Annual Report for ACS/PRF Grant 2018

Title: Measurement of Stretched and Curved Laminar Flames at Extreme Pressure

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1 Proposed objectives

The following objectives have been proposed for a two-year time period.

1. The principal objective is to study the effect of stretch and curvature on tubular flames at high pressures and validate the existing chemical kinetic mechanisms and molecular transport theory models such as developed by Frenklach et al. (1999) and Ern and Giovangigli (1995).

2. Raman spectroscopy and LIF techniques will be used to obtain the temperature field, major and minor species concentrations.

3. During the first year, it was proposed that both premixed and non-premixed H_2/air flames will be studied using Raman spectroscopy for major species measurements and LIF for minor species measurements. Suitable experimental conditions will be surveyed using chemiluminescence imaging. Data obtained will be reduced and compared with numerical simulations performed using an in-house DNS code (Hall and Pitz, 2016). Performance of H_2/air chemical kinetic and transport models such as those proposed by Burke et al. (2012) will be evaluated. A Hencken burner will be used for calibrating the Raman and the LIF systems.

4. During the second year, it was proposed that hydrocarbon/air premixed and non-premixed flames will be studied using similar techniques as those used in the first year. Reduced mechanisms for HC combustion will be validated and improved.

5. The high pressure experiments will be conducted in the high pressure duct located in the King Abdullah University of Science and Technology (KAUST) in the Kingdom of Saudi Arabia as a part of Clean Combustion Research Center. A graduate student will co-ordinate with the KAUST faculty for the same.

2 Completed and ongoing tasks

It may be noted that this project started six months after the original proposed start date[1]. The time line of the objectives has been modified to better accommodate them. During the first year of this project, it was planned that chemiluminescence imaging for both H_2 and HC flames would be undertaken by transporting the burner to KAUST in September, 2017. Premixed and non-premixed flames would be imaged. H_2/air and HC/air flames would be imaged to study cellular instabilities and extinction. Experimental conditions chosen are similar to those used by Shopoff et al. (2011a,b), Wang et al. (2007), Hu et al. (2009) and Tinker (2016). The effect of using different diluent gases on thermodiffusive instabilities through curvature, stretch rate and mixture Lewis number would also be investigated. However, the number of experimental cases that would be studied was subject to the time available and other practical difficulties such as burner assembly inside the high pressure duct, flame ignition etc.

Based on the chemiluminescence imaging from the first year, suitable candidates would be chosen for Raman and LIF experiments in the second year. Data obtained would be compared with numerical simulations to validate and improve chemical reaction mechanisms and transport models.

The burner was transported to KAUST in September, 2017. However, due to the many difficulties that were encountered in installing the burner in the high-pressure duct, no usable chemiluminescence images were obtained. The difficulties that were encountered are described below along with the proposed action plan for the next set of experiments.

1. **Limited accessibility into the high-pressure duct** - At the point of entry into the duct, there is only about 14 inches of room for the burner to be installed. The burner is about 2 feet long and, thus, needs to be tilted and pushed while installing. During this, the inner nozzle got decentralized and one of the welds got broken. To fix this, a sturdier holding and translation mechanism for inner nozzle will be used. This is achieved by using a more compact translation stage and the translation stage is now fixed onto the burner itself instead of the burner plate.

2. **Ignition of the mixture without disintegrating the inner nozzle** - Laser ignition was used last time. While aligning the laser beam to focus near the ignitable mixture, the inner nozzle was inevitably hit by the laser. It is suspected that this caused the sintered metal to melt and fuse together. For the next attempt, an alternative using a plasma ignitor or a hot rod will be employed. Testing is currently

[1] When the grant was started on July 1, 2016, there were no PhD students available to work on the ACS PRF grant. Ms. Harshini Devathi entered the PhD program in Mechanical Engineering in January 2017 to perform the research on this grant as part of her PhD dissertation.

under progress in Vanderbilt University to decide on the best alternative.

3. **Resistance of the mirror to high-temperature exhaust products -** The mirror under the burner was secured using aluminum screws in the previous attempt. However, due to the hot exhaust products, they got unfastened during the experiment and the mirror kept getting misaligned. This was only exacerbated by the fact that the burner was inside a duct and the hot products tended to stay closer to the setup than they would in an open environment. For the next attempt, the mirror mount will be modified to prevent loosening of the screws from the hot exhaust.

4. **Endoscope -** Request has been placed with KAUST to install an endoscope to look inside the duct to see if anything undesirable is happening and avoid it if possible.

(a) **(b)**

Figure 1: Chemiluminescence image obtained for non-premixed tubular flame inside the high-pressure duct. The flame is not circular due to decentralization of the inner nozzle and the breaking down of the weld while installing (left). Circular flame image of a non-premixed tubular flame is obtained outside the high pressure duct at 1 bar before damage (right)

As a result of the above difficulties, the final chemiluminescence image for a specific set of conditions for the non-premixed configuration was obtained as is shown in Fig. 1a. As it was not possible to do chemiluminescence imaging of the non-premixed flames, an attempt was made to image premixed flames. The team at KAUST was hesitant about performing hydrogen experiments due to the high possibility of flashback. Some experiments were performed using methane as the fuel. However, during laser ignition, one of the windows was broken and so the experiments could not be continued any further as the time alloted for the tubular burner experiments had run out and there were other experiments lined up for the duct.

The next set of experiments will be performed based on the high-pressure duct's schedule. The high-pressure duct has slots open for sometime after March/April 2019. Also, it may be noted that Raman experiments will not be performed as KAUST is still working on the optics setup for the high-pressure duct.

During the latest conversation with KAUST, it was informed that it is very unlikely for us to get to the Raman experiments in the upcoming year. Even if the Raman experiment setup gets completed in time, due to the complexity of the tubular burner, it may not be successful.

Thus, after redesigning the components of the experiment as described above, initial testing will be done at Vanderbilt University in Fall 2018. The burner will be transported to KAUST around March/April of 2019 and chemiluminescence and LIF experiments will be performed. We believe that these experiments will give valuable insights into the effect of stretch and curvature as a function of pressure. In the meanwhile, simulations are being performed with a variety of fuels such as hydrogen, methane, propane, dimethyl ether under a variety of stretch and curvature conditions at a variety of pressures. Currently, a lot of effort is being devoted to simulating cool flames as this has never been simulated in the past in the context of tubular flames and understanding stretch and curvature. The in-house DNS code is converging to the trivial solution. So, attempts are being made with different initial and experimental conditions. We are also observing multiplicity for cellular non-premixed hydrogen flames and are investigating this.

3 Expected outcome

Nishioka et al. (1991) have studied the effects of pressure on the structure and extinction of a premixed tubular flame. It provides a very useful insight into the behavior of these flames at high pressures. To the best of our knowledge, chemiluminescence imaging and LIF experiments to be performed in KAUST in 2019 are the first of their kind to characterize the effect of pressure on the formation of cells in a tubular flame. We expect to obtain meaningful insights into the thermodiffusive instabilities of these flames at high pressures which characterize realistic combustion environments such as those encountered in gas turbine combustors and internal combustion engines. This helps understand turbulent flames which are characterized by localized curvature and stretch effects although qualitatively. In addition, the extensive simulations are being performed to characterize pressure effects in tubular flames using the in-house code developed by Vanderbilt University. In terms of deliverables, up to three conference and/or journal papers are expected to be published.

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