Radiative Heat Flux Measurement in a Thermally Aggressive Environment via Optical Fibers

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It is difficult to gain a thorough understanding of the internal operating conditions of a solid rocket motor due to the harsh conditions found within the motor. An understanding of these conditions would provide further insight that would allow for continued optimization of rocket motors and their components. Quantifying the transient thermal radiative flux at the wall of a solid rocket motor has been elusive in the past. The baseline approach involves the use of Gardon gauges, of which some inherent weaknesses are gas flow invasiveness and extremely limited data collection due to soot accumulation on the instrument. A mechanical engineering senior project group at Weber State University has sought to design and implement a way to monitor the thermal radiative flux of oxyacetylene using a fiber optic cable embedded in ethylene propylene diene monomer (EPDM) rubber. Such a setup allows for data to be collected on light wavelength and intensity which are then transmitted to two ultra-compact spectrometers safe from the destructive forces of the torch. Our setup has suggested an advance of the state of the art, i.e., Gardon gauges, by providing data to the spectrometers continuously as the end of the fiber optic cable is burned and eroded. The measurements from the spectrometers, when carefully calibrated, have the potential to noninvasively quantify the thermal radiative heat flux at the wall of a solid rocket motor

I. Nomenclature

q	=	radiative heat flux
W	=	watts
m	=	meters
I	=	intensity
nm	=	nanometer
μm	=	micrometer
λ	=	wavelength

II. Introduction

Since the start of rocketry early last century, engineers and scientists have been working to improve the theory of rocketry. Most of the progress has been incremental and has come through rigorous research, development, and testing. Over time a strict set of standards has been built to provide guidelines for designing rocket engines. These guidelines often include high margins of safety to prevent unpredictable but critical failures. There are several advanced modeling methods that can be used to predict how a rocket design will behave. These predictions have been sufficiently accurate, but are limited to calculations, some of which are hard to confirm with direct testing and real-world data. Measuring conditions inside the pressure vessel of an operating solid rocket motor is a good example of this.

While in operation, the environment inside a solid rocket motor is too extreme for many instruments to survive for more than a few seconds. To measure the infrared thermal radiation environment inside the rocket motor engineers have been limited to tools such as copper-constantan circular foil heat-flux transducer (commonly known as Gardon gauges). These devices are expensive, large, and risk disturbing the regular flow of hot gases inside the motor, and quickly can be covered by soot or otherwise damaged by the environment of the rocket motor. They can even be dislodged and caught up in the flow and potentially damage other parts of the rocket. This generally means the Gardon gauge would only be able to capture a single "snapshot" of the radiation environment of the rocket, with high costs and some additional risks to any test burn.

III. Problem Statement

Our goal is to collect radiative heat flux data from fiber optic cables embedded in samples of rubber that are exposed to thermally aggressive ablative environments such as cutting torch flames. This is a step to eventually using the system inside a full-scale solid rocket motor. Using fiber optics in this manner is potentially a vast improvement on the current standard of Gardon gauges. First, due to the small size, the cable should not significantly affect the flow behavior inside of the engine during the burn. Second, the risk of debris that could damage other parts of the motor or engine from the optic is near non-existent. Another, and potentially the most exciting benefit of the system, would be the possibility of continuous monitoring of radiative heat flux inside a motor, rather than single momentary measurements that are reliable from Gardon gauges. Additionally, we are investigating the possibility that as the flame front erodes the fuel and insulation, the fiber optic will burn/break away at the same rate and continuously provide data throughout the test burn. In our preliminary testing with fiber optic embedded in a rubber insulator, erosion of the fiber while in the presence of a torch flame has provided some evidence that this advantage may be realized.

IV. Literature Review

The current standard method of measuring heat flux of high-intensity radiation sources is the Gardon gauge. The Gardon gauge uses a thin circular foil and a heat sink element with variable thermo-electric properties. When exposed to a heat source, it produces an electric potential proportional to the average heat flux, which can be measured [3]. As mentioned above, these are subject to sooting, and being rather large, have a significant chance of changing the normal fluid flow as surrounding insulation ablates. Additionally, this size makes them a potential hazard if dislodged. Generally, outside the field of rocketry, these instruments are designed to be placed in a relatively safe environment and not directly exposed to such harsh or hazardous conditions.

