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Experimental Design for Testing the Total Heat Flux through High-Temperature Components in High-Hydrogen Combustion Environments

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Abstract: High-temperature materials will need to withstand new environmental conditions in high-hydrogen gas turbines and so testing them in realistic environments is critical to predicting their performance. Obtaining the heat flux through materials in combustion environments is vital to predicting material life, but is often difficult and expensive to implement. This paper describes the design of a new facility for testing high-temperature materials in reacting environments with realistic gas turbine combustor flow features at a range of fuel compositions. A key component of this new facility is the heat flux block, which provides steady-state heat flux measurements by inducing one-dimensional heat transfer through the test material and block. The heat flux can be calculated from the temperature differential between several points along the block. Given the design of the heat flux block, is has an extremely high temperature limit lending itself well to testing high-temperature components in high-hydrogen combustion experiments. Initial testing of this heat flux block is presented and compared with theory.
Keywords: Heat transfer, Gas turbine, High-temperature material

1. Introduction

Next-generation high-hydrogen gas turbines can provide high-efficiency, low-carbon power by leveraging the high flame temperatures of hydrogen. However, the hot-section materials will face a harsher environment, with higher temperatures and water content in the combustion products. Ceramic matrix composites (CMCs), particularly environmental barrier coated (EBC) silicon carbide CMCs [1], have been proposed as a candidate material for these environments. This paper describes a testing facility that can test CMC samples in high-hydrogen environments that captures key features of real gas turbine combustors. The test facility is highly instrumented and can measure the temperature distributions on the CMC samples, the gas-averaged water concentration over the samples, and the total heat flux through the samples.

Components subject to combustion are required to withstand high temperatures and steep temperature gradients that threaten their structural integrity [2]. Therefore, it is important to measure the heat flux in combustors in order to know how to design components such as the combustion liner and any related cooling mechanisms. Measuring the heat flux while testing new candidate materials is particularly important in order to ensure that the material can handle the required

(a) CAD model of the combustion facility

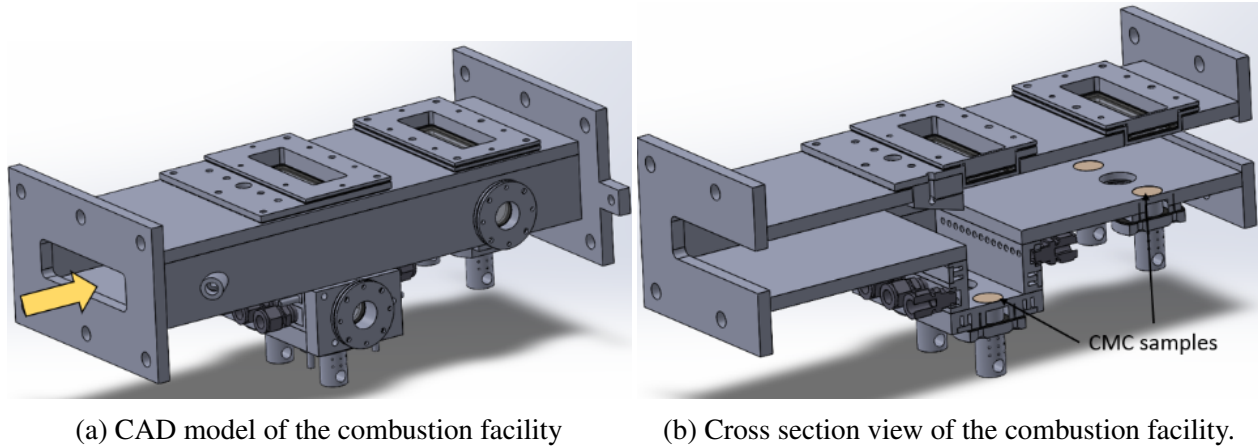(b) Cross section view of the combustion facility.

Figure 1: The test section of the test section of the combustion facility.

thermal loads. The issue is that much of the instrumentation for measuring total heat flux in high-temperature combustion settings is difficult and expensive to implement. Having a simple, inexpensive, and robust way to measure total heat flux in these settings would allow for a greater availability of reliable heat flux data. This paper will detail the theory and design of a simple method to measure heat flux through high-temperature components that will be implemented in a high-hydrogen combustion test facility. This method has been used in pool boiling experiments by others including [3–5].

