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Fluid dynamic analysis and experimental study of a low radiation error temperature sensor

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ABSTRACT

To improve the air temperature observation accuracy, a low radiation error temperature sensor is proposed. A Computational Fluid Dynamics (CFD) method is implemented to obtain radiation errors under various environmental conditions. The low radiation error temperature sensor, a naturally ventilated radiation shield, a thermometer screen and an aspirated temperature measurement platform are characterized in the same environment to conduct the intercomparison. The aspirated platform served as an air temperature reference. The mean radiation errors of the naturally ventilated radiation shield and the thermometer screen are 0.57 °C and 0.32 °C, respectively. In contrast, the mean radiation error of the low radiation error temperature sensor is 0.05 °C. The low radiation error temperature sensor proposed in this research may be helpful to provide a relatively accurate air temperature measurement result.

1. Introduction

Near surface air temperature is a type of fundamental information of climate change forecasting, data assimilation of satellite, weather forecasting, meteorological disaster warning. In recent years, a number of research projects has been focused on the surface air temperature [1–6]. Haines et al. [7] concluded that the air temperature increased 0.09 °C per decade by analyzing the data of satellite observation, and concluded that the air temperature increased 0.17 °C per decade by researching the data of weather stations. Dillon et al. [8] concluded that the air temperature increased 0.4 °C and 0.95 °C in tropical and northern hemisphere areas, respectively, by analyzing the data in the period 1961–2009, of 3186 weather stations throughout the world. In conclusion, the magnitude of air temperature change is on the order of 0.1 °C per decade. In order to observe the global, large scale and local climate change accurately, to study the influence of aerosol and the solar radiation on the climate, and to research the change of content of water vapor, CO_2, methane and other greenhouse gases quantitatively, the measurement accuracy of the air temperature observation on the order of or less than 0.01 °C would be desired.

Because the temperature stability of the fixed points of water, gallium, indium and mercury can be controlled within the order of ±0.0002 °C, and because the temperature measurement accuracy of a 1595A super-thermometer from Fluke is up to ±0.000015 °C, the accuracy of the platinum temperature sensor probe may be able to reach ±0.01 °C by utilizing the 1595A super-thermometer and the fixed points of International Temperature Scale of 1990 (ITS-90) [9]. Compared to the radiation error, the error induced by electronic devices and circuit is 1–2 orders of magnitude lower than the radiation error. The radiation error is a dominant error source. To minimize the influence of solar radiation and long wave radiation, a temperature sensor probe needs to be housed in a radiation shield or a thermometer screen. Ideally, the shield and the thermometer screen can prevent the direct solar radiation, reflected solar radiation and long wave radiation from heating the probe, and can allow adequate airflow to ventilate the probe. Nevertheless, the reflectivities of the thermometer screen and the shield are incapable of reaching 100%. Solar radiation and long wave radiation cause the air into the internal to be heated, and then produce radiation error. In addition, the structures of the thermometer screen and the radiation shield are harmful to air circulation, which reduce the response rate of the inner probes [10,11].

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A number of studies have investigated the performance of naturally ventilated radiation shields and thermometer screens. Erell et al. [12] concluded that the mean radiation errors of the naturally ventilated radiation shields were up to 0.8 °C by performing a series of comparative measurements. The wind [13], radiation [14,15], and different coatings [16] displayed remarkable impacts on the energy balance of the naturally ventilated radiation shields, which might lead to 2–8 °C radiation errors under the adverse conditions that include weak wind of ≤ 1 m/s and high solar radiation intensity of ≥ 800 W/m^2 [17–20]. Brock et al. [21] discovered that the radiation error of a Gill radiation shield might be up to 8 °C, when the wind speed was smaller than 0.2 m/s. Hubbart [22] proposed a new naturally ventilated radiation shield and tested it in a greenhouse. The mean radiation error of the new shield was 2.84 °C. Lopardo et al. [23] indicated a senescent shield might cause a large measurement error. Due to solar and weather exposure, the shields age and their coatings color changed from bright reflecting white to light beige. The temperature measured with the older shield was larger, and the maximum instantaneous difference was 1.63 °C (for 0–5 years comparison) in daytime. Because the new shield also had radiation error, the radiation error of the older shield was larger than 1.63 °C. Generally, because the average wind speeds are greater than 1 m/s, and because the shields are cleaned regularly, typical radiation errors of the naturally ventilated radiation shields and the thermometer screens range from 0.5 to 2.5 °C [24–29]. In conclusion, the naturally ventilated radiation shields and the thermometer screens may have difficulty to meet the present air temperature measurement accuracy requirements.

