

# Heat Transfer Measurements on A Micro Disk with High Rotational Speed

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**Abstract**—Compared with the conventional gas turbine, the micro gas turbine has the advantages of small size, light weight, and high power density energy. The application prospect is very broad in the future. However, lots of traditional cooling designs cannot be applied to the disks at the micro scale, which makes the heat transfer of such a disk system a major problem. In this paper, a transient experimental method is proposed to investigate the local heat transfer on a rotating micro disk with a diameter of 8 mm by measuring the temperature on the disk with an infrared scanning radiometer. The heat transfer of a single rotating micro disk is compared with the theoretical analyses when the rotating Reynolds number is low. The rotation speed which is measured using a high precision acceleration sensor based on the vibration signals ranges from 20000rpm to 110000rpm. The results show that heat transfer of the micro disk is in good agreement with the theoretical analyses, which proves that the method is effective for the micro disk with high rotation speed. Moreover, the choice of the time interval in the transient method has no influence on the results.

**Keywords**—rotating disk; micro disk; heat transfer; transient experiment

## I. INTRODUCTION

Advances in micro-electro-mechanical systems (MEMS) have focused on flow and heat transfer in micro channels. Classical continuum and thermodynamic equilibrium models begin to break down as channel size is reduced [1]. Specifically, the current development of micro-scale power generation systems demonstrates new directions in concepts for portable, disposable and low cost systems at the scale of a shirt button. At this size, thermodynamics is the same as for conventional gas turbine engines, but fabrication constraints in the micro scale prevent the conventional cooling methods of the micro turbine. Thus, the heat transfer from the turbine to the compressor becomes an important way to reduce the temperature of the turbine. The heat convection in the micro disc cavities between the turbine and the compressor is a very important factor for the heat transfer problem. Average heat transfer on the rotating disk in still air was the most common subject of experimental studies concerning heat transfer in the rotating systems [2, 3]. Von Karman [4] first described the flow near a single rotating disk theoretically using an approximate method. The thickness of the boundary layer is

independent of the radial distance but depends on the rotational speed and the fluid kinematic viscosity. The inertial effects due to the rotation cause the flow to move radially outwards in the boundary layer. Accordingly, ambient air moves from the outside of the boundary layer towards the surface of the disk. The convective heat transfers on a rotating disk have also been studied by many authors [5-9]. Flow and heat transfer in a rotor-stator disk system have been studied by Daily [10], Dorfman [8] and Owen [11].

There have been many results concerning single disks and rotor-stator systems, but they are often relative to the conventional disk systems. Micro scale disk systems are not quite well documented concerning the flows and the heat transfers. The diameter of the micro disks in micro turbines studied in this paper is 8 mm. At this size, temperatures have to be measured without contact of the disk. Since the shaft of the disk is solid, the heating device cannot be connected to the disk. For these reasons, this article proposes a transient experimental method to study the convective heat transfers over a micro disk with high rotational speed.

## II. EXPERIMENTAL APPARATUS AND PROCEDURE

### A. Apparatus

The sketch of the experimental apparatus is shown in Fig. 1. The apparatus consists of a 8mm diameter disk with a 1.6mm diameter solid shaft. The 0.5mm-thick micro disk with a solid shaft is made of 45 steel. The shaft is connected to a dental drill which can be rotated at speeds within the range 30000- 120000 rev/min by changing the pressure of the compressor. Under the rotation speed, all the conditions are under laminar flow. To enhance the IR radiant emissivity of the micro disk, the measured board surface is coated with a thin layer of black paint which has a total emissivity coefficient equal to 0.92 in the working IR window of the employed IR scanner.

The infrared thermo graphic system is based on FLIR SC7700M. The field of view is scanned by the detector in the 1.5-5  $\mu\text{m}$  IR window. Nominal sensitivity expressed in terms of noise equivalent temperature difference is  $\pm 1\%$  of the tested temperature when the scanned object is  $-20^\circ\text{C}$  - $150^\circ\text{C}$ . The thermal image is digitized in a frame of  $640 \times 512$  pixels.

Because of the micro scale of the disk and the structure of the dental drill, the current engine speed detection method cannot be used here. A PCB acceleration sensor based on the vibration signals of the dental drill is used to measure the high rotational speed.

