Technical Notes

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3500-K High-Frequency Induction-Heated Blackbody Source

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Introduction

A HIGH-temperature blackbody source is a radiation source whose emissivity is nearly unity. Its radiation energy distribution as a function of wavelength is in accordance with Planck's formula. It is mainly used to calibrate instruments measuring temperature and thermal radiation, such as radio pyrometers, photoelectrical pyrometers, and thermal radiometers. It can also be used for photometer and spectrometer calibration. There are two ways of heating the sources: resistance heating[1] and induction heating.[2-4] The resistance-heated source will save electric energy, and its radiation aperture is larger than that of the induction-heated source. However, for the former, there are two water-cooled clamps at the end of the blackbody, so therefore, its temperature distribution is not uniform. When the temperature is higher than 3300 K, the graphite blackbody will be loosened, the resistivity in local loosened regions will be increased, the temperature in these regions will be increased continuously and, therefore, easy to break down. The induction-heated source does not house the cooling clamp at the end of blackbody, so that the temperature distribution is uniform at high temperature and the radiation energy distribution is in accordance with Planck's formula. It has a maximum operating temperature greater than the resistance-heated source.

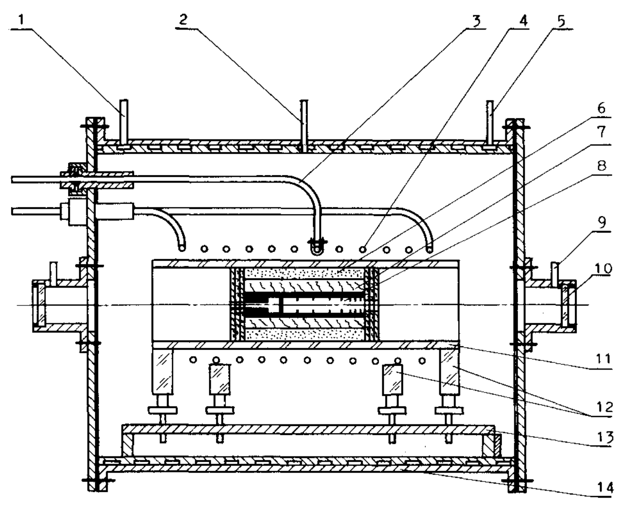
Structure of the Blackbody Source

The structure of the blackbody source is schematically shown in Fig. 1. The outer shell of the furnace shaft was a water-cooled double-layer sleeve made of stainless steel with two viewing windows 50 mm in diameter at both ends. The viewing window was made of calcium fluoride crystal, hence its transmission wavelength range was 0.2–8.5 μm. The furnace could be evacuated and filled with argon. Before operation, the furnace was evacuated to a pressure of 50 Torr. Then the furnace was filled with argon gas. Evacuating and filling must be repeated alternately several times to get a pure argon atmosphere. The purity of the argon gas is 99.985% ($H_2O < 30$ mg/m^3, $O_2 < 0.0015\%$, $N_2 < 0.01\%$). Before flowing into the furnace, the argon gas must pass through a desiccator to eliminate the aqueous vapor. During operation, the pressure of the argon gas in the furnace will be regulated at 1.05–1.2 atm. The high pressure could reduce the volatility of the graphite, but it will increase the possibility of high-frequency sparking within the coil. The inlet for the argon gas was located near the window to prevent it from contamination due to the volatility of the graphite.

The water-cooled induction coil has an outer diameter of 160 mm and a length of 360 mm, its inductance is 26 μH. To ensure inductance matching, there is a movable lead tube located in the middle of the coil. There are three Teflon sleeves and O-rings between the lead tubes and the shell of furnace to serve as an electric insulator and gas seal.

The blackbody cavity was made of high-purity graphite. On the inner wall of cavity, there is a screw-thread-shaped groove to increase the emissivity. The bottom target is cut into a large number of small pyramids by two orthogonal series of V-grooves with an included angle of 45 deg. There are some diaphragms and baffles at the open end of the blackbody to increase the emissivity of the cavity. To obtain a uniform temperature on the inner surface, the bottom target and rear regulative block are removable. When the high-purity graphite was heated to temperatures much higher than 3300 K, considerable volatile matter evolved. The graphite volatilization may cause more consumption of electric energy and even damage the blackbody. Because of this problem, pyrolytic graphite was used to cover the outer surface of the blackbody and its thickness was larger than 0.2 mm. Thus, the ability to resist high temperature was improved considerably.

