NON-INTRUSIVE COMBUSTION DIAGNOSTICS FOR MEMS

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Abstract: A non-intrusive diagnostic technique based on FT-IR spectroscopy for making temperature measurements in MEMS devices is improved and demonstrated in a silicon walled micro-combustor. The technique takes advantage of the fact that CO_2 (a natural combustion product) has a temperature sensitive absorption band in the mid-IR region. Temperature is measured by using a statistical narrow band model to fit measured absorption spectra. Since the functional form of the temperature profile across the flow channel is known from previously developed analytical models for flames in channels, the fitting can be done by iteratively adjusting three parameters controlling the shape of the temperature profile. The direction of heat flow in the burner is determined from the gradient of the temperature distribution in the gas and measurements of heat loss to the environment. The temperature measurements are repeated for a variety of equivalence ratios and flame speeds and are used to calculate the total heat recirculation.

Keywords: non-intrusive diagnostics, micro-combustion, FTIR spectroscopy, flame stabilization, MEMS

INTRODUCTION

The push to develop miniaturized heat engines and chemical reactors is driving the need for techniques to measure flow properties like temperature and chemical composition in millimeter and sub-millimeter scale channels. In addition to the challenge posed by the small scale, many of these systems – especially those associated with power generation – involve flows of hot (> 1000K), oxidizing gas mixtures that will destroy most physical probes. Non-intrusive diagnostics are essential in these systems but providing optical access and acquiring enough signal from tiny sample volumes pose very significant challenges. Previous work has shown that Silicon's transmissivity in the infrared enables completely non-intrusive measurements of velocity using particle image velocimetry [1] and of gas temperature and species concentration using infrared absorption spectroscopy [2]. Recent work [3] has shown that it is also possible to measure the gas temperature distribution along the optical path provided the basic functional form of the temperature distribution is known. This is important because it enables one to determine the temperature distribution in the gas and from this compute the heat flux to the wall.

APPLICATION OF DIAGNOSTICS

Flame Stabilization

The problem of flame stabilization in microchannels has been studied by various researchers. Leach et al. [4] used a simple thermo-electrical analogy to incorporate axial heat transfer through the gas and structure and a one-step mechanism for the heat generation. More recently, Schoegl and Ellzey [5] used a semi-analytical model to investigate both co- and counterflowing flames in two parallel oppositely flowing channels while accounting for heat conduction in the wall separating the channels.

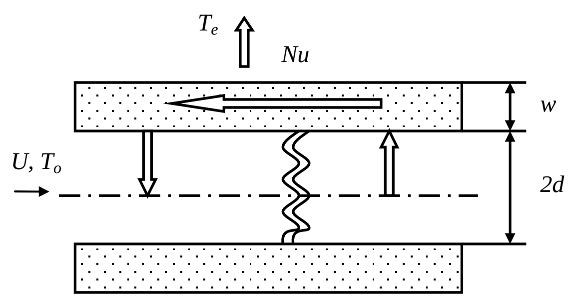

Fig. 1: Schematic illustration of flame stabilized in a micro-channel.

Our previous paper on this subject focused on the development of a two-dimensional analytical model [6] for pre-mixed flames stabilized in a channel in which the heat transfer was modeled [7, 8] by directly solving the governing energy equations for gas and wall after accounting for thermal coupling analytically (see figure 1). This resulted in a flame model (after coupling with a species transport equation) from which flame speed and temperature distributions in the channel could be predicted. The two dimensional analytical model was used to demonstrate that the temperature distribution in the transverse direction (wall-gas-wall) could be well approximated using a 4^{th} order polynomial in the transverse spatial coordinate [9, 10].

