|---------|----------|
| 1   | 37.3457 | -5.5309  | 7   | 29.5359 | -6.3781  |
| 2   | 36.6623 | -4.7122  | 8   | 28.8995 | -5.7669  |
| 3   | 36.8254 | -3.8714  | 9   | 31.1269 | -4.5991  |
| 4   | 33.1221 | -6.1447  | 10  | 30.6039 | -5.8219  |
| 5   | 32.5617 | -5.3280  | 11  | 30.5332 | -5.6000  |
| 6   | 33.4181 | -4.1429  | 12  | 33.1115 | -4.6436  |

The simulation results are \( K_2 = 0.510 \) W/(m²·K), The measured calculation results of the platform are \( K_1 = 0.518 \) W/(m²·K), The deviation between them is 1.5% < 5%, and the error is within the allowable range, meeting the detection requirements [5]. It is proved that Icepak software can meet the simulation requirements of steady-state heat transfer experimental platform.
5. Research and optimization of steady state thermal environment based on Icepak

5.1. Existing equipment simulation
The existing experimental prototype is used to reverse model, and the 3D model is introduced into ANSYS Icepak, and the simulation is carried out for the thermal environment in the hot box, as shown in Figure 8. The temperature of the deflector is set to 85 °C, the heater of the protective box is set to 70 °C, and 12 temperature data points are collected. The uniformity of the ambient temperature in the heat box is analyzed according to the data obtained.

Data processing and analysis are carried out by using sample variance formula by Maple software, and the formula is as follows:

\[
S^2 = \frac{1}{n-1} \sum_{i=1}^{n} (X_i - \bar{X})^2
\]

Through the above calculation, it can be seen that the temperature data variance of the existing equipment in the market is 4.086, and the data fluctuates greatly, which reflects the uneven phenomenon of fluid distribution and temperature distribution in the platform hot box under the existing standard.

5.2. Improvement scheme
Using the ANSYS Icepak software verified above, the steady-state thermal environment in the hot box is simulated by changing the position of the diversion fan. According to a large number of simulations and experiments, four representative fan positions are selected as variables to explore. The fan position setting is shown in Figure 9, 10, 11, 12.
5.2.1. Simulation analysis

Explore the temperature distribution of the experimental platform through Figure13: collect the temperature data of 12 points. The temperature data distribution and temperature fluctuation are shown in figures14 and 15. Import the data into Maple software to write the program. Through calculation, it can be seen that the scheme variance of upper wind is $W_1 = 0.047$; The variance of lower wind scheme is $W_2 = 0.051$; The variance of median wind scheme is $W_3 = 0.052$; The variance of side wind scheme is $W_4 = 0.132$. It can be seen that the smaller the variance, the more stable. The comparison of the four schemes shows that $W_1 < W_2 < W_3 < W_4$. To sum up, the axial fan configuration with upper air is selected, the simulation result is the best, and the thermal environment in the hot box is the most stable.

6. Conclusion

Icepak is used to simulate the steady-state heat transfer property measurement platform. The simulation results are highly consistent with the measured values. It is proved that the simulation of product design based on Icepak on virtual prototype can replace the test on physical prototype. Icepak software can reduce or even cancel the manufacturing of physical prototype, greatly shorten the R & D process, reduce the R & D cost and improve the design quality. It is suitable for the development of complex products with long manufacturing cycle and high cost. Through the simulation analysis of the experimental platform, the results show that when the upper air guide fan is selected, the air volume and
temperature in the hot box are the most uniform. The variance of 12 temperature data sampling points is 0.047, which is the minimum. By optimizing the steady-state thermal environment in the hot box, the uneven heat flow in the experimental block made- φ2 and heat flow through the wall of the metering tank -φ3 can be minimized to achieve the best heat flow balance in the test platform. So far, the total heat flow through the specimen can be approximately equal to the heat input into the metering tank. Improve the detection accuracy in order to obtain the optimal experimental results.

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