The requirements for the thermal insulator, which is located outside the blackbody, are that the insulator itself ensure against high-frequency heating, have low electrical and heat



1) Water inlet
2) Vacuum tube
3) Middle lead tube
4) Induction coil
5) Water outlet
6) Graphite sawdust
7) Carbon felt
8) Blackbody cavity
9) Argon gas inlet
10) Calcium fluorid window
11) Boron nitride tube
12) Ceramic seatings
13) Support
14) Furnace shaft

Fig. 1 Blackbody furnace.

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conductivities and high stability at high temperature, and that it is not easy to be agglomerated, which could improve the stability of blackbody temperature. After many types of thermal insulation materials were tested for a long time, finally, the acrylonitrile carbon felt and graphite sawdust combined thermal insulator was selected. The blackbody cavity was wrapped in the carbon felt directly, and the graphite sawdust was filled into the space between the carbon felt insulator and the boron nitride tube. Because the graphite sawdust is located at the outer layer and its electrical conductivity is lower than graphite blackbody and carbon felt, the blackbody can be heated efficiently by the high-frequency current. Furthermore, the sawdust is in a region of low temperature and not easily agglomerated.

A boron nitride tube is used for supporting the blackbody and thermal insulator. Because of its high insulation properties and strength at high temperature, the boron nitride tube does not undergo phase transition and avoids cracks as did the silica tube.

Power Supply and Temperature Control

The oscillating frequency of high-frequency generator GP 60-CR 13 is 200–250 kHz. Its available maximum power is 60 kW. A 200-kVA automatic voltage regulator was used as its power supply, and the voltage stability is less than 1%.

The graphite blackbody and carbon felt both are antiferromagnetic matter. When the blackbody and carbon felt are fed to the induction coil, the inductance of the coil decreases and the quality factor Q drops rapidly. In order to overcome these problems, some improvements had to be made, such as increasing the ratio of coil-to-blackbody diameter, increasing the inductance of the coil, and regulating the location of the middle lead tube to improve the load matching. After calculation and testing, all of these deficiencies were overcome.

Because of the fluctuation of the supply voltage and the slow change in the electrical conductivity and the thermal conductivity of both the blackbody and insulator at high temperature, the temperature of the blackbody will subsequently fluctuate and decrease slightly. A temperature controller has been developed. A signal received by the silicon cell from the blackbody radiation and another signal from the fluctuation of supply voltage will be checked against a predetermined level. The difference, if any, will be amplified by means of a PID (proportional-integral-derivative) regulator to control a pulser, changing its number of pulses to modulate the pulsewidth of the wide pulse circuit. Consequently, the output of the silicon-controlled voltage regulator will be changed, which is used again to control the high-voltage system to adjust its power output; therefore, the temperature stability of the blackbody will be improved considerably. As a result of using the PID regulator, the temperature controller used has a high sensitivity, rapid response, and a wide range of regulation. When the operating temperature is less than 3000 K, the temperature stability is within 2 K.

Temperature Distribution and Emissivity Calculation

If the temperature of the inner surface of the blackbody is not uniform, the spectral distribution will not be in accordance with Planck's formula. Therefore, temperature uniformity is essential to the blackbody. The temperature distribution of the present blackbody source can be regulated by moving the location of the induction coil and changing the interval of the coil. Using some temperature measurement targets distributed along the axis of the blackbody cavity, the temperature field can be measured by a precise optical pyrometer. The results obtained (see Fig. 2) show that uniformity of the temperature field within the length-to-radius ratio of $L/r = 5$ is better than the resolution of the precise optical pyrometer.

