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Design of a thermal control device suitable for airborne remote sensors

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HIGHLIGHTS

- A thermal control device suitable for airborne remote sensors was introduced.
- The device used the human circulatory system as a reference.
- Experiment proved its better temperature uniformity.

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ABSTRACT

An increasingly higher temperature is required with the rapid development of airborne remote sensors, giving rise to an urgent demand for a technology or device which can ensure both the uniform temperature and a high heat exchange capacity. This paper, based on the human circulatory system, proposes a thermal control device with a fluid circulation. The device is introduced in detail and an experiment is made to verify its thermal control effects. It is shown that the device has better temperature uniformity and a better heat transfer capability compared to the traditional heating films.

1. Introduction

The rapid development of airborne remote sensors requires increasingly higher accuracy and resolution. In the meanwhile, its requirement for temperature becomes much more demanding. The thermal control has become an essential part of airborne remote sensors [1–4].

Nothing is better than the case that the remote sensor can be incorporated into the aircraft's temperature control system [5,6]. However, due to a number of limiting factors, such as the priority constraints, the remote sensors usually need to bring their own temperature control system.

Typically, the aerial remote sensor's temperature control system takes one of the following forms:

(1) Heat exchange by air circulation in the pod [7,8].

The remote sensors are placed in the pod. The remote sensor's overall temperature is maintained by the air circulation and the control of the air temperature in the pod. Even though this ensured the temperature uniformity across the sensor's parts, it needs a large space to ensure the smoothing air flow. In addition, when the aircraft rises into the sky, the atmospheric pressure drops, reducing the convection's heat transfer capability and the effectiveness of the temperature control system.

(2) Paste heating films or thermoelectric films on the sensors' parts [9,10].

In this way, the temperature changes quickly, and the required space is relatively small. However, pasting films may cause the unevenness in temperature, hence the decreased image quality. Therefore to improve the temperature uniformity, more areas need to paste heating/thermoelectric films. Since each heating/thermoelectric film needs at least one temperature sensor, the more heating/thermoelectric films are pasted, the more temperature sensors are needed, which implies a more complex but less reliable control process.

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On top of that, the fast development of integration further depresses the available space for airborne remote sensors and generates more heat. In this context, a new thermal control device with stronger heat exchange capability, smaller space requirement, and better temperature uniformity is greatly needed. This paper proposes such a device based on these requirements.

2. Principle of the device

The heat balance of the human body is a very good example worth learning. It generates heat by oxidation reaction or anaerobic reaction, dissipates heat by radiation through the skin or human perspiration, etc., and maintains the human body at a constant temperature. Moreover, human body also has good temperature uniformity thanks to the blood circulation. The heat spreads out quickly and evenly throughout the human body with the blood's constant flow. The convection between fluid and other organizations brings the human body a strong heat exchange capacity.

The designed thermal control device in this paper shares a similar principle to the human body. Pipes are placed inside the remote sensors, and the constant fluid flows in the pipes and the resulting convection helps satisfy the remote sensor's heat demand.

2.1. Circulatory system

Similar to the body's circulatory system with both pulmonary circulation and systemic circulation, the thermal control device in this paper also takes a dual circulation system, as shown in Fig. 1. The advantages of this design include: a) the ease to arrange the pipes in a three-dimensional remote sensor, b) a reduced length of the pipe, and hence a lower required pressure, c) easy maintenance and repair, and d) convenience to add or replace parts in the future.

2.2. Choice of fluid

Given the aerial remote sensor's surrounding environment, an appropriate fluid should feature low freezing temperature, high boiling temperature, stable nature, strong heat exchange capacity and no collision explosions. The freezing temperature should be lower than the stratospheric temperature (-56 °C). For example, the fluid can be a concentration of 68% ethylene glycol aqueous solution or 40% aqueous dimethyl sulfoxide. Besides, the fluid is better to have the characteristics of solidification when exposed to air, like the blood so that when there are tiny cracks on the pipes, the cracks can be blocked due to the solidification, reducing the probability of liquid leakage. For example, adding a proportion of polyvinyl alcohol and a certain amount of lipids can bring the fluid the solidification characteristics like the glue when encountered with air.

