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Heat radiation measurement method for high pressure oxy-fuel combustion

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ABSTRACT

This paper describes a novel cost effective narrow-beam radiometer what was designed to measure incident heat flux at a specific location in high temperature and high pressure combustor. Beyond the radiometer the whole measurement assembly contains a water cooled plate for cold background, a high pressure window transparent for visible and IR radiation and a radiometer position/angle adjustment tool. The thermopile based radiometer measures the total heat radiation in a wavelength range of 0.6–8 μm. A special view tube was developed for decreasing the view angle to 0.35°, what angle was dictated by the dimensions of the combustor and the associated port sizes. Calibration curves were measured using a high temperature black body calibrator and the uncertainty of the measurement was evaluated. Although the presented radiant heat flux measurement method was developed for a specific combustor, it can be easily implemented for various combustion applications as well.

1. Introduction

Heat radiation is a basic, well-known and deeply studied heat transfer method with a long history of elaboration [1–3]. Among the theoretical evolution the experimental background was also continuously developed, including measurement devices [4–9] which nowadays are widely applied in many fields. However, based on the available literature, limited experience or study is available dealing with radiation measurements under pressure, especially during high pressure and high temperature oxy-fuel combustion. The extreme environment strongly limits the possibilities of instrumentation being used and the applied technique must be carefully designed to avoid false measurements. Several studies provide information about radiation measurement approaches or CFD modeling in oxy-coal flames [10–15], although these are carried out at ambient pressures. In fact, most detailed experimental data are limited to atmospheric pressure [16]. This paper presents a detailed insight into a novel, thermopile based narrow beam radiometer along with accessories developed for high pressure and high temperature oxy-coal combustion research.

Thermocouples, thermopiles, pyroelectric sensors, bolometers and quantum detectors are the mostly used elements in heat radiation measurement, each providing pros and cons. For example, the sensitivity of quantum detectors is higher than the sensitivity of thermocouples or thermopiles, but the spectral response is limited to a narrow wavelength range. The main goal in the recent application was measuring the total radiation arriving from a specific direction of the flame. A thermopile was selected for the application due to wide spectral response and the adequate sensitivity.

A thermopile is made of thermocouple junction pairs connected electrically in series. The Seebeck effect and other thermocouple laws describe the operation of a thermocouple [17,18]. Since the electromotive force (EMF) for one thermocouple is relatively low at low temperatures, the serially connected thermocouples give signal where the EMF is multiplied by the number of thermocouples [19]. Fig. 1 shows a simplified sketch of typical thermopile configuration. The radiation absorbed by the hot face heats up that side of the thermopile and creates a temperature difference between the hot face and the cold face. While ΔT temperature difference creates U_T EMF in one thermocouple, x number of thermocouples connected serially in the same system creates $x \cdot U_T$ EMF. This fact makes the thermopile powerful for example in radiation measurements. For a better illustration on Fig. 1 only 4 thermocouples are shown, but the number of thermocouples in reality is usually higher and the physical layout may also vary [20–24].

2. The radiometer setup

The assembly of the narrow beam radiometer is presented as Fig. 2 and it is based on 2 main parts: thermopile and view tube. The thermopile is responsible for converting the irradiation into an electric signal. In the present radiometer a pre-manufactured but custom specified thermopile is used made by Dexter Research Center [25]. The model number of the thermopile is 2M [26]. The thin film based thermopile is encapsulated with xenon gas what increases the sensitivity compared to other gases used in thermopile applications such as

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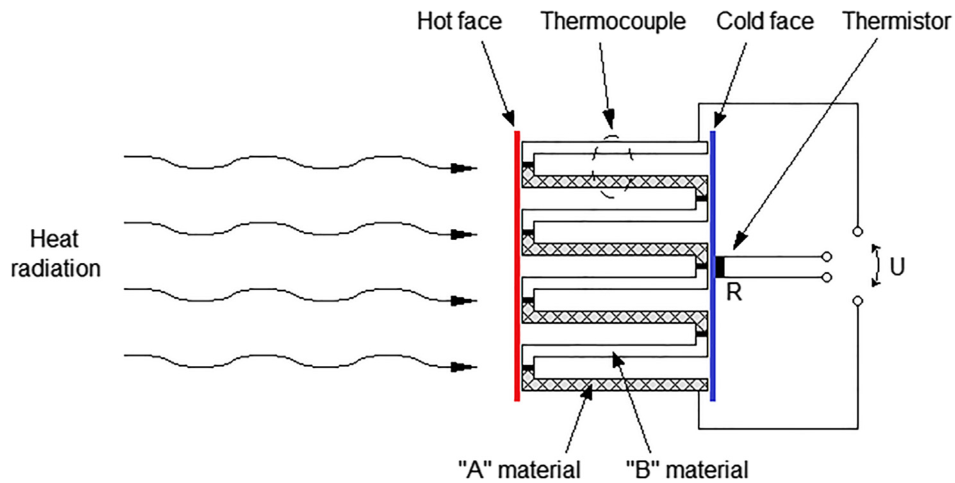

Fig. 1. Typical thermopile configuration.