2. Experimental Overview

The test section of the high-hydrogen combustion testing facility is shown in Figure 1. The combustor is a trapped vortex configuration where air is entrained into the cavity to form a strong recirculation zone. This configuration promotes superior flame-holding and high intensity combustion in the cavity, which allows for the facility to burn fuel blends of 100% natural gas up to 100% hydrogen. This configuration has been tested over a wide range of fuels by the Air Force Research Laboratory in a development effort for a compact, high-intensity combustor geometry [6]. CMC samples will be placed at the bottom of the cavity where the flame is anchored, as well as downstream where high-velocity combustion products (particularly water vapor) can accelerate oxidation of silicon carbide components [7]. This design provides two regions for samples – one low-velocity region with recirculating chemically-active species and one high-velocity region – to understand the impact of different parts of a typical combustor flow field on the CMC samples. There is optical access at each sample location where high-speed infrared imaging and tunable diode laser absorption spectroscopy (TDLAS) will be utilized to measure the temperature distributions on the CMC samples and the gas-averaged water concentration over the samples. Each CMC sample is mounted to a heat flux block, which serves as both the mechanism for mounting the CMC in the test facility and as a heat flux measurement device.

(a) CAD model of the heat flux block assembly

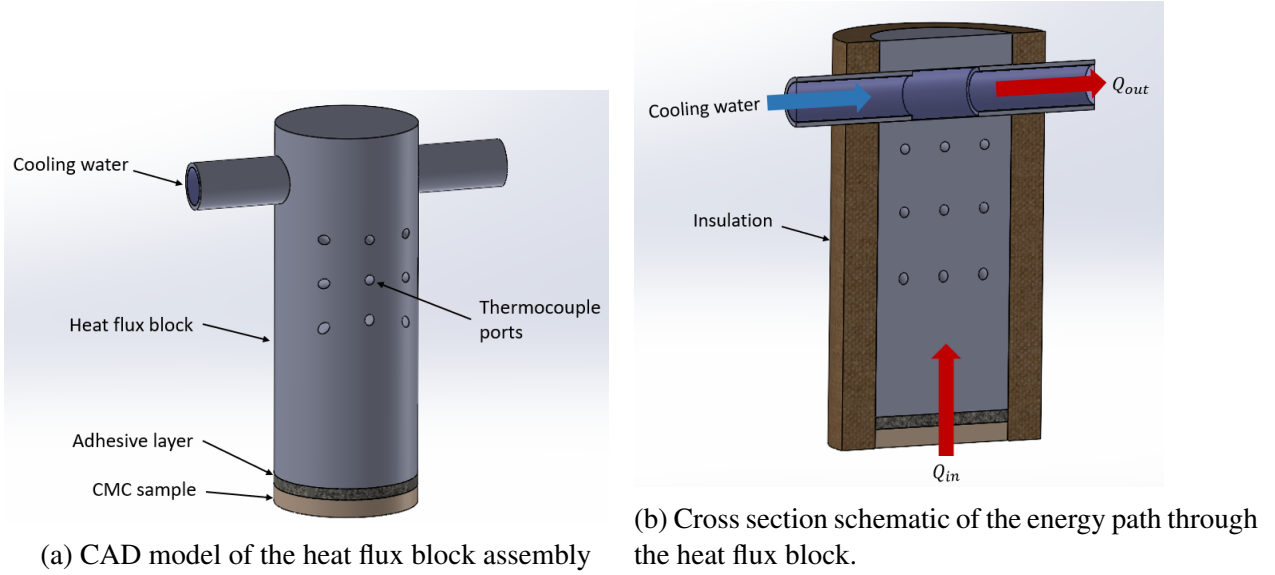(b) Cross section schematic of the energy path through the heat flux block.

Figure 2: Design and energy schematics of the heat flux block assembly

3. Heat Flux Measurement

The heat flux block assembly is the mode by which the total heat flux through the CMC sample is measured and can be viewed in Figure 2a. In the combustion facility seen in Figure 1, the heat flux block is positioned upside down as compared to Figure 2a, with the CMC sample level with the floor of the combustion chamber. However, for the testing of the heat flux block described in the remainder of this paper, the heat flux block is oriented as shown in Figure 2a. The heat flux block is a 316 stainless steel cylinder and is 1 inch in diameter to match the size of the CMC samples that will be fabricated. The sides of the steel cylinder are insulated and the end farthest from the CMC sample is water cooled to provide a heat sink, allowing some control over the heat flux through the sample. It is critical that there are no significant heat losses through the sides of the heat flux block in order to ensure one-dimensional heat transfer. A schematic of the energy path through the block is shown in Figure 2b.

