DESIGN OF A LOW-TEMPERATURE BLACKBODY RADIATION RESOURCE WITH A FROST PREVENTION UNIT

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Abstract: A new type of blackbody radiation resource for providing target temperatures between -80 ℃ and + 100 ℃ is presented. The blackbody adopts a stirred fluid bath to achieve temperature uniformity along the cavity and uses nitrogen gas to flush the cavity. The temperature of nitrogen gas is the same as that of the bath because the gas is heat exchanged with the working fluid in the bath. In this way, the designed blackbody can prevent air condensation on the wall and the window of the cavity when operated at temperatures below dew point, and furthermore the temperature distribution along with the wall is uniform. The calculated and measured emissivity of the designed blackbody cavity is large than 0.997.

Keywords: Blackbody; Frost prevention; Emissivity; Heat exchanger

1. INTRODUCTION

With the development of sensor technology and microelectronics, the infrared radiation thermometers have been widely used in the various fields of industry and science. Traditionally, they are used in high temperature. Now they are applied in low temperature case, even, in temperature below 0 ℃. The calibration facilities and techniques have been established for the infrared radiation thermometers to meet the demands of calibration [1], [2], [3], [4]. However, when the blackbody is operated below the dew point, it's easy to build up frost on the wall and the window of the blackbody cavity. Due to air condensation, the temperature in the wall of the cavity is inconsistent with that of the fluid bath. A large temperature gradient along with the wall happens also and the effective emissivity of the blackbody will decrease. In this way, the large calibration errors will happen when the infrared radiation thermometers are calibrated against the low temperature blackbody.

In order to solve the above problems, a new type of low temperature blackbody radiation resource is presented which has a frost prevention unit and can be used at temperature of -80 ℃. The unit uses nitrogen gas heat exchanged with the working fluid in the bath to flush the blackbody cavity. Therefore, the cool flush nitrogen gas can prevent frost buildup on the wall and the window of the blackbody cavity when the designed blackbody radiation resource works at temperatures below the dew point temperature of an ambient

air and it is possible to calibrate the infrared radiation thermometers down to -80 ℃.

2. DESIGN OF BLACKBODY

The components of the designed blackbody are shown in Fig.1, which consists of a blackbody cavity, a cooling unit, a heating unit and electrical control systems. The cooling unit, heating unit and electrical control systems are used for temperature controlling.
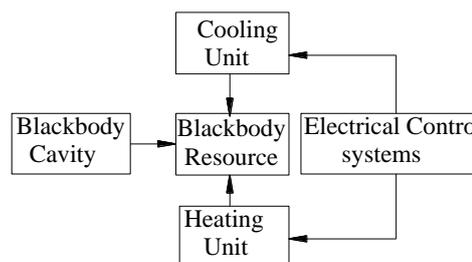

Fig.1 the basic components of the designed blackbody

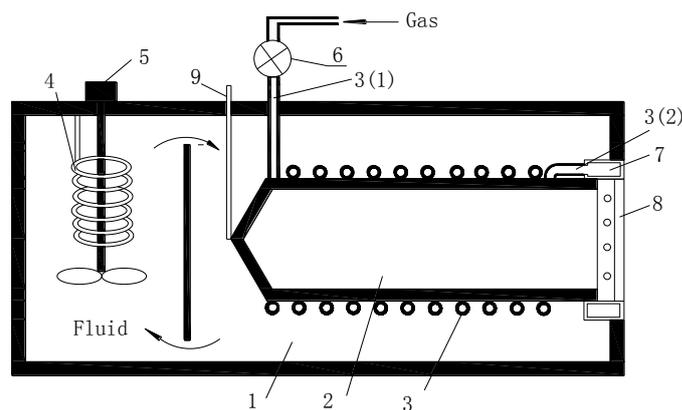The structure of the designed blackbody is shown in Fig.2.

