Investigations of thermal conductivity of metals in the field of centrifugal and vibration accelerations

A R Lepeshkin and P A Vaganov

Baranov Central Institute of Aviation Motors Development, Aviamotornaya Street 2, Moscow 111116, Russia

E-mail: `lepeshkin.ar@gmail.com`

Abstract. The methods of investigations of a thermal conductivity of materials in the field of centrifugal radial and circumferential and vibration accelerations have been developed. The setup for investigation of thermophysical characteristics properties of materials on a spin rig, using a vacuum chamber, under the influence of centrifugal radial and circumferential accelerations and on a vibration rig under the influence of vibration accelerations have been proposed. The results of the investigations of an unsteady thermal state of heat-conductors (metal samples) in the field of centrifugal and vibration accelerations are given. From the analysis of the results of experimental investigations one can conclude that the thermal conductivity of the heat-conductors increases significantly by increasing the rotation frequency or amplitude of oscillations in comparison with a steady state. Thus, this increase of the thermal conductivity is associated with an increase of the electron drift velocity under the influence of centrifugal and vibration accelerations according to Wiedemann–Franz law. The results obtained are of practical importance for the calculations of the thermal state of the rotating parts of aircraft engines and other energy turbomachines.

1. Introduction

The knowledge of thermophysical properties of materials (thermal conductivity, *etc*) is required to determine a thermal state of various structures and components of aircraft engines and other energy turbomachines [1–4]. The investigations of the thermal conductivity of metals in the field of action of centrifugal and vibration accelerations is a new work which is important for aerospace engineering. The thermal conductivity of material of blades and disks is used in the calculation of the thermal state of parts of a turbine rotor. Turbine blades operate at centrifugal accelerations of (4000–20000)g and vibration accelerations (100–5000)g and we can expect significant thermoconductivity change in these conditions [5, 6]. The information on electronic phenomena in metals is given in [7, 8]. The Russian scientists Mandelstam and Papaleksi observed this phenomenon experimentally in 1913. In their experiment the variable potential difference across the ends of the wire coils arises during its rotation and the phone attached to the ends of the coil wire rang. This experiment has been enhanced in 1916 by the American scientists Tolman and Stewart [7, 8]. In this experiment the coil had been rotating rapidly and then it braked abruptly. In this case, the electrical current pulse was recorded by a ballistic galvanometer. This pulse is associated with the inertial motion of free charges (electrons have mass) in a thin copper wire of the coil. The electrons continue to flow during abrupt braking of conductor acceleration. These experiments confirmed that the accelerations (inertial

Figure 1. Spin rig and flat disk.

forces) effect on the electron phenomena in metals under braking. In these experiments the braking accelerations were (4–30)g. However conclusions and assumptions about the influence of electronic effects in the thermal processes in the short wires and rotary parts had not been done from these experiments. In [5] the investigations of the thermal conductivity of materials using a single radial heat-conductor have been carried out. In this paper the methods and devices for investigations of thermal conductivity of materials in the field of centrifugal radial and circumferential and vibration accelerations have been presented.

2. Experimental methods, results and discussion

We investigated the thermal conductivity of the materials in the field of centrifugal radial and circumferential accelerations during tests on the spin rig (figure 1). The method of the investigations and device are developed and presented in work [6]. The first radial heat conductor with angle 45 degrees to the radial direction and the second heat conductor in the circumferential direction were placed on the surface of the model flat disk. The insulated conductors consist of a copel wire (length $l = 55$ mm, diameter 0.5 mm) and electric heater with length of 10 mm (figure 2). Thermocouples welded to the ends of the heat-conductors. The model disk with the heat-conductors and heater was installed inside the vacuum chamber of the spin rig (figure 1).

The investigations that we carried out in a vacuum chamber on the spin rig equipped by electromotor with an automatic control system of rotation frequency. Monitoring of a thermal state of the heat-conductors (placed on a rotating disk with a heater) provided with computerized measuring system. The processing of the results was provided by the specially developed program. The wires of the electric heater and thermocouples of the heat-conductor were joined to mercury current collector. The electric heater was supplied from stabilized power source.