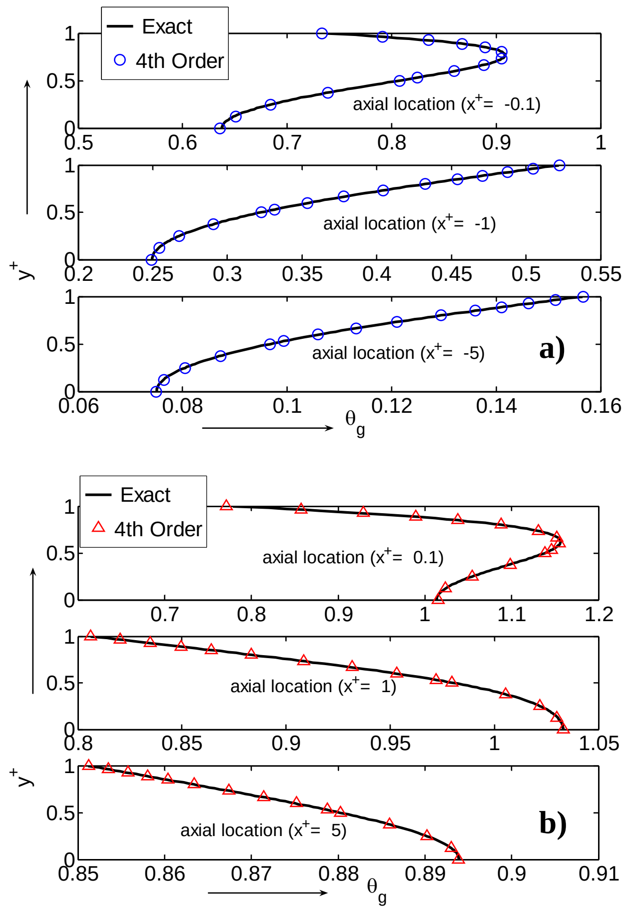

Fig. 2: Comparison of transverse temperature profiles for Poiseuille flow a) Pre-flame b) Post-flame

Figure 2 shows non-dimensional temperature (θ_g) as a function of non-dimensional transverse coordinate ($y^+=y/d$). The 4th order approximation fits the exact solution very well in both pre and post-flame regions at different axial locations. Since the temperature distribution actually peaks off the channel centerline at certain locations, a minimum of a 4th order profile is required and we use this here.

Non-intrusive Diagnostics

The non-intrusive diagnostic technique is based on the fact that the shape of a CO_2 absorption band in the mid infrared is a well known function of temperature. The details of the diagnostic technique have been presented elsewhere [3] and are only summarized briefly here. The instrumentation (figure 3) consists of a Thermo Nicolet Nexus 870 Fourier transform infrared spectrometer (FTIR) and an external set of optics that direct the FTIR beam through a simulated micro-combustor and onto the FTIR's Mercury Cadmium Telluride (MCTA*) detector which has been removed from the instrument and attached to the optical table. A scanning Michelson interferometer inside the FTIR varies the wavelength of light passing through the combustor so that a Fourier Transform of the detector signal gives the absorption spectrum of the sample.

The external optics consist of a 190 mm focal length off-axis parabolic mirror that brings the beam to a focus inside the micro-combustor and another off-axis mirror with a focal length of 50.8 mm to focus the transmitted beam on the FTIR detector. The first mirror reduces the beam diameter from approximately 38 mm to 10 mm.

The absorbance $A(\bar{\upsilon})$ is defined as follows:

$$A(\bar{\upsilon}) = \log_{10} \frac{I_0(\bar{\upsilon})}{I(\bar{\upsilon})} \tag{1}$$

where I is the transmitted intensity and I_o is the incident light intensity. The Beer-Lambert law relates the absorbance to the path length L, concentration C, and the molar absorptivity $\varepsilon(\bar{\upsilon})$:

$$A(\bar{\upsilon}) = \varepsilon(\bar{\upsilon})\, C\, L \tag{2}$$

Gas temperature is inferred by comparing the measured CO_2 infrared absorption spectrum to one computed using equation 2 and a statistical narrow band model from EM2C laboratories [11] for $\varepsilon(\bar{\upsilon})$. Previous work has shown that this is the best method for inferring gas temperature from absorption measurements [2].