The electric hot air blower is used to heat the disk when the disk arrives at a steady rotational speed. The heating time is about 20 s, and then the IR detector begins to record the temperature of the disk surface in the following 5s.

### B. Procedure

The Biot number presents the ratio of the resistance of heat conduction and the thermal resistance of heat convection. The Biot number is an important factor in the transient experiment:

$$Bi = hl/\lambda_s \quad (1)$$

where,  $\lambda_s$  is the thermal conductivity of the 45 steel,  $l$  is half of the thickness of the micro disk and  $h$  is the local heat transfer coefficients. Under the conditions of the experiment,  $\lambda_s \approx 50 \text{ W/(m}\cdot\text{K)}$ ,  $l = 0.25 \text{ mm}$ ,  $h < 1000 \text{ W/(m}^2\cdot\text{K)}$ ,  $Bi$  is less than 0.1, and thus the resistance of heat conduction can be ignored. At any time, the temperature distribution normal to the disk surface in the 45 steel is uniform. Given that the disk is fairly thin, the radial conduction can be ignored, and the energy equation is obtained:

$$\rho_s c V dT/d\tau = -h_r A (T - T_f) \quad (2)$$

where,  $\rho_s$  is the density of the disk,  $c$  is the heat capacity of the disk,  $V$  is the volume of the disk,  $T$  is the temperature of the disk surface,  $T_f$  is the ambient temperature,  $A$  is the area of the disk in the flow and  $\tau$  is the time interval.

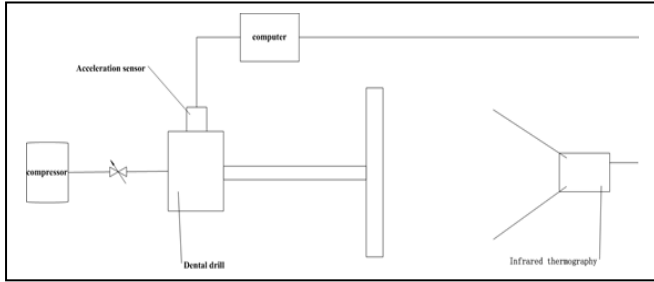


Fig. 1. Experimental apparatus.

Then the expression of the local heat transfer coefficient  $h_r$  is determined:

$$h_r = (\rho_s c l / \tau) \ln(\theta / \theta_i) \quad (3)$$

where,  $\theta = T - T_f$  is the temperature difference and  $\theta_i = T_i - T_f$  is the temperature difference at different time.  $T$  and  $T_i$  are measured by the IR detector, and also the time  $\tau$  is recorded.

For the 45 steel, the physical properties are determined by the temperature of the disk in the experiment. The density, the heat capacity and the thickness of the disk are as follows:  $\rho_s = 7850 \text{ kg/m}^3$ ,  $c = 472.5 \text{ J/(kg}\cdot\text{K)}$ ,  $l = 0.25 \text{ mm}$ . The ambient temperature  $T_f$  is measured by a k-type thermocouple away from the disk. The infrared scanning radiometer records the temperature of the disk surface  $T_i$  and the time  $\tau$ . Then the local heat transfer coefficient over the micro disk surface is obtained.

### III. RESULTS AND DISCUSSION

This part is about the experimental results compared with the heat transfer coefficient over a single rotating disk. All the conditions are under laminar flow due to the micro scale of the disk. The Rotating Reynolds number  $Re = \rho_a \omega R^2 / \mu$  ranges from 2220 to 11652, where  $\rho_a$  is the density of the cooling air,  $\omega$  is the rotational speed,  $R$  is the max radius of the micro disk, and  $\mu$  is the dynamic viscosity of cooling air.