2.3. Power systems

The power system relies on the servo motor to control the hydraulic pump. The fluid circulation is driven by the hydraulic energy generated by the pump. The entire power system is designed as a closed system to avoid any impacts from the external atmospheric pressure.

2.4. Pipe system

The pipes should have high/low temperature resistance, aging resistance, corrosion resistance and stable characteristics. The preferred pipes should also have good thermal conductivity and elasticity. In this system, the shunt conduit is designed and adopted. The throttling device is provided in the primary shunt, as shown in Fig. 2 and the flow rate is adjusted for the implementation of thermal control strategy.

2.5. Heating and cooling systems

2.5.1. Heating system

As usual, heating films or thermoelectric films could be used to transform the electrical energy into the heat energy. The heating films heat the fluid, which further heats the components by convection.

2.5.2. Cooling system

As a stand-alone system, airborne remote sensor usually has its own cooling system. Based on past experience, there are two main cooling methods: one is using heat sinks or thermoelectric films to directly refrigerate parts. Another amounts to using liquid nitrogen for cooling. The liquid nitrogen is sprayed into the air, and the system is cooled through the air circulation.

The cooling mode of heat sinks or thermoelectric films is greatly affected by the external environment: its controllability is relatively low, and the cooling effects depend on the temperature of the hot junction.

The cooling mode of liquid nitrogen is not affected by the outside temperature, which is controllable and a good way to cool the system in the pod through air circulation. However, the storage of liquid nitrogen must rely on high-pressure jars, which permits the possibility of explosion. There has been a flight accident simply because of this.

In this paper, since the thermal control system adopts a liquid circulation, it leaves more available options for the choice of cooling

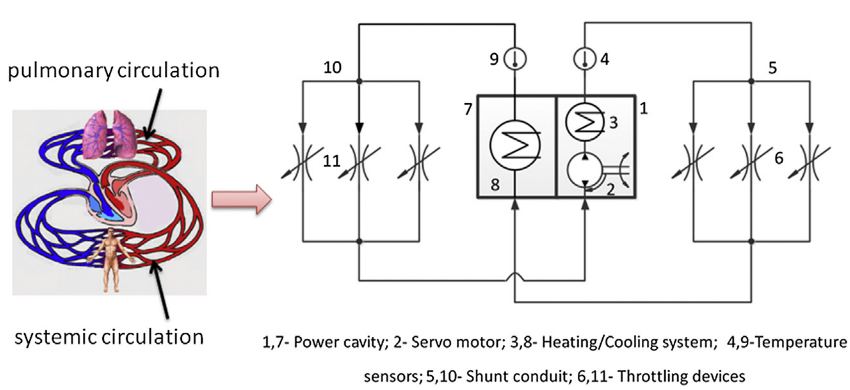

Fig. 1. Schematic diagram of the device.

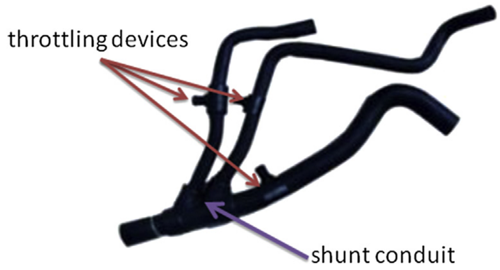

Fig. 2. Schematic diagram of the pipe system.

methods. There are a variety of cooling methods, such as thermoelectric refrigeration, compressor refrigeration, Stirling refrigeration, and physical or chemical refrigeration, etc. For example, some ammonium salt absorbs a lot of heat when it dissolves in water, which could be used in refrigeration.

3. Experiment

The material Titanium Alloy has been widely used in the field of aerial remote sensor. However, its overall temperature unevenness due to the relatively low heat transfer coefficient leads to its higher requirement for the thermal control system. In this experiment, the Titanium Alloy plates are used to test the thermal control effects in two different conditions: (1) using the thermal control device designed in this paper and (2) pasting heating films.