Another method of measuring radiative heat flux is demonstrated by an experiment using a Hybrid Rocket motor [1]. In this, they attempted to measure the radiative heat flux directly by placing a sapphire window in a cutout of a rocket nozzle. They then used a fiber optic to channel the light to a spectrometer. However, this method seemed to have problems with sooting or other interference, similar to what has been seen when using a Gardon gauge.

V. Design Concept

The fiber optic is embedded in a rubber sample approximating solid rocket motor insulation. The priority was to use as many commercial-off-the-shelf (COTS) products for the system as possible. The items that were not COTS we could cheaply and easily manufacture ourselves, generally through additive manufacturing techniques.

Unsurprisingly, most anything one puts in front of a cutting torch is not expected to survive the experience. We opted to use glass-fiber core OM3 optic cable, a cheap and easily obtainable standardized communication optic as the consumable portion of the measurement system. The glass fiber has the advantages of having a relatively low melting point (compared to the normal temperatures we would expect from a torch), being non-reactive, and unlikely to affect the torch's normal combustion process. The low melting point combined with the fragility of the glass fiber should mean the optic will erode more or less at the same rate as the insulation or grain it is embedded. Glass vaporizes at about 2300°C and an acetylene torch can get up to 3500℃, so as the glass erodes some may become a gas. This constant erosion has the benefit of not affecting the nominal flow of the hot gasses, but also exposing new optic to the environment, and mitigating, if not eliminating, the problems of soot buildup seen on other methods. This means not only the quality of data should remain consistent, but also will give dependable and continuous measurements of the environment. However, OM3 optical fiber is communication fiber that has been optimized for an IR signal range that may not be ideal for this heat flux measurement.