Quinn's equation[5] was used to estimate the emissivity of blackbody:

$$\varepsilon_0 = 1 - \left[1 + \left(\frac{\rho}{1-\rho}\sin\frac{\theta}{2}\right)^{-1}\right]^{-1}\frac{a^2}{D^2} - \rho^2 a^2 I^2 \qquad (1)$$

where ρ is the reflectivity of graphite ($=0.25$), θ the angle of the grooves on the bottom target ($=45$ deg), a the radius ratio of the aperture to the cavity ($=0.5$), D the ratio of the length to the radius of the cavity ($=6.7$), and I_2 Quinn's second-order correction coefficient. When $D = 7$, $I_2 = 0.0105$. Calculations show that the value of ε_0 is 0.999.

Considering the nonuniformity of the temperature distribution, Buckley's equation[6] was also used to calculate the emissivity of the blackbody:

$$\varepsilon_0 = \varepsilon + (1-\varepsilon)\frac{1}{T_0^4}\int_0^L T_x^4\left(-x + \frac{\sqrt{x^2+4}}{2} + \frac{x^2}{\sqrt{x^2+4}}\right)dx \qquad (2)$$

where ε is the emissivity of high-purity graphite ($=0.75$), T_0 the temperature of bottom target, x the distance from bottom target, T_x the temperature at the location x, and L the length of blackbody cavity. The computed value of ε_0 is 0.996. Because there are a large number of small pyramids and grooves on the bottom target and inner wall, respectively, the emissivity of blackbody is larger than 0.996.

Performance of the System

The quality of the pyrolytic graphite is important. Operating at high temperature, if the quality of the pyrolytic graphite was bad, the blackbody would suffer some damage and could not attain the temperature of 3500 K. After operating for a long time above 3000 K, the thickness of carbon felt will decrease and must, therefore, be replaced. The operation can endure only 30 min at a temperature of 3500 K. After that, the temperature drift would increase rapidly and the temperature controller could not attenuate it.

After extensive testing and developing, the present source achieves the desired specification. The maximum operating temperature is 3500 K, the temperature fluctuation is less than 2 K at 3000 K and 4 K at 3400 K. The radiation aperture is 15 mm, and emissivity of blackbody is about 0.996–0.999. At $L/r = 6$, the temperature of the inner wall is 16 K lower than the temperature of the bottom target at the blackbody temperature of 2656 K, and 30 K at the blackbody temperature of 3266 K.

Up to now, this blackbody source has found wide use for the calibration of various pyrometers, such as the radiation

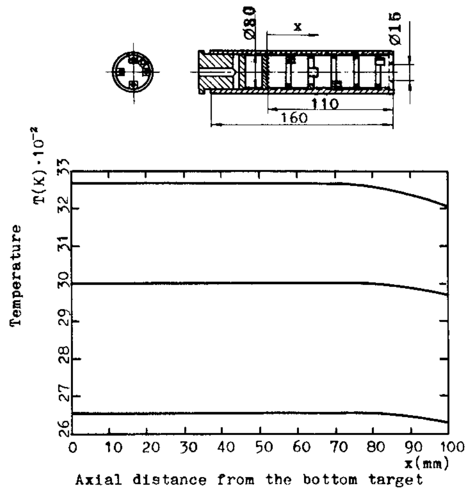

Fig. 2 Axial temperature distribution of blackbody cavity and arrangement of targets for measuring temperature.

pyrometer with a vaccum thermopile detector, the multispectral pyrometer with a photomultiplier tube detector and an InSb detector, and the multiwavelength range thermal radiometer with an InSb detector. The results of its application are sufficiently satisfactory.

References

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Natural Convection of a Variable Property Gas in Asymmetrically Heated Square Cavities

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Introduction

NATURAL convection flows of Boussinesq fluids confined in rectangular and cylindrical enclosures have been extensively investigated, and reviews of the literature are found in Ostrach[1,2] and Catton.[3] Although these analyses yield understanding of flows of technological importance, little research effort has been made in investigating the effects of the fluid property variation on the flow and heat transfer characteristics that may be significant when a large temperature difference is present in problems of interest. In order to study these flows, the original Navier-Stokes and energy equations (without simplification by the Boussinesq approximation) must be solved with specified relationships for the fluid property variation.