Fig.2 the structure of the designed blackbody

where 1 is the fluid bath, 2 is the blackbody cavity, 3 is the heat exchanger, 3(1) is the inlet of heat exchanger, 3(2) is the outlet of heat exchanger, 4 is the cooling unit and heating unit, 5 is the motor stirring machine, 6 is the pressure reducer, 7 is the flange, 8 is the insulation layer, 9 is the platinum resistance thermometer.

A stirred fluid bath is adopted to achieve temperature

uniformity along the cavity .The bath covers the temperature range from -80℃ to 100℃ and has the blackbody cavity immersed horizontally. The shape of the blackbody cavity is cone-cylinder. It is easy for this type of cavity to achieve temperature uniformity. The heat exchanger coils along the blackbody cavity horizontally. Inlet of the heat exchanger is connected with the pressure reducer and outlet is connected with the flange in which there are apertures. The cooled gas sprays out off the apertures. There is an insulation layer close to apertures.

As shown in Fig.2, in the left side, there are cooling unit, heating unit and motor stirring machine. The right side is the working area, where the blackbody cavity with the heat exchanger is placed. Two sides are communicating by a fluid circulation flow.

The designed blackbody covers the temperature range from -80℃ to 100℃, different temperature ranges with different medium, -80℃ to 0℃(industrial ethanol), below 0℃ (water). A compressor cooling unit starts working for operated at temperatures below an ambient temperature and it can make temperature down to -80℃. Synchronous heating technology is used to make the temperature of the bath stable. Electric heaters are applied in the appliance. The temperature control adopts the fuzzy adaptive PID control mode [5], shown in Fig.3. Fuzzy adaptive PID control mode has the advantage of short adjustment time, fast response and small overshoot compared with the traditional PID control mode.
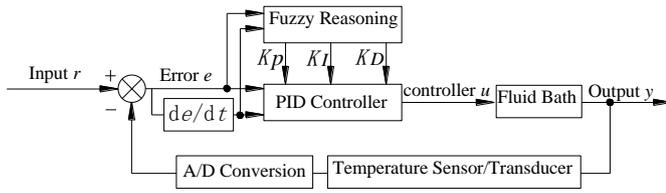

Fig.3 the fuzzy adaptive PID control mode

In order to obtain a uniform temperature source, a motor stirring machine is used. The motor stirring machine makes the liquid circulated. The circulated liquid increases the heat exchange, so temperature of different parts of the liquid becomes uniform. The experiment results show that the temperature stability is better than 0.05℃/30min.

Taking into account the needs of the calibration of infrared radiation thermometers, we choose a cavity which is a cone-cylinder of length 300mm with a maximum aperture of diameter 50mm. The cavity is made of stainless steel. The inner wall of the cavity is coated with a special paint [6]. The paint itself has the emissivity factor of 0.95.

The frost prevention unit will start working when the blackbody is operated below 0℃. The decompressed nitrogen gas or dry air flows into the heat exchanger, and exchanges the heat sufficiently with the liquid of the bath until the temperature of gas is the same as that of the bath, then enters the flange and sprays out off the apertures finally. Because of continued outflow of gas, an nitrogen gas curtain comes into being at the window of the blackbody cavity, which isolates the air nature convection between the cavity and environment. In this way, the designed blackbody can prevent air condensation on the wall and the window of the cavity when operated at temperatures below the dew

point temperature of an ambient air, and furthermore the temperature distribution along with the wall becomes uniform.

In order to ensure that heat exchanger works well, we need to calculate the heat exchange. Calculation is as follows[7]:

$$Q = KA\Delta t_m = \pi d_2 LK \frac{2t_0 - t_1 - t_2}{2} = \pi d_2 LK \frac{t_0 - t_1}{2} \quad (1)$$

where Q is the capacity of heat transmission, K is the overall heat transfer coefficient, A is the area of heat transfer, Δt_{tm} is the temperature contrast, d_2 is the outside diameter of the heat exchanger, L is the length of the heat exchanger, t_0 is the temperature of the fluid, t_1, t_2 are the inlet and outlet temperature of the gas, here $t_0 = t_2$.