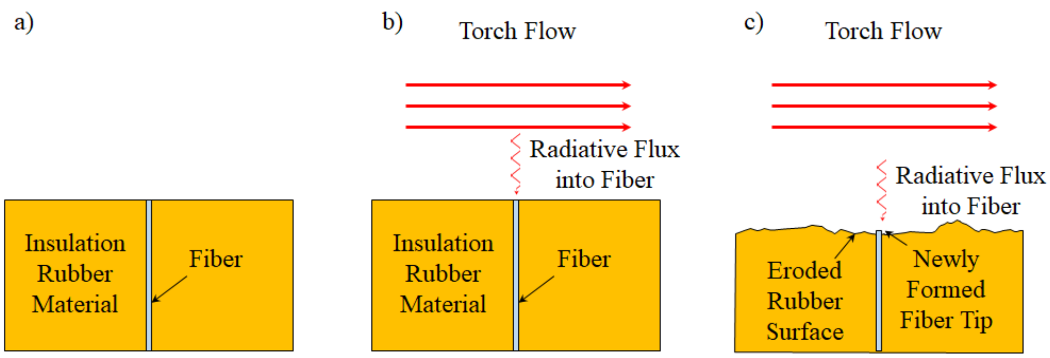

Fig. 1 Continuous data collection during ablation

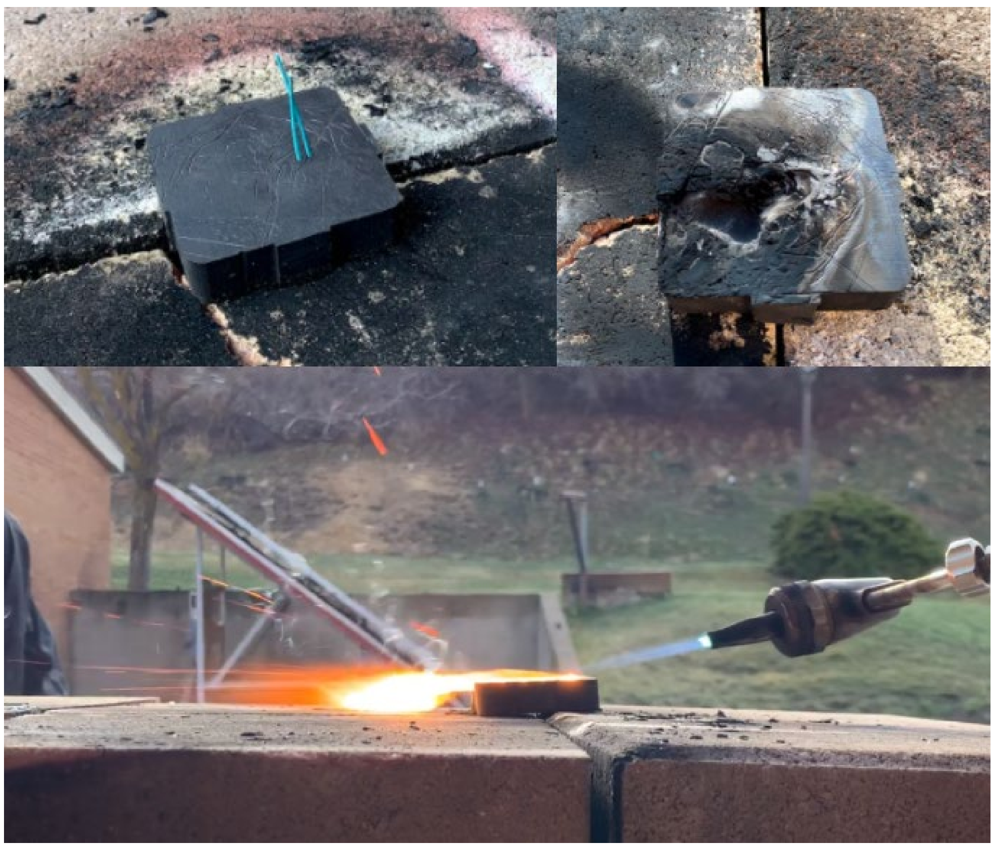

Fig. 2 Test Burn Setup

The radiation/light from the flame front is passed through the optic and using a standard connector fiber optic connector, is sent into a spectrometer. The spectrometer is a Hamamatsu MS series C11708MA Ultra-compact mini-spectrometer with a spectral response range of 640 nm to 1050 nm. This spectrometer has the advantage of being portable, and we would expect the most significant of the radiative heat flux from the torch to be in the near infrared range. The spectrometer measures the intensity of each wavelength and provides data to a computer that can be interpreted and analyzed.

We used a 3D printed enclosure to protect the spectrometer, and precisely and securely align the fiber optic connector with the spectrometer. Even slight deviations from an optimal position over the spectrometer leads to unreliable readings.