The investigations of the thermal conductivity affected by centrifugal radial and circumferential accelerations were carried out in accordance with the developed method. In the first investigation the basic thermocouple temperature measurements were recorded during the test without rotation. The subsequent investigations in the vacuum chamber using the thermocouple temperature measurements were recorded at each rotation frequency during electric heater work time. The results of the investigations of an unsteady heat of the radial and circumferential heat-conductors are shown on figures 3 and 4. It is known that the thermal conductivity of a material is a function of the heating rate. The processing of experimental heating curves (see figures 3 and 4) with regard to this functional dependence was carried

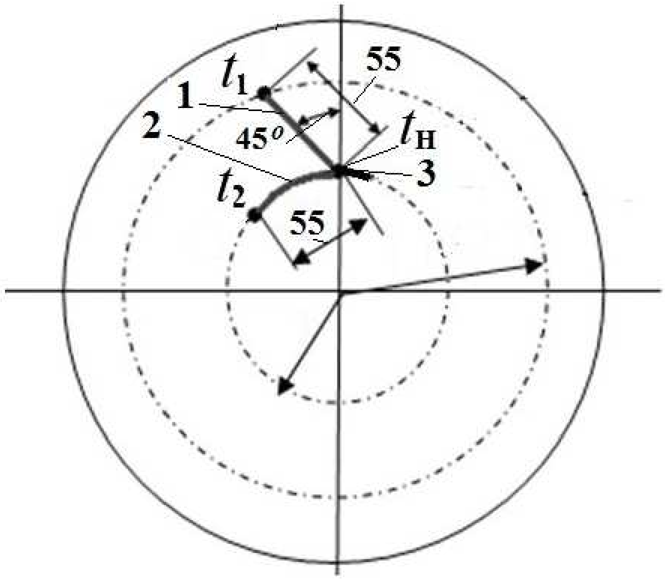

Figure 2. Experimental scheme of a heat-conductor placed on rotating disk: 1—insulated radial heat-conductor, 2—insulated circumferential heat-conductor, 3—small heat source—electric heater on the flat disk; t_1, t_2, t_H—temperatures.

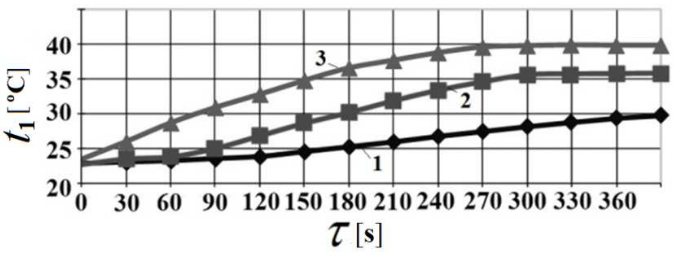

Figure 3. Temperatures on the end of the radial heat-conductor t_1 depending on the heating time at different rotation frequencies: 1—0, 2—2500 r.p.m., 3—5000 r.p.m.

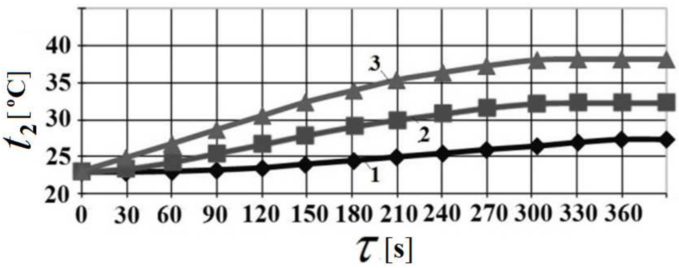

Figure 4. Temperatures on the end of the circumferential heat-conductor t_2 depending on the heating time at different rotation frequencies: 1—0, 2—2500 r.p.m., 3—5000 r.p.m.

out. As a result the heating rate curves of the radial and circumferential heat-conductors were obtained (figures 5 and 6).

As analysis of curves in figure 4 shows, the centrifugal radial and circumferential accelerations significantly influence on the thermal conductivity of a material of the heat-conductors. As well known for metals, the electron mechanism of heat transport is much more efficient than the phonon contribution. Since free electrons are responsible for both electrical and thermal conductivity in metals, theoretical treatments suggest that the two conductivities should be related according to the Wiedemann–Franz law. The typical electron drift velocity (average velocity of the free electrons) is 1–2 mm/s [9, 10]. The value of heating rate (and electron drift velocity) of the samples are increasing approximately to 2.5 and 3.0 times in radial direction (figure 5) for rotation frequencies 2500 and 5000 r.p.m., respectively, in comparison with the steady state without rotation. Moreover, the heating rate in the radial direction is much greater than that in the circumferential direction respectively for 35% and 15% at 2500 and 5000 r.p.m. (figures 5 and 6). This can be explained by the fact that the radial inertia forces greater than

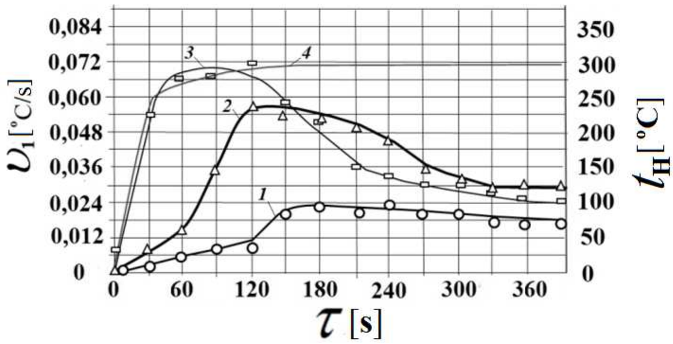

Figure 5. Heating rate on the end of the radial heat-conductor depends on the heating time at different rotation frequencies: 1—0, 2—2500 r.p.m., 3—5000 r.p.m., 4—temperature of the electric heater t_H.