The purpose of the experiment is to test the temperature uniformity resulting from different heating methods. To facilitate the implementation of the experiment, the shunt conduit is not arranged in the experiment, which does not affect the heat transfer's comparison. The experiment starts with two same Titanium Alloy plates, with the initial temperature at 20 °C. They are heated from 20 °C to 30 °C and their temperature distributions are recorded in the heating process. The two Titanium Alloy plates are heated by heating films and the fluid inside the pipe, respectively, as shown in Fig. 3. In this experiment, water is used because of its economy and convenience. And it does not affect the purpose and process of the test. Both plates dissipate heat to the surrounding environment by radiation. The heating process is controlled according to the value of the temperature sensors, which is introduced in detail as follows.

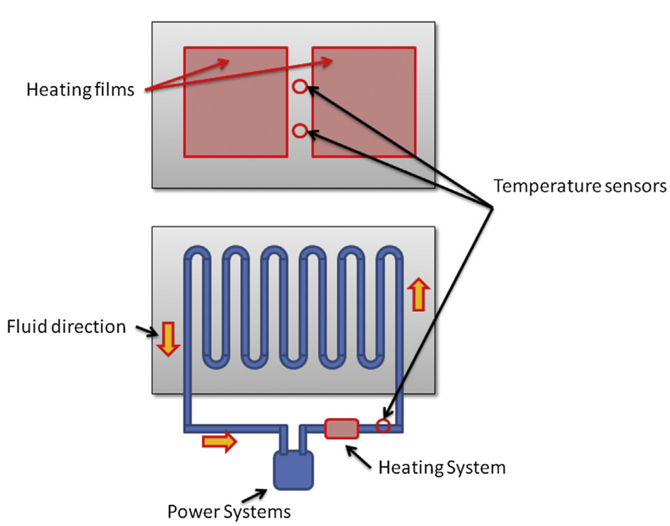

Fig. 3. Schematic diagram of the test.

3.1. Heating settings

The experiment adopts two identical TC4 (Titanium Alloy) plates, with the size of 400 mm × 240 mm × 5 mm each. As in Fig. 4, plate A is uniformly arranged by the pipe which is part of the thermal control device. The pipe, 5 mm wide, is fixed to the plate with snaps. The thermally conductive glue is put between the pipe and the plate, which could increase the contact area of heat transfer and assist fixing. The fluid in the pipe is heated with the power of 50 W. As for plate B, two pieces of heating films are pasted on it. Plate B is heated directly, using the heating power of 25 W for each film, i.e., 50 W in total for both films.

3.2. Temperature sensors

There are seven temperature sensors. Three(a,b,c) of them are used for temperature control; i.e., the thermal control behavior is determined by temperature sensors' feedbacks. The other four(d,e,f,g) are used to test temperature. The distribution is shown in Fig. 5 (The dashed lines mean they are located on the back).

3.3. Temperature control strategy

The TC4 plates are placed in a room with constant temperature of 20 °C. They are heated and the target temperature is 30 °C. When the temperature control sensor's value is lower than 30 °C, the device is heated; when its value is higher than 30.5 °C, heating stops. The sampling period is once a second.

3.4. Temperature test results

The temperatures of the two TC4 plates are recorded for comparison. The time-varying paths of the recorded temperatures are shown in Fig. 6.

Fig. 6 shows that there exists excessive heating in the case of using heating films. This is because the TC4 plate has a low heat transfer coefficient and the overall temperature is uneven. When the film is heated, its central region reached 30 °C fast, while its edge region has not reached that temperature due to the low heat transfer coefficient. Since the temperature control sensors are pasted at the edge of the heated films, heating would continue. This causes the excessive heating phenomenon.

