

Development and calibration of heat transfer coefficient sensor for rotational state

QUAN Yong-kai, XU Guo-qiang, LUO Xiang, ZHANG Da

(School of Jet Propulsion,

Beijing University of Aeronautics and Astronautics, Beijing 100000, China)

Abstract: A novel heat transfer coefficient sensor is introduced and the design, manufacture, and calibration are described. The intended application of this instrument was on a high rotational speed test disc. In the experiments, the heat transfer coefficient sensor was calibrated under static state and rotational state respectively. The calibration under the static state was accomplished in a pipe: the inside diameter (ID) was 0.048 m and the total length was 4 m, the distance between the sensor and the inlet of the pipe was 3.5 m; the standard value was measured using a self-made calibrator. The calibration under the rotational state was accomplished using a rotating disc; the diameter and thickness of the stainless disc were 800 mm and 25 mm, respectively; the sensor was installed at the location of $r=250$ mm; the rotating disc driven by a 30 kW direct current motor can supply the maximum rotational speed of 3000 r/min. The standard value under rotational state was provided by an approximate empirical formula. The results show that the designed sensor can measure heat transfer coefficient directly under rotational state and static state with good accuracy and stability; the correlation factor of K are constant under static state and rotational state.

Key words: rotational state; steady method; heat transfer coefficient; sensor; calibration

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Nomenclature

h	heat transfer coefficient	Re	Reynolds number ($\rho VL/\mu$)
Φ	heat flux	μ	dynamic viscosity of air
A	heat exchange area	L	characteristic length
T	temperature	ρ	density of air
U	voltage added to the heating plate	V	bulk-average velocity
I	electric current passing the heating plate	ω	rotating velocity
K	correlation factor		

Subscripts and superscripts

hot	heating plate	f	reference value
w	value at the wall	loss	heat loss

Introduction

The efficiency and performance of gas turbine engines are limited by the materials used and the need for internal cooling. Internal cooling becomes necessary because temperatures may

exceed the melting point of the materials used in some engine components. Internal cooling is achieved by diverting a proportion of the mainstream flow. However, the cooling air supply is adverse to the engine efficiency and thrust. Therefore, a balance is sought between raising

turbine inlet temperatures and increasing cooling air requirements. This is achieved by understanding of heat transfer of components, and requires instrumentation that can directly measure heat transfer coefficient with minimal disruption. It is difficult to directly measure heat transfer coefficient under rotating operating conditions because that regimes of rotationally induced free convection can occur where heat transfer coefficients vary with temperature difference. It is also difficult to transport the data under rotational state.

Conventional thermocouples and heat balance technique are used to calculate heat transfer coefficient firstly. Early researchers^[1-3] numerically calculated local and average heat transfer coefficients using Laplace's equation and Newton's cooling equation together according the boundary conditions measured by thermocouples. It is unreasonable that the heat transfer coefficient calculated using this method is negative in some special location. Some studies also shown^[4-5] that small errors in surface temperature measurement can incur large errors in heat flux computed from the numerical solution of Fourier's equation, and then lead to larger errors in heat transfer coefficient. Some studies^[6-10] improved the method by measuring heat flux directly, but the results were also unfavorable.

Instantaneous heat flux measured focused more and more attentions because it provides very useful information to understand mechanism of heat transfer. Amarante et al.^[11] measured heat transfer coefficient of industrial freezing equipment using heat flux meter and temperature measuring device, and studied mechanism of heat transfer. Delaplace et al.^[12] measured instantaneous heat transfer directly in agitated vessel using heat flux sensor; the results were compared with conventional method. Harris et al.^[13-14] developed a sensor to measure local heat transfer. It has good accuracy but bad stability. Xu et al.^[15] developed a heat transfer coefficient sensor to measure instantaneous heat transfer coefficient directly, but accuracy and stability

limits the application of the sensor. Quan et al.^[16] designed a heat transfer coefficient sensor to measure instantaneous heat transfer coefficient under static state.