Because the flowing air can facilitate the diffusion of radiant heat, the radiation error can be reduced with the increase of wind speed through the shield. Hence, a high performance shield need to be mechanically aspirated to increase the wind speed. For example, the range of wind speed of a 43502 aspirated radiation shield manufactured by R.M. Young is 5–11 m/s. The radiation error induced by solar radiation is 0.2 °C, when the wind speed and the solar radiation intensity are 11 m/s and 1000 W/m^2, respectively. Thomas and Smoot [30] proposed a new aspirated shield. The radiation error of the new aspirated shield was approximately 0.2 °C, which hardly meets the demand of high accuracy observation. An air pump driven by relatively high power seems to be necessary to achieve higher wind speed, if a radiation error of 0.1 °C or even lower is desired. However, the power requirement and maintenance cost of such systems limits the applications of the aspirated radiation shields. Most of the solar power supply system in weather stations cannot support the power demand, and the environmental factors such as dust, snow, insect, may compromise the long-term reliability of the fan. In conclusion, it is difficult for the aspirated radiation shields to be widely applied by the weather stations in near future.

It has been pointed out by a WMO report [31] that investigations into the wind attenuation ratio modeling by using a Computational Fluid Dynamics (CFD) method, and into estimation of the radiation error were both necessary. Richardson [32] modeled the airflow through a Gill shield using a CFD software Fluent to attain the airflow profile inside the shield. The model was relatively simple, and the simulation results could offer only wind speed and direction inside the shield. Because of the limited level of maturity, the CFD technologies in 1990s and early 2000s were unable to construct a heat transfer model of the radiation shields and the thermometer screens. As a result, the numerical results of the temperature distribution and radiation error cannot to be obtained.

A good design for temperature sensor used in climate observation should minimize the radiation reaching the probe and radiation absorbed by the shield. On the other hand, maximizing the wind speed around the probe is indispensable. The shield cannot block all undesired solar radiation and long wave radiation without reducing the wind speed near the probe. It is difficult to fuse these two design methodologies into one single design of traditional naturally ventilated radiation shields and thermometer screens. In this paper, a low radiation error temperature sensor is proposed. The CFD method is used to deliver an accurate quantitative value of radiation error of the low radiation error temperature sensor. A radiation error correction equation is obtained by fitting the CFD results using a Genetic Algorithm (GA) method. A number of experimental comparisons have been performed to verify the actual performance of the low radiation error temperature sensor and the radiation error correction equation.

2. Design of the low radiation error temperature sensor

2.1. Computational fluid dynamics model

The low radiation error temperature sensor consists of a temperature sensor probe, a temperature measurement module that includes a high accuracy thermometer circuit and a radiation shield. The shield consists of two aluminum plates with a silver mirror surface, four plastic supporting pillars, two metal hanging poles, a plastic fixed column and two metal fasteners. A copper spherical shell with a silver mirror surface is manufactured for the temperature sensor probe. A platinum resistance probe is fixed at the center position of the copper spherical shell by using a heat-conducted silica gel. Moisture is prevented from going into the inside of the copper spherical shell by adopting a sealant. The diameter, thickness and reflectivity of the copper spherical shell are 8 mm, 0.5 mm and 95%, respectively. In order to decrease the errors induced by direct solar radiation, reflected solar radiation and long wave radiation, the 4270 AG aluminum plates manufactured by Alanod Company are installed above and below the temperature sensor probe. The reflectivity of the silver mirror surface of the plate is 98%. In order to reduce the reflected solar radiation and long wave radiation induced by the inner surfaces of the aluminum plates to the probe, the inner surfaces of the plates are covered with a layer of black paint. The reflectivity of the inner surface can be decreased within 10%. The size of the aluminum plate is 60 mm × 60 mm × 1.5 mm. The diameter and length of the supporting pillars are 5 mm and 40 mm, respectively. Because the supporting pillars feature a relatively low heat conductivity coefficient, and because the coating of the supporting pillar is white, the radiant heat of the supporting pillars is relatively small. In order to fix the probe stably, the probe is tied to a fixed column, which is installed on the center of the lower aluminum plate. The diameter and length of the fixed column are 5 mm and 10 mm, respectively. The supporting pillars and the fixed column are made by a type of low thermal conductivity material, which can prevent the radiant heat pollution from the aluminum plates, when supplying mechanical support. The temperature measurement module is placed inside a protective case. To improve the long-term reliability, the low radiation error temperature sensor is installed on a weather station by using metal fasteners (Fig. 1).

A grid software ICEM-CFD is used to mesh the CFD model. The technology of unstructured mesh is adopted to generate a tetrahedral mesh. A CFD software Fluent is used to calculate the CFD model. A solar ray tracing model is used to load solar radiation. A standard k–epsilon model, a SIMPLE algorithm and a standard initialization method are employed in the numerical computation. To solve the momentum, energy and turbulence parameters, a first order upwind method is applied in the CFD model. Boundary conditions of the CFD model are set according to the physical envi-