The overall heat transfer coefficient K is given by the equation of

$$K = (\frac{d_2}{d_1}\frac{1}{h} + \frac{d_2}{2\lambda_2}\ln\frac{d_2}{d_1})^{-1} \quad (2)$$

where d_1 is the inside diameter of the heat exchanger, h is the convective heat transfer coefficient, λ_2 is the coefficient of heat conductivity of heat exchanger.

The convective heat transfer coefficient h is given by the equation of

$$h = 0.023\frac{\lambda_1}{d_1}Re^{0.8}Pr^{0.3} \quad (3)$$

Where λ_1 is the coefficient of heat conductivity of fluid, Re is the Reynolds number, Pr is the Prandtl number.

The Reynolds number Re is given by the equation of

$$Re = \frac{4m_s}{\pi d_1 \mu} \quad (4)$$

Where m_s the mass flow rate of the gas, μ is is the viscosity of the gas.

Using equation (3) and (4), we obtain

$$h = Bd_1^{-1.8}m_s^{0.8} \quad (5)$$

where

$$B = 0.023\lambda_1(4/\pi\mu)^{0.8}Pr^{0.3} \quad (6)$$

According to the heat balance equation

$$Q = m_s C_p(t_2 - t_1) \quad (7)$$

and equation (1), (2), (5), (7), finally we can obtain the following relationship:

$$L = \frac{2m_s C_p}{\pi}\cdot(\frac{1}{Bd_1^{-0.8}m_s^{0.8}} + \frac{1}{2\lambda_2}\ln\frac{d_2}{d_1}) \quad (8)$$

Based on the size of the designed blackbody cavity and equation (8), we choose the heat exchanger with 2.5mm of outside diameter and 2mm of inside diameter. If the length is fixed, we only need to adjust the pressure reducer that the temperature of nitrogen gas is the same as that of the bath after heat exchanged with the working fluid in the bath.

Experiment result shows that the blackbody with the frost prevention unit are very effective to prevent frost buildup on the wall and the window of the cavity in 30mins when operated at temperatures below the dew point temperature of an ambient air.

3. EFFECTIVE EMISSIVITY CALCULATION

The effective emissivity of the cavity is an important indicator to evaluate the performance of the blackbody radiation source, which reflects the extent of the actual black body close to the ideal blackbody. The calculation of the effective emissivity of the cavity commonly uses theory approximation method [8]. A method called rectangular-region approximation is developed to calculate the effective emissivity distribution in blackbody cavity [9]. Comparing with Bedford's method of trapezoidal-zone approximation, this method has advantage of avoiding the singular point problem, so the calculation is simplified and easy to use.

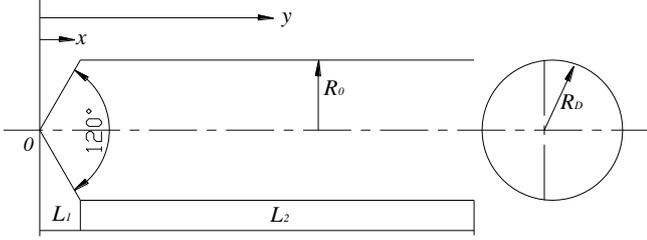The coordinates are defined as shown in Fig.4:

Fig.4 cone-cylinder blackbody cavity

Where x and y are variable length, L_1 is the length of the cone, L_2 is the length of the cylinder, R_0 is the radius of cylinder, R_D is the radius of a detector.