Thermographic images at different moments of the micro disk rotating at 27360rpm are shown in Fig. 2. As expected, most of the disk surface appears at uniform temperature due to the thickness and high thermal conductivity of the disk, so the micro disk can be treated as an isothermal disk. Then the theoretical solutions for the isothermal rotating disks can be compared with our experimental results. For laminar flow, when the Prandtl number  $Pr = 0.71$  and the temperature of the disk surface is isothermal, Dorfman [8] suggests:

$$Nu_r = 0.326 (Re_{\omega,r})^{0.5} \quad (4)$$

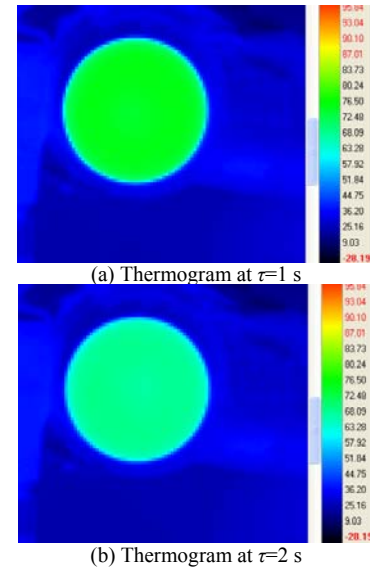


Fig. 2. Thermogram for  $\omega = 27360 \text{ rpm}$  at different time.

where, the local Nusselt number  $Nu_r = h_r r / \lambda_a$ ,  $r$  is the local radius of the micro disk,  $\lambda_a$  is the thermal conductivity of the cooling air,  $Re_{\omega,r} = \rho_a \omega r^2 / \mu$  is the local rotating Reynolds number,  $\rho_a$  is the density of the cooling air,  $\omega$  is the rotational speed, and  $\mu$  is the dynamic viscosity of cooling air. Then the local heat transfer coefficient is

$$h_r = 0.326 \lambda_a (\rho_a \omega / \mu)^{0.5} \quad (5)$$

The physical properties of the air are determined by the ambient temperature  $T_f$ , and then the density, thermal conductivity and dynamic viscosity of the air in the experiment are as follows:  $\rho_a = 1.185 \text{ kg/m}^3$ ,  $\lambda_a = 0.0263 \text{ W/(m}\cdot\text{K)}$ ,  $\mu = 1.835 \times 10^{-5} \text{ Pa}\cdot\text{s}$ .

#### A. Influence of Time Interval $\tau$

In (3), there is a variable  $\tau$ . The record time in the experiment is 5 s, so the time interval  $\tau$  ranges from 0 to 5 s. Different time intervals ranged from 0.1 s-4 s are chosen to simulate the local heat transfer coefficient. For example, if  $\tau = 0.1 \text{ s}$ , each time interval of 0.1 s is used to calculate a heat transfer coefficient. Then an average of all the heat transfer under  $\tau = 0.1 \text{ s}$  can be obtained. Fig. 3 shows the local heat transfer coefficient under different time intervals  $\tau$  at  $\omega = 106740 \text{ rpm}$ . It is obvious that the heat transfer coefficient does not change with  $\tau$ .

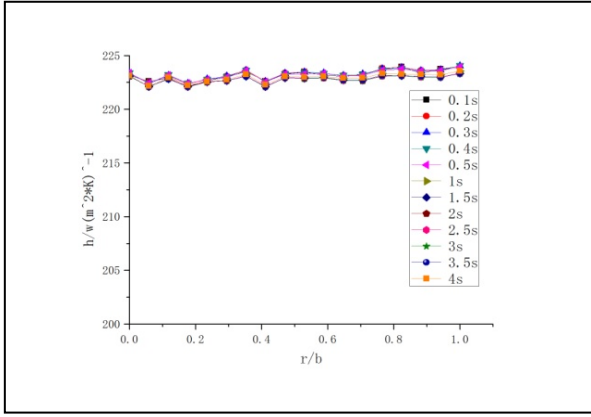


Fig. 3. Local heat transfer coefficient under different  $\tau$  at  $\omega = 106740$ .

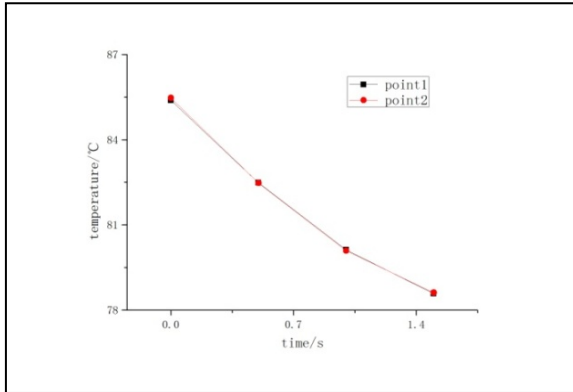


Fig. 4. The temperatures of two axisymmetric points at different moments at  $\omega = 2000 \text{ rpm}$ .

