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Study of amplification coefficient in a water-cooling Gardon-type heat power measuring apparatus

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Abstract A new water-cooling Gardon-type heat power measuring apparatus is designed to meet the need of heat power source management and distribution. The steady state measurement mathematic model of the apparatus is built up in theory and the system amplification coefficient is defined as the ratio of the heat power to the temperature difference of the device, with which the value of the measured source power can be calculated easily with the corresponding temperature difference. In order to obtain an optimal heat power measuring system, the coefficients that can influence the relationship between the amplification coefficient, the temperature difference, and the heat power are analyzed. On the basis of these analyses, a set of experimental device is constructed and a number of experiments are carried on. Compared with the input heat power sample data, the error of the experimental measuring results is less than ±2%, and the experimental measuring values are in good agreement with the calculated theoretical ones. The heat power measuring apparatus can be applied in heat flux or heat power measurement in other fields due to its simple structure and high accuracy.

1. Introduction

During the past centuries, many kinds of heat and power supply devices have been researched for space exploration. Of those schemes, the following four have been applied the most times and gained the most attentions: chemical battery, fuel battery, solar-storage cell, and radioisotope thermoelectric generator (RTG) or radioisotope heater unit (RHU).[1] RTG or RHU, generating heat by radioisotope decay, is chosen as the ideal heat and power supply device in the exploration of

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outer space and planets. In American space exploring history, more than 29 missions were equipped with RHUs or radioisotope power devices to supply onboard equipment.[2–5] In the former Soviet Union, RTGs named "Orion-1" and "Orion-2" were used on "COSMOS-84" and "COSMOS-90" Earth artificial satellites in the year of 1965; 800-W heat power output radionuclide heat units were loaded on "Lunokhod-2" in 1973; RTGs had no progress but more than 30 nuclear power plants (NPPs) were launched during 1970–1988, and the "Mars-96" project opened the research of RTGs in Russia again in recent years.[6–10] In the European Space Agency (ESA), radionuclide power sources were performed in the "Rosette" project developed by scientific consortiums from Germany, Finland, Italy, Hungary, Great Britain, and Austria.[11]

When an RHU is equipped on a spacecraft, it needs a heat power measurement to distribute its heat power and also manage the heat of the spacecraft rationally. Usually, there is a deviation between the matter of an RHU manufactured and the theoretical design objective since the heat power of a radioisotope heat source changes with time, and its power value must be measured experimentally. At present, a few studies have addressed the measurement of heat power RHUs; as for most of them, the heat power is indirectly measured through measuring heat flux.

Various types of heat flux meters have been developed by researchers in different fields. There are several general heat flux meters which are mostly used, such as the water-calorie method based on the heat equilibrium principle, the burn erode method that operates on the relationship between material burn erode rate and heat flux, the boundary layer heat transfer method which is based on the high temperature electrolytic gas boundary layer heat transfer, and the gradient method taking advantage of the temperature difference generated between two points on a test component based on the Fourier's conduction law.[12] Christopher et al. categorized conventional heat flux gauges as three kinds: gauges based on the dissipation of electrical power from a heater, gauges based on transient surface temperature measurement such as thin-film resistance elements, and gauges based on temperature difference measurement.[13] Astarita et al. investigated the most commonly used one-dimensional sensor models: thin-film sensors, thick-film sensors, thin-skin sensors, gradient sensors, heated thin foil sensors, and Gardon gauges.[14] Nie at Beijing University of Technology researched a thin film transient heat flux sensor utilizing thin-film depositing technology to realize some miniature space heat flux measurement.[15] Cao and Epstein developed a double film heat flux gauge using Kapton-Polamide adiabatic film as the base component and pure nickel as the sensitive element for transient heat flux measurement on turbine blades.[16] NASA Glenn Research Center and US Army Research Laboratory have reported high temperature thin film sensors for some advanced turbine engine components,[17] for which some special materials were needed as the thin film sensitive element and substrate, as well as complicated calibration techniques. When it came to gradient heat flux measure sensors, two typical heat flux measuring sensors are the Gardon-type gauge composed of a foil and a heat sink[18] and the Schmidt-Boelter gauge made of a thermopile.[19] Wang et al.[20] and Li et al.[21] designed and calibrated a kind of Gardon-type gauge. Their experimental results indicated that the output temperature difference and the output thermoelectric voltage produced by the sensor were almost in direct proportion to the exterior radiation.

The heat power measurement of an RHU needs a noncontact measure to prevent the RHU surface being contaminated, and a Gardon-type heat flux sensor can easily meet this requirement. Therefore, a Gardon-type water-cooling heat power measuring apparatus for gauging of the heat power generated with the decay of radioisotope in an RHU is designed, and parameters of the sensitive elements used in the sensor fabrication are calculated and analyzed in theory. The repeatability errors and heat power measuring errors of this apparatus are presented and compared with the input sample electric power data.

2. Principle and apparatus scheme design

2.1. Measurement principle

Gardon invented a heat flux sensor to measure the radioactive heat transfer in 1953[18] as shown in Fig. 1.

The Gardon-type heat flux sensor consists of a thin sensitive element which absorbs the exterior radiation and a heat sink which takes the energy away. When the heat flux is irradiated on the sensitive element uniformly, the temperature of the sensor center is higher than that of the edge around because of its contact with the heat sink. The sensitive element is made of constantan foil and the heat sink is made of copper. They are two different materials, and thus, the Gardon-type heat flux sensor is a thermocouple in essence. Thermoelectric voltage is generated because of the relatively high and low temperatures of the two different materials, and it is directly in proportion to the heat flux of incident radiation, which could be expressed as

$$E = k_{q,e} \cdot q \tag{1}$$

where E is the thermoelectric voltage; q is the incident radiation heat flux and $k_{q,e}$ is the proportionality factor.

The temperature difference produced in the Gardon-type heat flux sensor can be described as

$$\Delta T = k_{q,t} \cdot q \tag{2}$$

where ΔT is the temperature difference and $k_{q,t}$ is the proportionality factor.

The values of proportionality factors $k_{q,t}$ and $k_{q,e}$ depend upon the geometry and materials of the Gardon-type heat flux sensor.

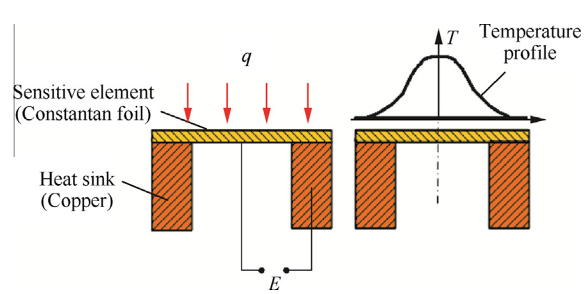

Fig. 1 Sketch of a Gardon-type heat flux sensor.