This paper improved the sensor of Quan et al.^[16] to measure heat transfer coefficient under rotational state. It shows the design, manufacture, and calibration of heat transfer coefficient sensor. In the experiments, the heat transfer coefficient sensor was calibrated under static state and rotational state respectively.

1 Elementary theory of heat transfer coefficient sensor

Newton's Law of cooling can be expressed as

$$\Phi = hA(T_w - T_f) \quad (1)$$

where Φ is the total heat flux, h is the average heat transfer coefficient, A is the heat exchange area, T_w is the wall temperature, and T_f is the fluid temperature. According Eq. (1), heat transfer coefficient h can be determined using the following equation according the measured total heat flux Φ and temperatures

$$h = \Phi / A(T_w - T_f) \quad (2)$$

2 Design and manufacture of heat transfer coefficient sensor

The heat transfer coefficient sensor is a cylinder with diameter of $D=10$ mm and height of $H=7$ mm. It includes heating plate, thermocouples, shell of the body, and adiabatic dope. A drawing of the sensor is shown in Fig. 1 and a photograph giving an indication of scale is shown in Fig. 2.

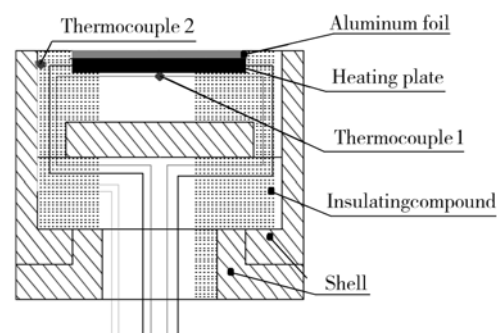


Fig. 1 Schematic representation of the sensor



Fig. 2 Photograph of the heat transfer coefficient sensor

The heating plate is the core component of the sensor. It is made up of lacquered wire ($d=0.06\text{ mm}$) with double layer. The advantage of using heating plate is that: thinner thickness, uniform temperature distribution, convenient for adding electric field. The heat power of heating plate is determined by values of added voltage and current; it can be calculated using the following equation

$$\Phi_{\text{hot}} = UI \quad (3)$$

where Φ_{hot} is the heat power of heating plate, U is the voltage added to the heating plate, and I is the electric current passing the heating plate. Under the perfect thermal insulation and equilibrium state, the convective heat flux is equal to the heat power of heating plate, $\Phi = \Phi_{\text{hot}}$. When T_w and T_f are measured using thermocouples, the heat transfer coefficient is calculated using the following equation

$$h = \Phi / A(T_w - T_f) = U \cdot I / A(T_w - T_f) \quad (4)$$

In order to ensure that the convection heat flux is equal to the heat power of heating plate, $\Phi = \Phi_{\text{hot}}$, the heating plate must to be adiabatic with environment. It is the core principle of design and manufacture. The heating plate is covered using aluminum foil to reduce radiant heat loss. The heatconducting heat loss is reduced through two methods: first, the material of the shell is polyfluortetraethylene with low coefficient of heat conductivity; second, the space between the heating plate and the shell is filled

with insulating compound ($0.03\text{ W/(m} \cdot \text{K)}$).

The temperature of the heating plate is measured using thermocouple 1; and the temperature of the shell is measured using thermocouple 2.

3 Calibration of heat transfer coefficient sensor under static state

The need for calibration of these heat transfer coefficient meters arises because there is no acceptable standard. Past experience has also shown that it is unacceptable to calibrate the sensors against a commercially available sensor using the calibration data supplied with it. Another reason to calibrate is that heat loss in measurement is avoidless although the heating plate is covered using insulating compound.

1) Calibration apparatus

This paper doesn't use the classical empirical formula of internal flow to calculate the standard heat transfer coefficient. The reason is that the empirical formula is obtained based on experiments under special experimental conditions. The error cannot be calculated for different experimental conditions. This paper designs a calibration apparatus to calibrate the sensor. The detail of the calibration apparatus is shown in Quan et al. [16]. The calibration apparatus and system are shown in Fig. 3 and Fig. 4 respectively.