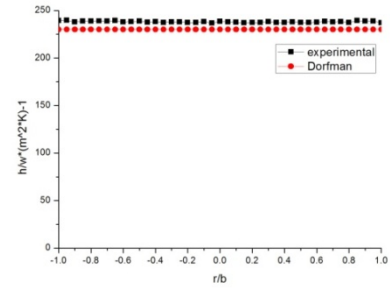
#### B. Influence of the Rotation Speed

The max full frame rate of the infrared camera is 115 Hz, but the frequency of the micro disk is much higher. If the

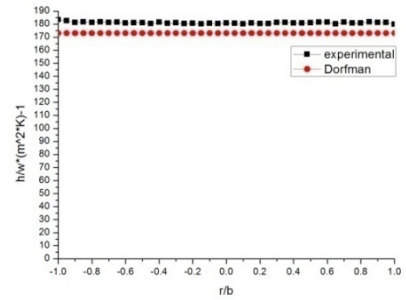
temperature on the disk surface is axisymmetric, the temperature captured by the infrared camera will be reliable. Fig. 4 shows the temperatures of two axisymmetric points at different moments at  $\omega = 2000 \text{ rpm}$ . It is obvious that the temperatures of the two points are almost the same at different moments, and thus the temperature distribution on the micro disk can be treated as axisymmetric. Then the temperature captured when the rotation speed is high is reliable.

#### C. Comparison With The Conventional Disk

Fig. 5 shows the local heat transfer coefficient for tested rotating Reynolds numbers. Each profile is compared with the theoretical solutions for the conventional disk proposed by Dorfman. For a rotating Reynolds number of 6621, the experimental results are in good agreement with Dorfman's solution for the max error about 6%. For a higher rotating Reynolds number of 11652, the experimental results are in good agreement with Dorfman's correlation for the max error less than 4%. Thus, when the rotating Reynolds number is low, the solution of heat transfer over the micro rotating disk is the same with the conventional disk. Fig. 6 shows a comparison of the local heat transfer coefficient between the micro disk with a diameter of 8mm and a conventional disk with a diameter of 200mm at the rotating Reynolds number of 11652. It is obviously seen that when the rotating Reynolds number is small, although they have the same  $Nu_r$ , the local heat transfer coefficient of the micro disk is much larger than the conventional one. Consequently, size reduction of the disk enhances the heat transfer coefficient over the disk surface.



(a) Local heat transfer coefficient when  $Re = 6621 (\omega = 60660 \text{ rpm})$



(b) Local heat transfer coefficient when  $Re = 11652 (\omega = 106740 \text{ rpm})$

Fig. 5. Local heat transfer coefficient over the rotating disk

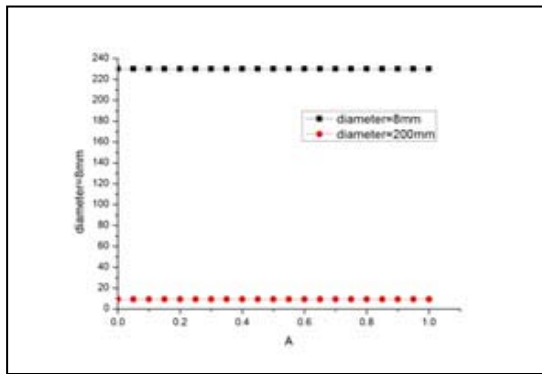


Fig. 6. Local heat transfer coefficient over the rotating disks of different diameters at  $Re=11652$

#### IV. CONCLUSION

A transient method to measure heat transfer on a rotating micro disk is proposed by using an infrared scanning radiometer. The transient method is proved to be advantageous on short research period and small error. Simultaneously, the use of the infrared camera has the advantages of good spatial resolution for the micro disk and thermal sensitivity. Moreover, in the experiment, the authors measured the high rotational speed using PCB acceleration sensor based on the vibration signals.

When the rotating Reynolds number is low, experimental results of the micro disk are in good agreement with the theoretical analyses of a single rotating disk, but the size reduction of the disk enhances the heat transfer coefficient over the disk surface. Comparison with the theoretical analysis demonstrates the method can be applied to the micro disk. The time interval has no influence on the heat transfer.

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