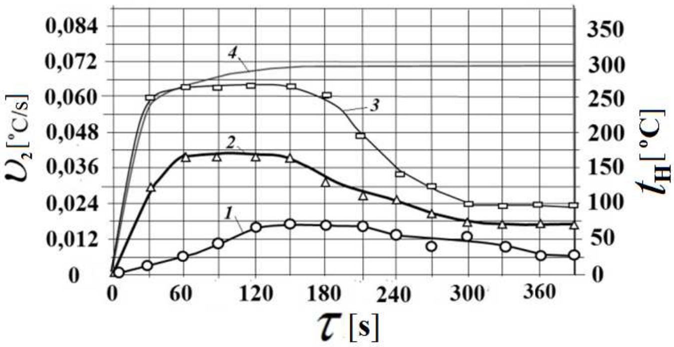

Figure 6. Heating rate on the end of the circumferential heat-conductor depends on the heating time τ at different rotation frequencies: 1—0, 2—2500 r.p.m., 3—5000 r.p.m., 4—temperature of the electric heater t_H.

Figure 7. The vibration rig.

the Coriolis forces (in the circumferential direction) during influence on the average velocity of the free electrons.

The investigations of the thermal conductivity of the materials in the field of vibration accelerations were carried out on the vibration rig (figure 7) using developed method and the

Figure 8. The gear for the thermal conductivity investigations of the materials in the field of vibration accelerations.

gear (figure 8). The test chromel heat conductor wire (length $l = 55$ mm, diameter 0.5 mm) and a small electric heater (length of 10 mm) are fixed on the end of the arm. The arm is mounted on a vibrating rig. The thermocouples (figure 9) welded on the ends of the heat conductor: 1—the thermocouple in the end of the heat-conductor 3, 2—the thermocouple in the front end of the heat-conductor 3 (before heater 4). The electric heater 4 and heat conductor 3 are insulated from four arm 5 (figure 9). The arm mounted on a rig (figure 8). The studies were conducted using an automatic control system to maintain a predetermined amplitude and frequency of the oscillations. Monitoring of the temperatures of the heat-conductor (placed on the arm) provided with a computerised measuring system.

The results of a research of non-stationary heating of the heat conductor in the field of vibration accelerations at different amplitudes vibrations at a frequency of 120 Hz were obtained. The curves of the heating rates depending on the heating time (or the time of heat transfer) after processing of the experimental data are obtained and presented in figure 10. Analysis of experimental results and behavior of heating rate curves (figure 10) show that the thermal conductivity of the chromel heat-conductor (at vibration acceleration $120g$) increases by 50% in comparison with a static state. The curve of the heat transfer time (from front end to rear end of the heat-conductor) at different oscillation sweeps $2A$ (0, 3.5 and 7 mm) shown in figure 11. The heat transfer time on the heat conductor is reduced by 1.5 times at $120g$ in comparison with a static state from the analysis of the data in figure 5. The increasing of the thermal conductivity (the decreasing of the heat transfer time) can be also explained by the fact that the motion of free electrons becomes more orderly and the electron drift velocity increases under the influence of vibration accelerations.

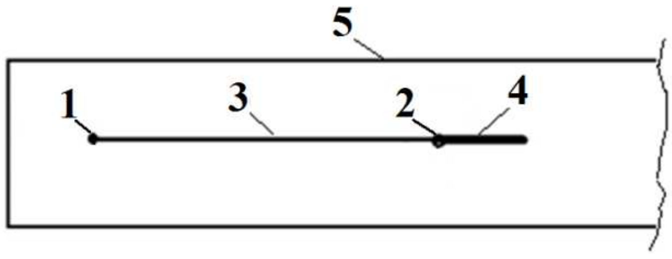

Figure 9. Scheme of the placement: 1, 2—thermocouples, 3—heat conductor, 4—electric heater, 5—arm.