The properties of different fluids behave differently with temperature. For gases, the specific heat varies only slightly with temperature, density varies inversely with the first power of the absolute temperature, whereas viscosity and thermal conductivity increase with about the 0.8th power of the absolute temperature. Thus, the Prandtl number does not vary significantly with temperature, but viscosity for Newtonian liquids and thermal conductivity for pseudoplastic liquids vary markedly with temperature. Hence, investigations on variable property effects need to be carried out for specific fluids. The effects of the temperature-dependent fluid properties on boundary-layer natural convection flows are reviewed by Kakac et al.[4] For flows in enclosures, previous investigations[5-10] consider air as the medium. Zhong et al.[8] address the limits of the validity of the Boussinesq approximation for square cavities with differentially heated side walls. They also suggest using a weighted reference temperature for better correlation of heat transfer results. A volume-weighted mean temperature is proposed in Ref. 10 that analyzes the flows in horizontal isothermal concentric cylinders.

The present paper studies convective flows of a variable property gas (air) in an asymmetrically heated square enclosure. The geometry of the problem is shown schematically in Fig. 1. The cavity has a centrally located heated section on its bottom plate and a cooling element on one side wall. These partial heaters are maintained at constant temperatures with different values, whereas the remaining portions of enclosure walls are insulated. The present investigation assumes an infinitely long enclosure.

Mathematical Formulation

The laminar, steady, two-dimensional natural convection flows studied here are described by the Navier-Stokes and energy equations. The viscous dissipation is neglected because of the small magnitude of the velocity induced by natural convection. The governing equation system is

$$\frac{\partial}{\partial x}(\rho u)+\frac{\partial}{\partial y}(\rho v)=0 \tag{1}$$

$$\frac{\partial}{\partial x}(\rho uu)+\frac{\partial}{\partial y}(\rho vu)=-\frac{\partial p}{\partial x}+\mathrm{Pr}\left\{\frac{\partial}{\partial x}\left[\mu\left(2\frac{\partial u}{\partial x}-\frac{2}{3}D\right)\right]+\frac{\partial}{\partial y}\left[\mu\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)\right]\right\} \tag{2}$$

$$\frac{\partial}{\partial x}(\rho uv)+\frac{\partial}{\partial y}(\rho vv)=-\frac{\partial p}{\partial y}+\mathrm{Pr}\left\{\frac{\partial}{\partial x}\left[\mu\left(\frac{\partial v}{\partial x}+\frac{\partial u}{\partial y}\right)\right]+\frac{\partial}{\partial y}\left[\mu\left(2\frac{\partial v}{\partial y}-\frac{2}{3}D\right)\right]\right\}-\frac{\mathrm{GrPr}^2}{\epsilon}\rho g \tag{3}$$

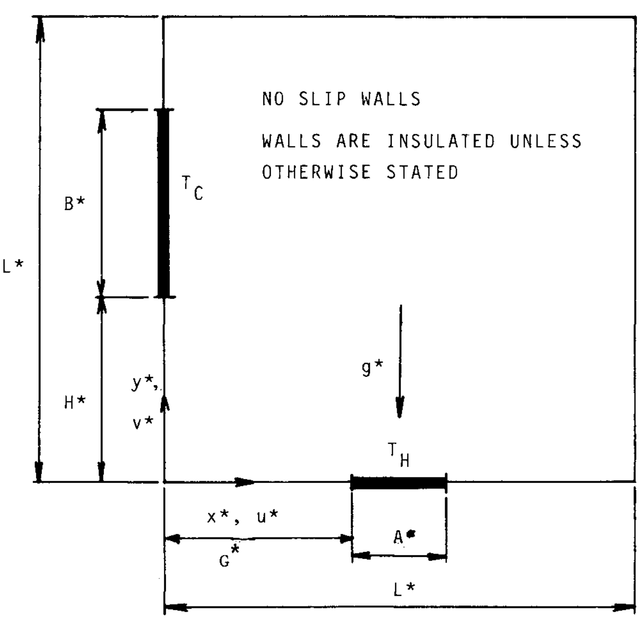

Fig. 1 Geometry and boundary conditions of the problem.

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