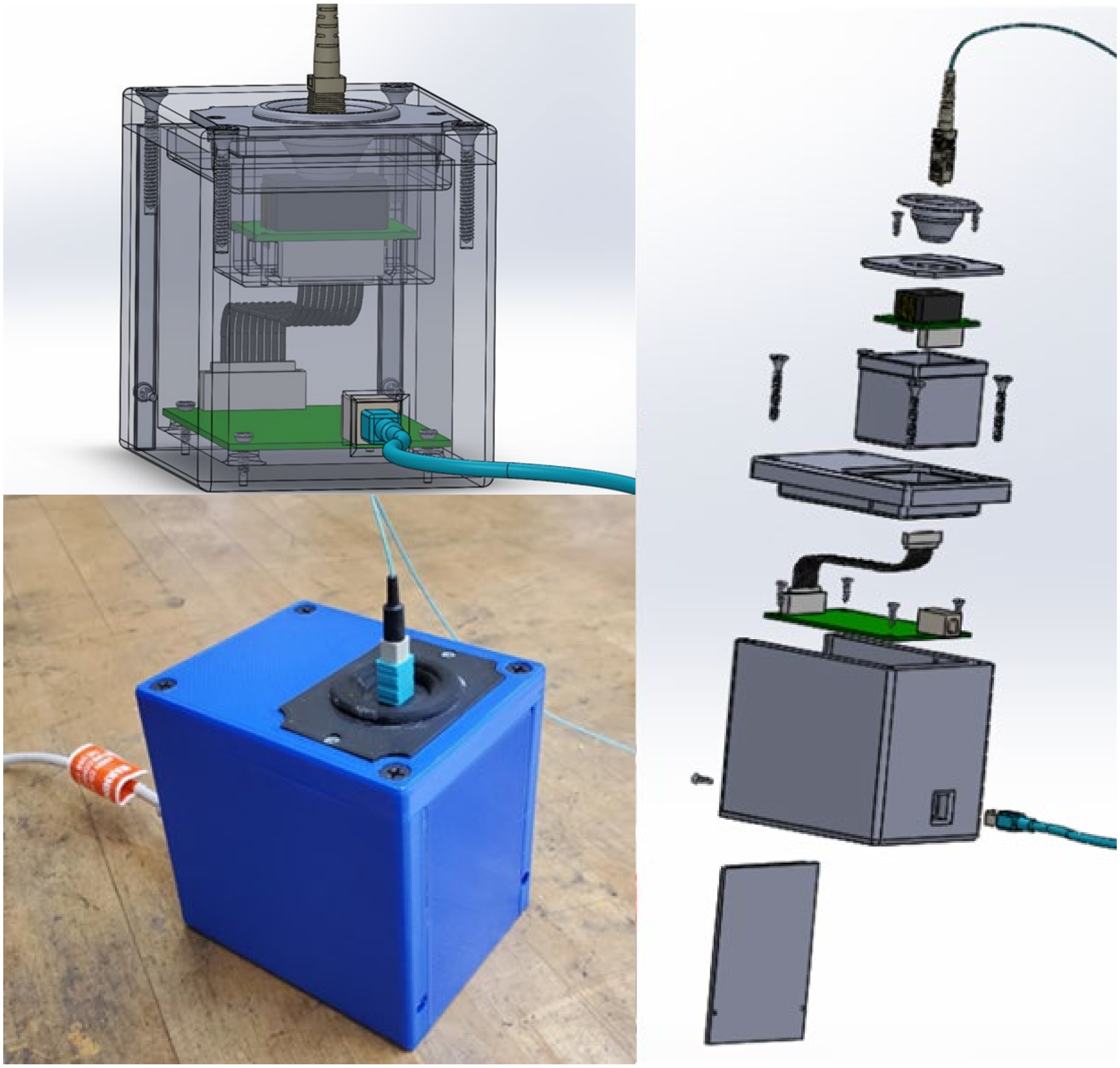

Fig. 3 Spectrometer Enclosure

VI. Data/Results

We have conducted a number of tests to help refine and provide proof of concept using an oxyacetylene cutting torch applied to fiber optic embedded in a rubber sample to as an approximation of solid rocket motor insulation. This method will lack the pressure environment of a rocket motor, but has a flame temperature theoretically higher than most rocket motors.

Using two fiber strands closely positioned in the rubber we were able to observe that both spectrometers produced similar patterns of spectral distribution. Most importantly, the spectrometer was receiving consistent signal from the optic throughout the test burn, providing significant evidence that continual measurements of transient radiative heat flux might be possible.