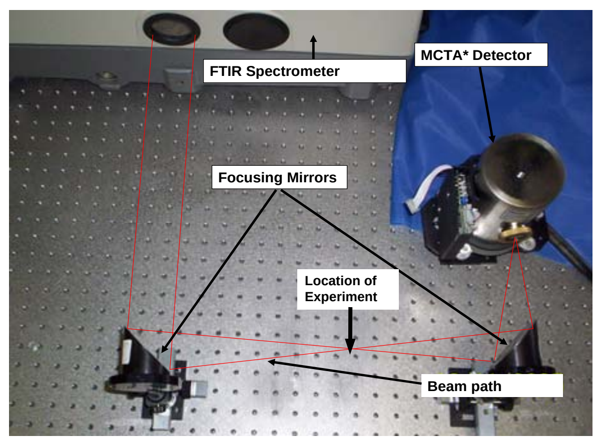

Fig. 3: External optical arrangement (IR beam path in red).

The gas temperature distribution along the line of sight is obtained by dividing the optical path between the simulated micro-combustor's walls (two silicon wafers) into n equal cells as illustrated in figure 4. While one might be tempted to perform a large optimization to find the gas temperature in each cell that produces the best fit to the experimental measurements, this presents a number of problems including the loss of spatial information. Spatial information is retained by assuming that the functional form of the temperature profile is known and well represented by a 4th order polynomial.

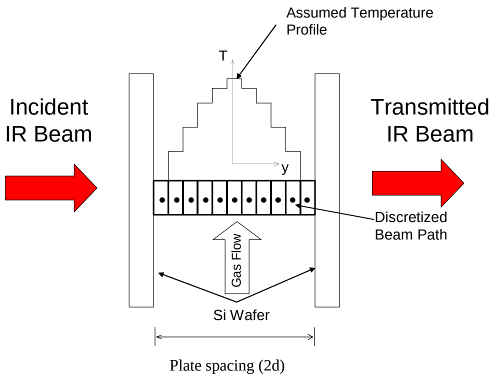

Fig. 4: Illustration of discretized beam path with an assumed temperature distribution.

The 4th order temperature profile is given by

$$T(y) \;=\; a_4\, y^4 + b_4\, y^3 + c_4\, y^2 + d_4\, y + e_4 \qquad (3)$$

In this expression, y varies from zero to $2\,d$, the passage width, which in the current experiment is around 2.10 mm. The temperature profile is forced to be symmetric about the channel centerline by requiring that:

$$T(0) \;=\; T(2d) \qquad (4)$$

$$\left.\frac{dT}{dy}\right|_{y=d} = 0 \qquad (5)$$

$$\left.\frac{dT}{dy}\right|_{y=0} = -\left.\frac{dT}{dy}\right|_{y=2d} \qquad (6)$$

Subjecting eq. 1 to these conditions gives

$$b_4 = -4d\,a_4 \quad and \quad d_4 = -2d\,c_4 + a_4\,(2d)^3 \qquad (7)$$

Equation 5 relates two of the fitting parameters to the other three. Therefore, there are only three independent temperature fitting parameters (namely a_4, c_4 and e_4) even though we fit for a 4th order profile. The implementation of the actual fitting is as follows: A Matlab script was created that loads the experimental data files into the workspace and uses an internal least-squares based optimization routine (‘lsqcurvefit) to find the values of a_4, c_4, and e_4 that produce the best match to the measured absorption spectrum. The optimization routine calls another custom function that takes the fit parameters and the CO_2 mole fraction, generates a temperature profile, modifies the input files used by the EM2C program, runs EM2C, and returns the predicted absorption spectrum. The optimization proceeds until values of a_4, c_4, and e_4 converge. These values are assumed to describe the temperature profile that produces the best match between the predicted and measured absorption spectra. A critical requirement, however, is a good starting guess for the temperature profile. This is provided by the analytical model.

RESULTS AND DISCUSSION

The diagnostic technique described in the previous section is applied to reacting flow in a planar microchannel intended to simulate conditions in a micro-combustor. The power of the technique (despite some of its short comings [10]) is that it enables measurement of temperature in both axial and transverse directions in a very small volume. Figure 5 shows 2-D temperature distributions in the pre-flame and post-flame regions.