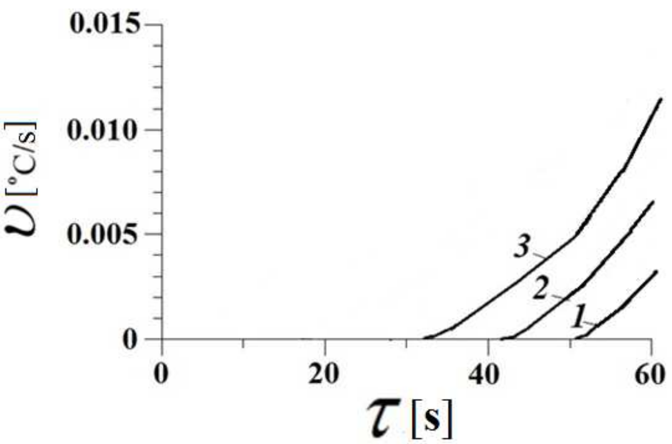

Figure 10. The curves of the heating rates v depending on the heating time at oscillation sweeps $2A$: 1—0, 2—3.5 mm, 3—7 mm.

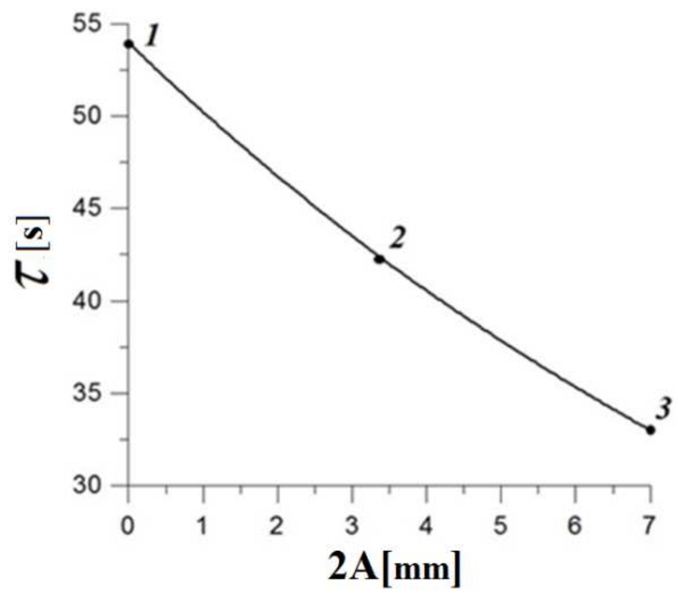

Figure 11. The curve of the heat transfer time depending on oscillation sweeps $2A$: 1—0, 2—3.5 mm, 3—7 mm.

3. Conclusion

The methods for investigation of thermal conductivity of materials in the field of centrifugal radial and circumferential and vibration accelerations have been developed. The gears with heat conductors for the measurement of the thermophysical properties of materials on the spin rig using the vacuum chamber in conditions of centrifugal radial and circumferential accelerations and on the vibration rig in conditions of vibration accelerations have been developed. The results of the investigations of unsteady thermal state of heat-conductors (metal samples) in the field of centrifugal and vibration accelerations are given. From the analysis of the results of experimental investigations it is concluded that the thermal conductivity of the heat-conductors increases significantly with an increase of a rotation frequency or amplitude of oscillations in comparison with a steady state. Author supposes that significant thermal conductivity increasing is associated with the increasing of the electron drift velocity under the influence of centrifugal and vibration accelerations. The obtained results are of practical importance for the assessment of the thermal state of the rotating parts of aircraft engines and other energy turbomachines.

References

[1] Gori P *et al* 2015 *J. Phys.: Conf. Ser.* **655** 012065
[2] Pabst W and Gregorova E 2012 *J. Phys.: Conf. Ser.* **395** 012021
[3] Gregorova E *et al* 2012 *J. Phys.: Conf. Ser.* **395** 012022
[4] Matine A *et al* 2012 *J. Phys.: Conf. Ser.* **395** 012014
[5] Lepeshkin A R and Bychkov N G 2014 *XXIX International Conference on Equations of State for Matter, March 1–6, 2014, Elbrus, Russia. Book of Abstracts* (Moscow, Chernogolovka, Nalchik) pp 40–41
[6] Lepeshkin A R and Bychkov N G 2011 method and device for determining the thermofysical properties of solid materials in the field of centrifugal forces Patent RU 2417367 c1
[7] Ginzburg V L and Kogan S 1972 *J. Exp. Theor. Phys.* **34** 3
[8] Tolman R C and Stewart T D 1916 *Phys. Rev.* **8** 2
[9] Karjakin N I, Bystrov K N and Kireev P S 1969 *Short Guide to Physics* (Moscow: Higher School)
[10] Pavlov P V and Hohlov A F 2015 *Solid State Physics* (Moscow: Lenand)