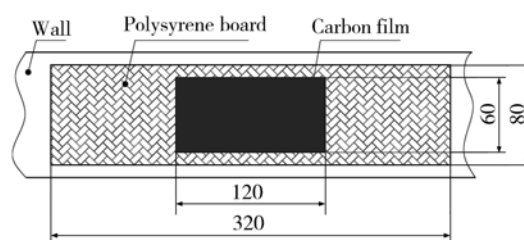


Fig. 3 Schematic diagram of the apparatus used for heat transfer coefficient sensor

The calibration under the static state is accomplished in a pipe: the inside diameter (ID) is 0.048 m and the total length is 4 m ; the distance between the sensor and the inlet of the pipe is 3.5 m ; the calibration apparatus is installed at same location of the sensor. According $L/d =$

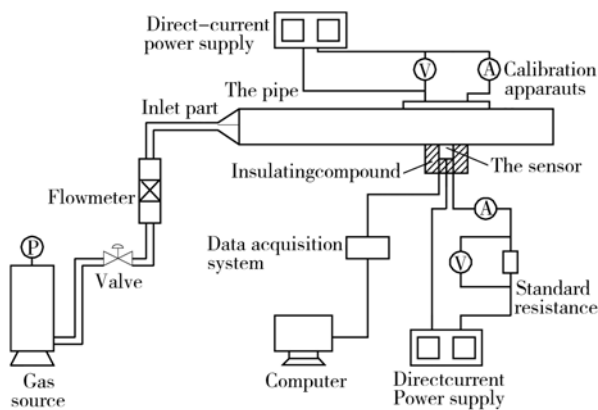


Fig. 4 Schematic diagram of the system used for heat transfer coefficient sensor

$3.5/0.0483=73>60$, the flow at the location of sensor is regarded as turbulent.

2) Calibration results

The experiments were repeated more times under the same conditions, and the results indicate great repeatability. The classical experimental results are shown in Fig. 5 and Fig. 6.

Fig. 5 shows that under the constant inlet Reynolds number, the error between the sensor and the calibration apparatus linearly increase with the increasing of the temperature difference (which is implemented by increasing the power of the heating plate) between the heating plate and the air. The design points 1, 2, ..., 5 are corresponding to the temperature difference of 20°C , 30°C , ..., and 60°C , respectively. A correlation factor of K , which is the ratio between the heat transfer coefficient measured by sensor and that measured by calibration apparatus, is defined as $K = \bar{h}_{\text{sensor}} / \bar{h}_{\text{stand}}$, where $\bar{h}_{\text{sensor}}$ is the heat transfer coefficient measured by sensor. It can be seen that as the temperature difference increasing the value of K is approximately linear increasing. This indicates that K is determined by the heat loss of heating plate, and the heat loss can be regarded as one dimensional heat transfer.

Figure 6 shows that the correlation factor K against the inlet Reynolds number. K is calculated using weighted average method based on the values of K under different temperature difference, which is described in Fig. 5. The value of

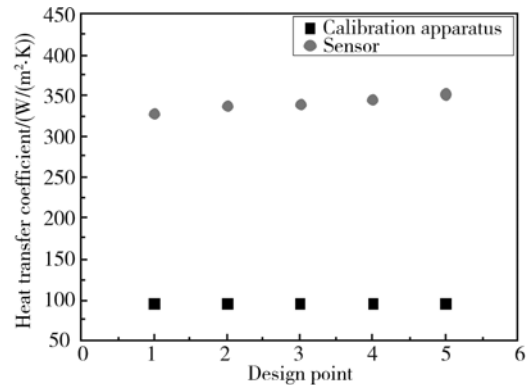


Fig. 5 Calibration characteristic of the heat transfer coefficient sensor (inlet Reynolds number $Re=6.78 \times 10^6$)