Since the stirred fluid bath is used, the temperature gradients along the cone-cylinder cavity are negligible. According to rectangular-region approximation method, the effective emissivity distribution of an isothermal blackbody cavity is given as follows:

$$\varepsilon_a(x_{0i}) = \varepsilon + (1-\varepsilon)[\sum_{m=1}^{N_1} \varepsilon_a(\frac{x_m + x_{m+1}}{2})\left|dF_{x_{0i},x_{m+1}} - dF_{x_{0i},x_m}\right|$$

$$+\sum_{n=1}^{N_2} \varepsilon_a(\frac{y_n + y_{n+1}}{2})\left|dF_{x_{0i},y_{n+1}} - dF_{x_{0i},y_n}\right|]$$

$$i = 1,2,3,\cdots,N_1. j = 1,2,3,\cdots,N_2$$

$$x_{m=1} = 0, x_{N1+1} = y_{n=1} = L_1, y_{N2+1} = L_1 + L_2$$

$$x_{0i} = \frac{x_{m=i} + x_{m=i+1}}{2}, y_{0i} = \frac{y_{n=j} + y_{n=j+1}}{2}$$

$$\tag{9}$$

$$\varepsilon_a(y_{0j}) = \varepsilon + (1-\varepsilon)[\sum_{m=1}^{N_1} \varepsilon_a(\frac{x_m + x_{m+1}}{2})\left|dF_{y_{0j},x_{m+1}} - dF_{y_{0j},x_m}\right|$$

$$+\sum_{n=1}^{N_2} \varepsilon_a(\frac{y_n + y_{n+1}}{2})\left|dF_{y_{0j},y_{n+1}} - dF_{y_{0j},y_n}\right|]$$

$$\tag{10}$$

Where ε is the paint emissivity factor, N_1, N_2 are the region segmentation points of x, y, $dF_{x0,x}$, $dF_{y0,y}$ are radiation angle factors, which are evaluated by the following equation, given in [9]:

$$dF_{\xi 0,\xi} = \frac{1}{2r_1} \cdot \left|h\cos\theta + r_1\sin\theta - \frac{(h^2 + r_1^2 + r_2^2)(h\cos\theta + r_1\sin\theta) - 2r_2^2 r_1\sin\theta}{\sqrt{(h^2 + r_1^2 + r_2^2)^2 - 4r_1^2 r_2^2}}\right| \tag{11}$$

The geometrical significance of parameters from equation (11), we can refer to [9].

With the help of the equation (9) and equation (10), we can obtain the effective emissivity distribution of the cavity. As shown in Fig.5.
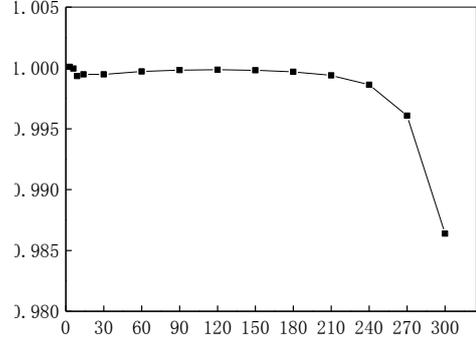

Fig.5 the effective emissivity distribution of the cavity

And then we can obtain the effective emissivity of the cavity ε_c form equation (12).

$$\varepsilon_c = \frac{\int_0^{L_1} \varepsilon_a(x)dF_{x,D}dA_x + \int_{L_1}^{L_1+L_2} \varepsilon_a(y)dF_{y,D}dA_y}{\int_0^{L_1} dF_{x,D}dA_x + \int_{L_1}^{L_1+L_2} dF_{y,D}dA_y} \tag{12}$$

where $dF_{x,D}$, $dF_{y,D}$ are the radiation angle factors, dA_x, dA_Y are the area elements of inner wall.

Finally, the calculated effective emissivity of the designed blackbody cavity is 0.998.