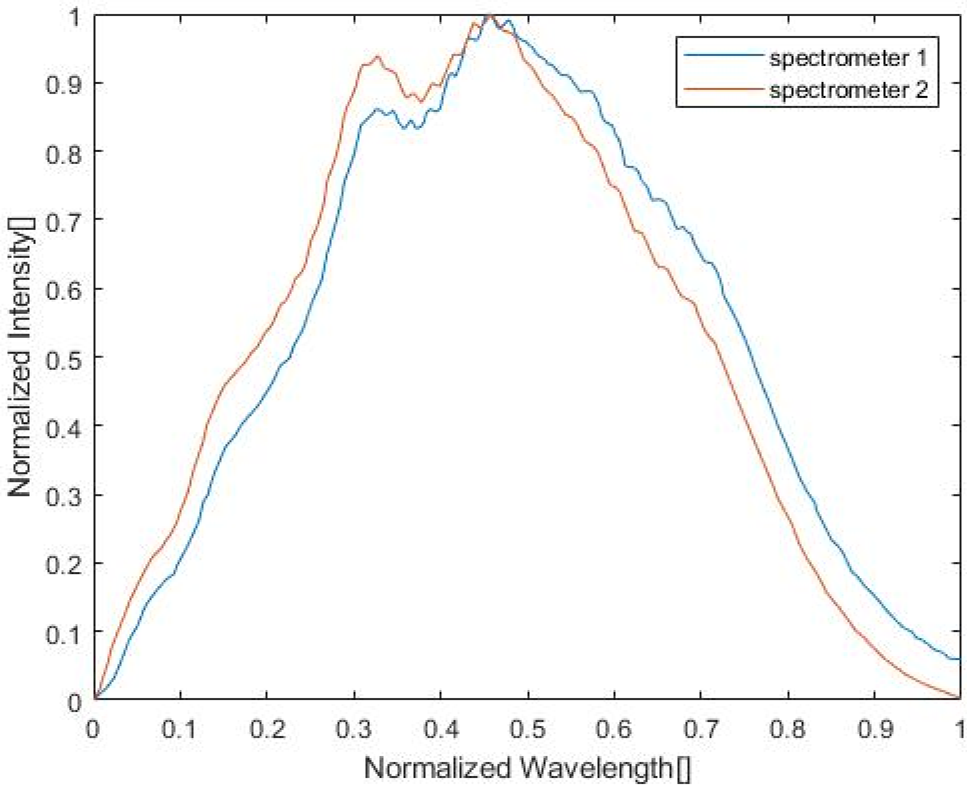

Fig. 4 Normalized Intensity vs. Wavelength Curve from Identical Spectrometers

Currently, the spectrometers are not sufficiently calibrated to provide exact data but should be reliable even at this point to provide data for relative comparisons. Once calibrated, the generated data curves can be integrated to get a direct measurement of radiative heat flux by using the following:

$$\breve{q} = \int_0^\infty \breve{I}(\breve{\lambda}) d\breve{\lambda} \qquad (1)$$

Where the function $I(\lambda)$ is the curve generated by the spectrometer, along with any factors to normalize both the intensity I and wavelength λ.

Figure 4 shows a normalized distribution from two spectrometers at the same time during the same burn test. Applying a numerical integration technique on the two curves we find that the ratio of heat flux would be 1.021, or there is about a 2% difference between the radiative heat flux measured between both spectrometers. This discrepancy is likely due to the need to further calculate the spectrometers and typical measurement noise and uncertainty.

VII. Further Considerations

While this method shows a lot of promise, there is a significant amount of work that still needs to be performed to prove its viability, and more testing evolutions and improvements have already been identified.

The utility of the data collected is limited until the instrument is calibrated. While drawing a comparison between data could prove useful, the goal would be for the data to output exact values as additional conclusions could be drawn from the data. There is the standard calibration for the wavelength of the spectrometer done with spectral tubes. We have already started the process of calibrating and between the two spectrometers it is apparent that it is needed. Then there is a power calibration which is much more complex as it is not so simple to take a single measurement and adjust. The losses in the optic cable, the end conditions of the fiber and other factors must be accounted for all the range of wavelengths to calibrate the intensity of the radiation observed. Once this is accomplished the radiative heat flux can be calculated accurately and that will provide the most reliable and useful data.

After properly calibrating our system we can conduct more precise and refined tests and experiments. For example, by running additional experiments with different gases such as MAPP or butane propellants. By doing a comparative analysis between two radiation sources of different intensity, e.g. Oxy-acetylene flame and MAPP or butane flame, we can compare the ratio of radiant properties of each flame in both theoretical and experimental situations, demonstrating the sensitivity of the method to different radiative heat flux intensities.

More significantly, we would like to test the system inside the pressure vessel of a rocket. We are currently slated to test the system in the 75mm hybrid rocket at Utah State University. Upon successful completion of testing on that scale, the method can be quickly and easily adjusted to match nearly any scale of static test.

Additionally, our system can be refined to better capture radiative heat flux by using more specialized components. Our current configuration consists of components that are readily available and have been developed to meet industry standards, not specific to rocketry applications. The fiber optics and connectors are designed to transmit a relatively narrow band of the IR spectrum and the spectrometers measure light over a slightly different range of wavelengths. While they do overlap and allow us to capture some of what is occurring within the rocket motor, the best method of gathering data would be to use an optic cable with greater range transmissibility, and a spectrometer that is somewhat more sensitive and has a greater range.

VIII. Conclusion

Using embedded fiber optics has shown significant promise in directly measuring the radiative heat flux. In our current testing format, we have collected data from these burns which appears to be consistent. This is a step closer to being able to measure thermal radiative heat flux inside a solid rocket motor accurately, using a fiber optic cable and a spectrometer. The ability to reliably and continuously measure the heat flux can provide scientists and engineers with more information about the environment inside a rocket motor. This could lead to better understanding of the thermo-fluid conditions of this environment and potentially aid in the development of better and more efficient rockets in the future.

IX. Acknowledgements

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X. References

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