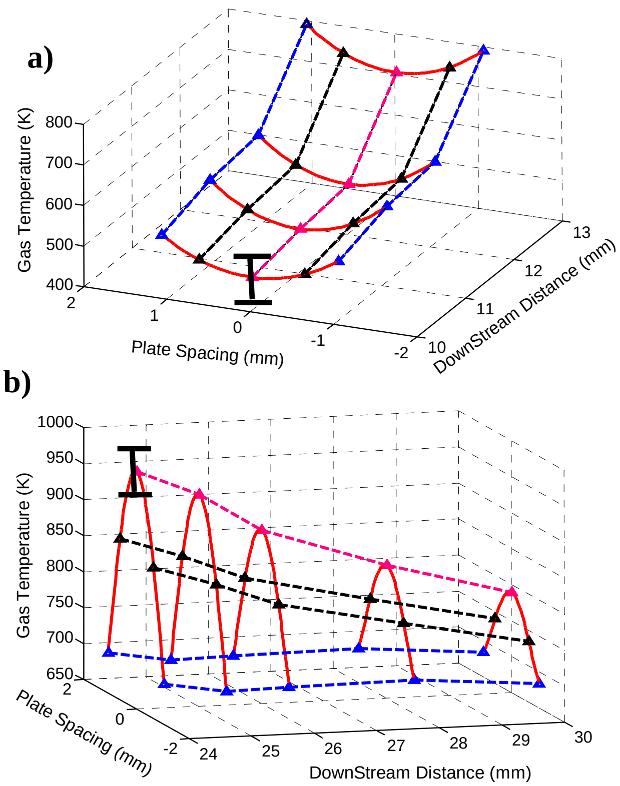

Fig. 5: 2D temperature distribution in the channel (ϕ = 1.15, U = 50 cm/s) a) pre-flame region b) Post-flame region

The figure shows that in the pre-flame, the walls are hotter than the gas and hence heat transfer occurs from wall to gas. In the post-flame the trend is opposite as the hot post combustion gases lose heat to the wall. The wall-gas heat recirculation and the total heat recirculation can be calculated from the temperature profiles as follows:

$$H_{\mathrm{Re}circ,wall} = k_g \left. \frac{dT}{dy} \right|_{wall} dx \qquad (8)$$

$$H_{\mathrm{Re}circ,\,total} = H_{\mathrm{Re}circ,wall} + H_{\mathrm{Re}circ,gas} \qquad (9)$$

Repeating the measurements are repeated for a variety of equivalence ratios (ϕ's) and flame speeds enables one to relate flame speed to heat recirculation.

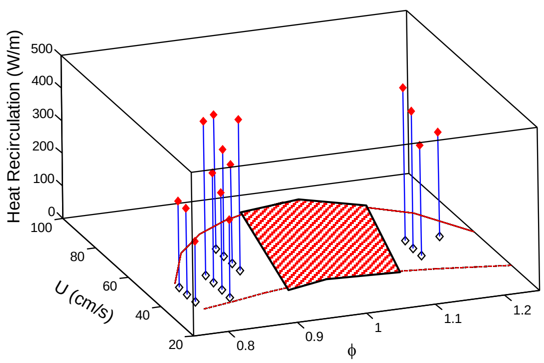

Fig. 6: Heat Recirculation as a function of ϕ and U for CH_4/Air

Figure 6 shows the heat recirculation plotted as a function of the equivalence ratio and flame speed. It shows that the flame speed increases with total heat recirculation for a given equivalence ratio. Measurements were not possible in the hashed region because the silicon wafers lose their IR transmissivity at temperatures exceeding ~350 ^{o}C.

CONCLUSION

A non-intrusive technique for measuring gas temperatures in micro-combustors has been extended to enable measurement of gas-wall heat fluxes. It relies on line-of sight measurements of CO_2 absorption, a well-established model for the temperature dependence of CO_2's absorption spectrum, and knowledge of the functional form of the temperature profile across the channel established by previous analytical modeling efforts. The technique is used to measure the gas temperature distribution and the gas-wall heat flux in a simulated microcombustor. The flame speed observed in the burner was found to be proportional to the net heat recirculation.

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