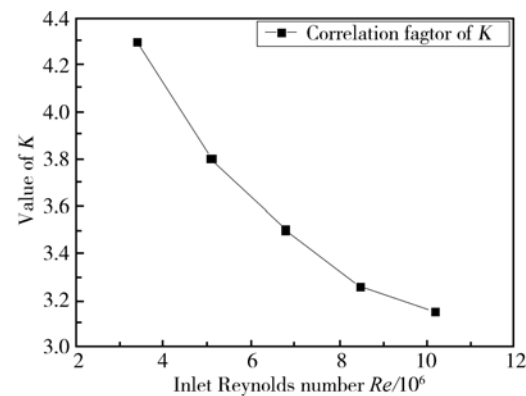


Fig. 6 Correlation factor of K against the inlet Reynolds number

K decreases with the increasing of the inlet Reynolds number. This is because heat transfer coefficient increase as the increasing of inlet Reynolds number, the air takes away more heat and then the heat loss decreases. K decreases with the decreasing of the heat loss.

Fig. 5 and Fig. 6 also show that although the heating plate is processed adiabatically, the heat loss is so strong that revise is necessary.

3) The modificatory method of heat loss

During the development of the sensor, it can be found that the main source of heat loss is conduction through the shell. Then, the modify method of the lateral conduction is necessary. The modificatory method of heat loss is that: thermocouple 2 is embedded at the wall of the shell; it located at the same level with the heating plate, as shown in Fig. 1. The sensor is covered using insulation material. The power of

$\Phi_{\text{loss-1}}$ added to the heating plate. Under the steady state, the temperature difference ΔT_1 between the heating plate and the shell is calculated according to the temperatures of thermocouple 1 and thermocouple 2. A fitting relationship between the temperatures ΔT_i and the heat loss $\Phi_{\text{loss-i}}$ is obtained by channaging the power of Φ_{loss} .

$$\Phi_{\text{loss}} = F(\Delta T) \quad (5)$$

When applying the sensors, the modified heat loss Φ_{loss} can be calculated by submitting the real temperature difference ΔT to Eq. (5). The modified heat transfer coefficient can be calculated using the following equation

$$\begin{aligned} h &= \Phi / A(T_w - T_f) = \\ (\Phi_{\text{hot}} - \Phi_{\text{loss}}) / A(T_w - T_f) = \\ (UI - \Phi_{\text{loss}}) / A(T_w - T_f) \end{aligned} \quad (6)$$

Fig. 7 and Fig. 8 show the modified experimental results, according to Eq. (6). The results show that the error between the sensor and the calibration apparatus is reduced dramatically. The results also show that the correlation factor K is constant of 1.97 for different inlet Reynolds number; the effects of heat loss and Reynolds number can be ignored. The relative error is lower than 3.2% after modified work.

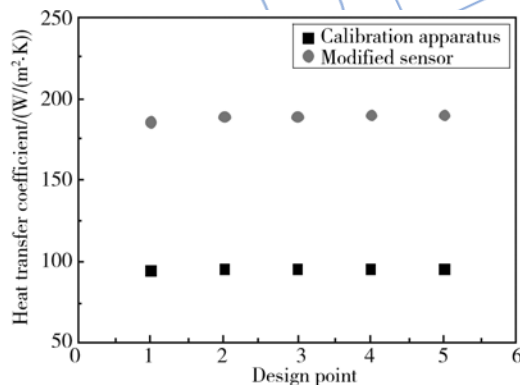


Fig. 7 Modified calibration characteristic of the heat transfer coefficient sensor (inlet Reynolds number $Re=6.78 \times 10^5$)

Under the ideal condition, when the heat loss is modified, the measured heat transfer coefficient should be equal to the measured by calibration apparatus, i. e. K should be close to 1. It can be explained that why K is not equal to 1 according to Eq. (6): the measured coefficient of