4. EXPERIMENTS AND RESULTS

The pressure reducer and the window of the blackbody cavity will be opened when the temperature is below 0 ℃. And the cooled nitrogen gas starts to flush the blackbody cavity. We observe the frost buildup phenomenon of blackbody cavity after temperature of the bath is stabilized at -50 ℃. We find there is no frost on the wall and the window of the cavity in 30mins. The experiment results show that the designed prevention frost unit works perfectly. 30mins are enough to finish calibrations for radiation thermometers.

A comparison method is used to measure the emissivity of the blackbody. A second-class standard platinum resistance thermometer (PRT) is applied to measure the temperature near the bottom of the cavity (shown in Fig.2). The temperature of the liquid bath is set at -50 ℃. The reading of the PRT is very close to the setting. The temperature difference at both sides of the cone is neglected because the width of the wall is only 3 mm. An ITS/N2812 precision radiation thermometer is used to measure the radiation temperature of the blackbody. The average of 5 readings of the radiation thermometer is -49.8 ℃.

The computational formula of measured emissivity is

$$\varepsilon_c' = \frac{T_p^4}{T^4} \tag{13}$$

Where T is the measured temperature of PRT, T_P is the radiation temperature by ITS/N2812 precision radiation

thermometer. The measured emissivity of the designed blackbody cavity is larger than 0.997.

5. CONCLUSIONS

In this paper a detailed description of the designed blackbody cavity with a frost prevention unit and the characterization of its performance are presented. The conclusions are:

1. In -80 ℃ ~ +100 ℃, the temperature stability of blackbody cavity is better than ±0.05 ℃ / 30min.

2. The calculated emissivity of the designed blackbody cavity coated with the special paint is 0.998. The measured value is large than 0.997. The measured emissivity agrees well with the calculated one.

3. The blackbody cavity with a frost prevention unit can prevents air condensation effectively on the wall and the window of the cavity in 30mins when operated at temperatures below dew point, and furthermore the temperature distribution along with the wall is uniform. It can able to calibrate the infrared radiation thermometers down to -80 ℃.

6. REFERENCES

[1] Y. Zhu, H. Ma, R. Wang, "- 50 ℃ to 150 ℃ Heat Pipe Blackbody Sources for Radiation Thermometer Calibration," TMCSI , vol. 5, no. Par t 1, pp. 559-565,1982

[2] T. J. Quinn and J. E. Martin, "Blackbody Source in the - 50 ℃ to 200 ℃ Range for the Calibration of Radiometers and Radiation Thermometers," Appl Opt, vol.30, no.31, pp. 4486-4487,1991.

[3] C. G. Jr. Burkett and K. Daryabeigi, "Cryogenic Blackbody Radiation Calibration Source," in Proc. of the 38th International Instrumentation Symposium, pp.273-285, 1992.

[4] D. T. Huang, J.Q. Lu, Z. D. Yuan, Y. N. Duan, Q. Zhao, "An Ammonia/Stainless-Steel Heat-Pipe Blackbody Radiation Source," Acta Metrologica Sinica, vol. 18, no. 1, pp. 1-4，1997.

[5] N. Li, J. Xu, L. H. Yang, "A new technique for automatic temperature control of cryogenic blackbody," Spacecraft Environment Engineering, vol. 28, no. 4, pp. 362-366, 2011.

[6] X. Jian, Y. J. Zou , G. D.Chen, "Development of high Radiation and Heat Resistant Coatings," Paint & Coatings Industry, vol. 35, no. 5, pp. 1-3,2005.

[7] L. X. Yan, "Optimum Design of Coil Heat Exchanger," Journal of Hubei Institute of Technology, vol. 9,no. 2 , pp. 106-110,1994.

[8] Z. Xie, K. M. Gao, The infrared radiation temperature measurement theory and technology. Northeast university of technology press, Ch.3, pp. 95-96 1990..

[9] Z. Xie, K. M. Gao, "Method of Rectangular-Region Approximation for Calculating Effective Distribution in Blackbody Cavity," Journal of northeast university of technology, vol. 55, no. 2, pp. 202-209, 1988.