In the case of using the device designed in this paper, there is no excessive heating, and the change in temperature is more

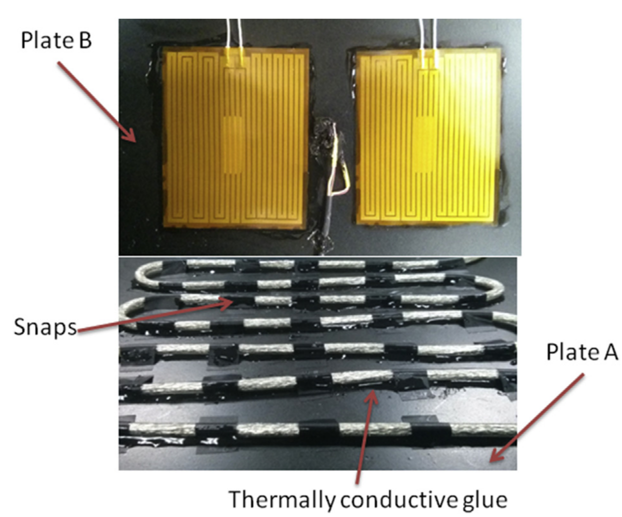

Fig. 4. Two identical TC4 plates.

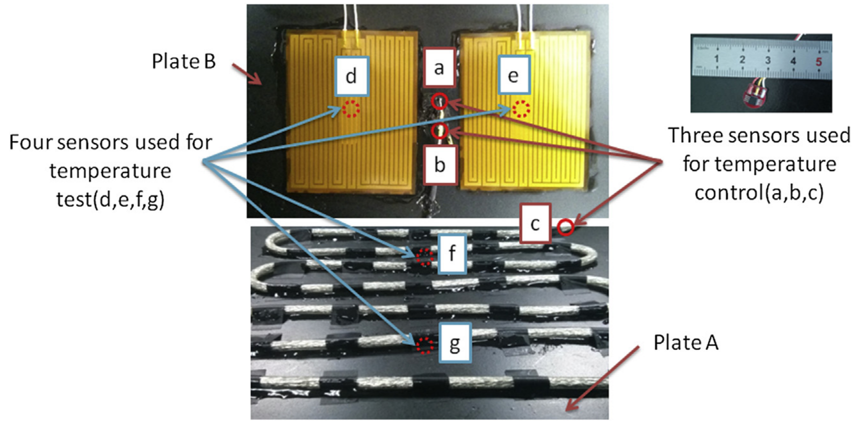

Fig. 5. Temperature sensors' distribution.

smoothing. There is a certain temperature difference between the two temperature sensor regions, which is due to the reduced heat energy carried by the fluid. The magnitude of the temperature difference is related to the fluid's specific heat capacity. The larger the specific heat capacity, the smaller the temperature difference.

3.5. Temperature error analysis

Heating films: The TC4 plate could be regarded as a two-dimensional heat conduction. The heating film heats the covered area uniformly, which is a non-stationary process of heat transfer. During the heating period, the radiation, compared to 50 W heating power, is small enough to be ignored. Therefore heat conduction becomes the primary mode of heat transfer. The direction of heat flow goes from the heating area (pasted by heating films) to the surrounding non-heated area. While within the heating area, the direction of heat flow is illustrated in Fig. 7. An X–Y coordinate system is established in the center of the area. X_0 and Y_0 represent the edge points of the heating film. Take the X-axis for an example and insert n points between 0 and X_0. Compared to the point X_0, the temperature of non-heated region is lower, and the heat flows out of X_0 (towards the direction of $+X$ axis). That reduces X_0's energy and leads to the temperature of X_0 than X_n. So the heat flows from X_n to X_0. This causes X_n's temperature lower than X_{n-1}'s, and the heat flows from X_{n-1} to X_n. This process continues until the heat flows to point 0. The direction of heat flow could be shown by Fig. 7.