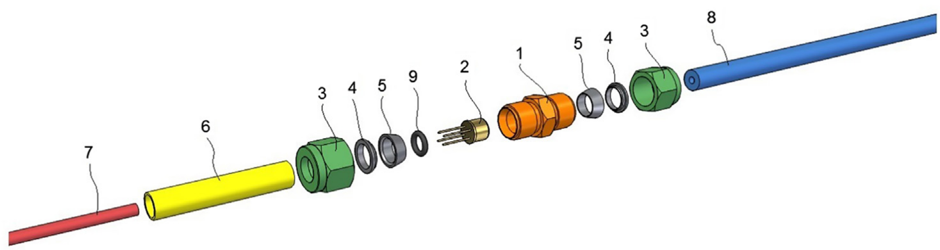

Fig. 2. Radiometer assembly. 1 – Compression fitting body; 2 – Thermopile; 3 – Compression fitting nut; 4 – Compression fitting rear ferrule; 5 – Compression fitting front ferrule; 6 – Standard 3/8″ tubing; 7 – Cable; 8 – View tube; 9 – O-ring.

argon or nitrogen. The standard TO-5 package is equipped with ZnSe window, which is transparent for radiation in the range from 0.6 µm to 22 µm. The absorber area is 4 mm^2. The cold face temperature is measured by a thermistor.

A special view tube was developed and connected to the thermopile to reduce the view angle. The "view angle" was defined as the angle belonging to 50% signal strength. The view tube characteristics, such as dimensions, material properties and inside surface properties play an important role in the radiometer design. By varying these characteristics different view angles can be created. The recent application requires to have as low view angle that the heat radiation arriving from the hot refractory wall surfaces does not affect the measurement, so the view angle is dictated by the dimensions of the entrained flow combustor (EFC) and the associated port sizes which is described later. In this case no corrections are necessary due to wall radiation influences. It was found that for the EFC a 305 mm long view tube with a 9.5 mm outside and 3.5 mm inside diameter give optimal geometry, while AISI 4130 material gives optimal mechanical properties.

The inner surface of the view tube is modified: particles with high emissivity factor are glued to the surface to reduce the reflectivity. Fig. 3 illustrates the difference between the raw and particle coated surface. The rough surface reflects the incident radiation in various directions, so the possibility of absorbing the radiation by the view tube is higher compared to the smooth surface. The heat absorbed by the inner surface is conducted through the wall to the outside surface, where the heat is released into the environment. Recent view tube contains pulverized coal particles in a size range of 150–210 µm. The coal is from Illinois Basin, USA. Fig. 4 shows the actual field of view (FOV) difference between the different surface types. The smooth, uncoated surface has 1.45°, while the surface coated with 150–210 µm particles shows 0.35° view angle. Particles in different size range influence the FOV. As seen on the graph finer particle size resulted in higher view angle.

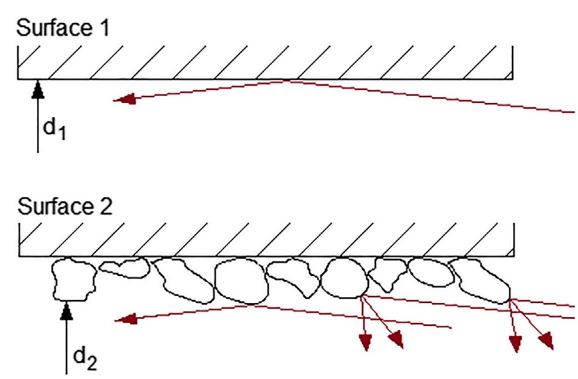

Fig. 3. Difference between the coated and uncoated surfaces. The solid particles glued to the inside surface reduces the view angle.

It was found that the surface coating decreases the view angle more efficiently than just a simple tube diameter reduction. This observation can be explained by the inside surface reflection differences. Obviously, the length of the view tube has also essential impact on the view angle: the longer view tube the smaller view angle (Fig. 5), but the length is limited by mechanical and other radiometer specific properties. Although several other techniques are known for view angle reduction (for example using baffles), a tube with modified surface provides a simple, easy to build and highly efficient view limiting device.

3. Results and discussion

3.1. Radiometer calibration

The radiometer was calibrated using an M390-A2 type black body calibration source [27]. The operational range is 600–2300 °C. The