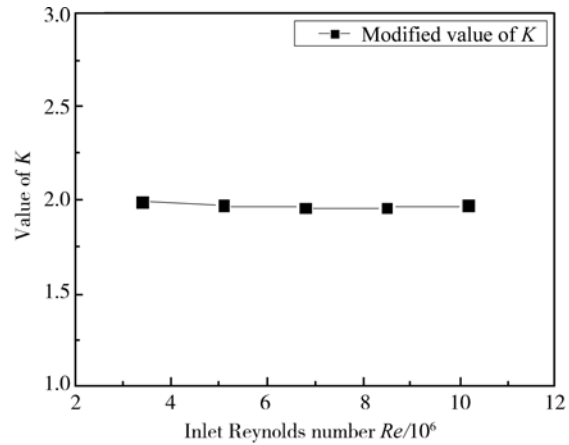


Fig. 8 Modified correlation factor of K against the inlet Reynolds number

heat transfer is not only influenced by the heat loss but also the area and the measured temperature of heating plate. It is difficult to ensure the diameter of heating plate is 6 mm, which is the design diameter. Besides, the temperature of heating plate is obtained with measure error, which is because the thermocouple and the heating plate are agglutinated by the neutral silicone sealant. Because of the combined action of the two reasons, the value of K is not equal to 1, and this the common point of this sensor, such as thermal mass flow.

Moreover, artificial factors have important influence on the manufacture of sensors, so different sensor has different value of K .

4 Calibration of heat transfer coefficient sensor under rotational state

The heat transfer coefficient sensor is calibrated under rotational state to verify the reliability and usability. The calibration is carried out in the rotating heat transfer test facility at the National Key Laboratory of Science and Technology on Aero-Engines Aero-thermodynamics in Beijing University of Aeronautics and Astronautics (BUAA). The test facility includes rotating disc, supporting seat, transmission agent, and data acquisition system. The rotating disc driven by a 30 kW direct current motor can supply the maximum rotate speed of 3000 r/min.

The diameter and thickness of the stainless disc are 800 mm and 25 mm, respectively; the sensor is installed at the location of $r=250$ mm. The experimental data is recorded using rotating AD-AM module, and then the data is translated to computer using carbon-brush-copper callar. The test facility of calibration under rotational state is shown in Fig. 9.

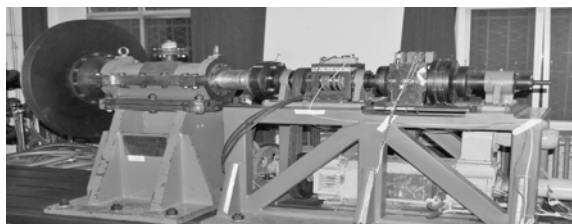


Fig. 9 Test facility of calibration under rotational state

For turbulent flow, Dorfman^[17] provide one approximate empirical formula to calculate heat transfer under rotational state

$$Nu_r = 0.0197(n+2.6)^{0.2}[(r/r_0)^2 Re_\omega]^{0.8} Pr^{0.6} \quad (7)$$

In the experiment, $n=0$ for isothermal disc.

The results show that the correlation factor of K has the same value under static and rotational state. The sensor can be used to measure heat transfer coefficient under rotational state.

5 Conclusions

A heat transfer coefficient sensor based on static measurement has been designed, manufactured and calibrated. The intent is to use this sensor on a rotating surface. The results showed that:

1) It is critical to reduce the heat loss as low as possible for the sensor. After calibration, the correlation factor of K is constant; the maximum error of measurement is 3.2%. K has the same value under static state and rotational state.

2) Different sensor has different value of K .

3) The sensor can measure heat transfer coefficient under rotational state.

This sensor possess many advantages such as, high measuring accuracy, high reliability, excellent durability, strong plasticity of the con-

figuration, and small disturbance on the flow field. Because the output signal is voltage, it is beneficial to signal acquisition.

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