Heat from combustion is introduced at the face of the CMC sample and flows vertically along the block. Nine 1/16" K-type thermocouples are placed in the small holes that reach the center of the cylinder so that the heat flux through the block can be calculated through the temperature differential between the thermocouples. The temperatures from thermocouples at each downstream distance of heat flow are averaged, resulting in a single temperature at three distinct vertical locations. Temperature measurements are collected when the block reaches a steady-state condition, which is determined when the temperature at each of the thermocouples fluctuates within 0.1°C for 30 seconds. Equation 1 is used calculate the heat flux through the heat flux block from the temperature measurements:

$$Q_{block} = -kA_{block}\frac{T_i - T_j}{x} \quad (1)$$

where k is the thermal conductivity of the steel at the given temperature, A_{block} is the cross sectional area of the heat flux block, T_i and T_j are the average horizontal thermocouple temperatures,
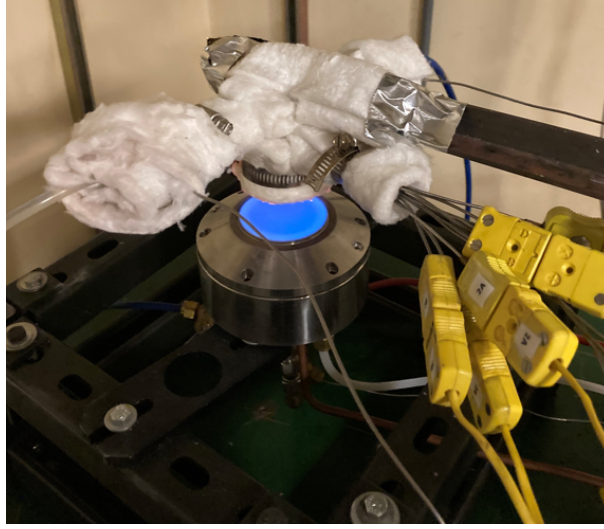
Figure 3: Testing setup for the heat flux block over the McKenna burner test bench.

and x is the distance between the thermocouples.

Initial tests were operated on the heat flux block alone, without a CMC sample attached. To verify the accuracy of the heat flux block, a first test was conducted with a known heat flux entering the block using an element heater on the face of the heat flux block. Insulating the back side of the heater causes all of the heat to flow along the heat flux block. The total heat flux measured through the block should match the power through the heater; differences between these two values allows us to estimate losses from the heater in any other direction.

A second test of the heat flux measurements can be derived from the amount of heat removed by the cooling water on the top of the heat flux block. This value can be calculated from Eq. 2:

$$Q_{coolingwater} = \dot{m}_{H_2O} C_{P,H_2O}(T_{out} - T_{in}) \tag{2}$$

where $\dot{m}_{H_2O}$ is the mass flow rate of the cooling water, C_{P,H_2O} is the heat capacity of water, and T_{in} and T_{out} are the inlet and outlet temperatures of the water. As seen in Figure 2b, the amount of energy removed from the cooling water should be equal to the amount of energy entering in through the face of heat flux block. Since Q_{block} and $Q_{cooling}$ are calculated independently, if the heat flux from the two calculations match, it can be concluded that the measurements are correct.

Further verification of the heat flux block concept is being conducted over an open flame from a McKenna burner, as seen in Figure 3. Various blends of methane and hydrogen will be used to test the heat flux block at a range of thermal powers. A variety of samples will be tested, including just the heat flux block, a sample of monolithic silicon carbide, and CMC samples.

4. Conclusions and Future Work

Obtaining the steady state heat flux through materials in combustion environments can be done in a simple and cost effective way through a heat flux block. Much depends on the one-dimensionality of the heat flux, so the sides of the heat flux block must be heavily insulated. The results of the heat flux block can be validated in multiple ways quantitatively. Once tested and validated, this method will provide reliable heat flux measurements in high temperature combustion settings. Since the block is pure steel, and the high-temperature sample piece acts as a thermal barrier this method has an extremely high temperature limit, lending itself well to testing high-temperature components in high-hydrogen combustion environments. This method will be implemented in a new combustion experiment designed to test high-temperature ceramic materials at a range of high-hydrogen fuel blend conditions.

5. Acknowledgements

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