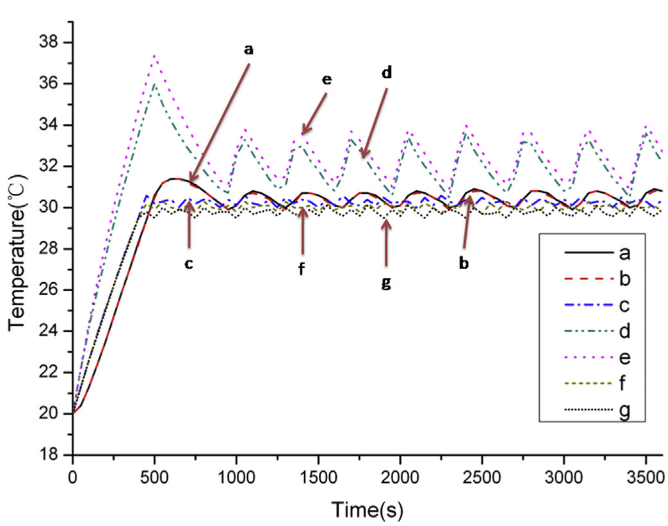

Fig. 6. Results of temperature.

The center temperature stays the highest, with certain temperature difference between the center point and the edge point.

Pipe system: The direction of heat flow is shown in Fig. 8, which feature a shorter flow path, a lower thermal resistance, and a smaller temperature difference. The overall temperature is more

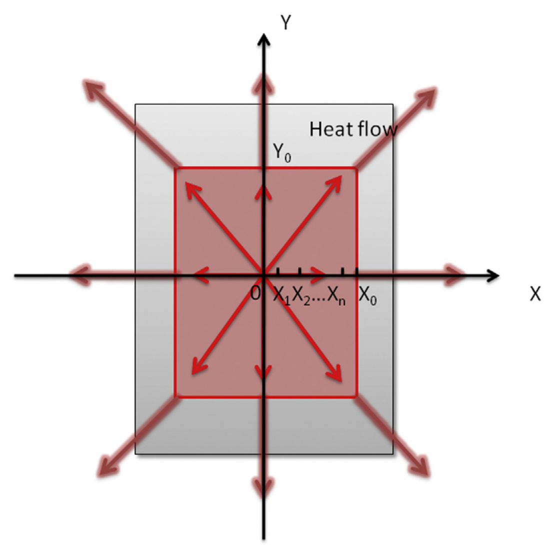

Fig. 7. Analysis of the heat flow's direction.

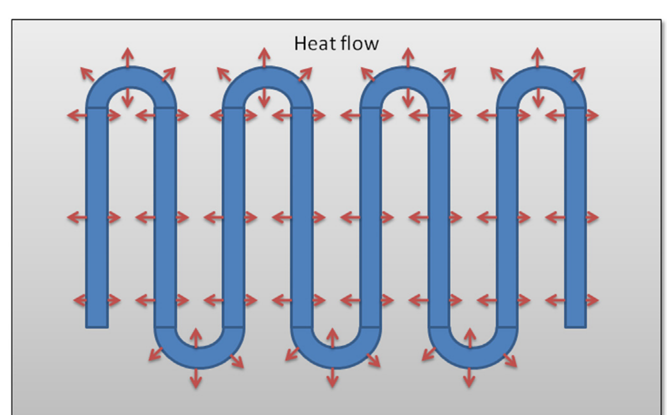

Fig. 8. Heat flow's direction of the device.

uniform. The speed of temperature change depends on the capability of the convective heat transfer.

For aerial remote sensors, the temperature uniformity is more important than the value of the temperature level. The uniformity of temperature in heating films system is lower due to the excessive heating. Based on the above comprehensive comparison, the temperature effects controlled by the device designed in this paper is more suitable for airborne remote sensors' thermal demands.

4. Summary

Based on the demanding characteristics of airborne remote sensors' thermal control, this paper proposed a thermal control device, modeled on the human circulatory system. The working principle, circulatory system, fluid, power system, pipe system and heating and cooling systems were introduced in detail. An experiment was made to compare the thermal control effects of this system with these from pasting heating films on components. The experiment showed that the proposed device was more suitable to the temperature control of airborne remote sensors.

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