

# Predicting Lean Blowout Using the Damkohler Number

Matthew Bloxham

July 28, 2006

## Purpose

The purpose of this study is to investigate the possibility of correlating the premixed combustion lean blowout of IR's set of MT70 microturbines that burn a variety of fuels. In particular, three different combustion systems are used to bridge the fuel range from 350 Btu/ft<sup>3</sup> up to 1300 Btu/ft<sup>3</sup> (LHV). The idea was that if a universal correlation could be derived, the microprocessor-based control system could use this information to accurately predict when to stage fuel and turn on a diffusion flame circuit to prevent lean extinction and permit further reductions in power.

Data from a chemical kinetic code was used to create universal correlations for the flame speed, flame thickness, and equivalence ratio based on a range of methane/CO<sub>2</sub> mixtures. These parameters were then used to calculate the Damkohler number, which has been shown by other authors<sup>[1]</sup> to identify lean blowout. These correlations are only dependent on temperatures, pressures, the lower heating value of the fuel, and the equivalence ratio in the primary zone of the combustor. Measurements for the required temperatures and pressures are continually taken at a limited number of state points in the engine during microturbine operation. The lower heating value is identified on a site by site basis, and a correlation was created to predict the equivalence ratio. An algorithm was then identified to use the Damkohler number correlation to determine when the pilot fuel should be engaged.

## Procedure

The Damkohler number predicts the blowoff limits of a premixed flame and is defined as the ratio of the residence and chemical kinetic times,  $\tau_{res}/\tau_{chem}$ <sup>[1]</sup>. In their paper, Noble et al. defined the residence time as the ratio of a characteristic length scale (recirculation zone length),  $d$ , and a characteristic velocity scale,  $U_{ref}$ . The chemical time was defined as the ratio of the thermal diffusivity,  $\alpha$ , and the square of the laminar flame speed,  $S_L$ . The complete Damkohler equation as defined by Noble et al. can be seen in Eq. 1 below.

$$Da = \frac{\tau_{res}}{\tau_{chem}} = \frac{S_L^2 d}{\alpha U_{ref}} \quad \text{Eq. 1}$$

In this study, the Damkohler number was modified slightly from Eq. 1 to eliminate the thermal diffusivity and incorporate the flame thickness,  $f_T$ . The resultant relationship can be seen in Eq. 2.

$$Da = \frac{\tau_{res}}{\tau_{chem}} = \frac{S_L d}{f_T U_{ref}} \quad \text{Eq. 2}$$

The subsequent sections explain the procedures used to determine each of the parameters needed to calculate the Damkohler number (Eq. 2). Correlations were used to predict the flame thickness and flame speed given the combustor inlet temperature, inlet pressure, lower heating value of the fuel, and the equivalence ratio. A correlation was also created to predict the equivalence from measured cycle state points in the engine and the lower heating value of the fuel. These correlations and the length/velocity scales are described below in greater detail.

## Characteristic Length

The characteristic length scale was somewhat arbitrarily assigned to be 1/2 the radius of the prechamber. A rough sketch of the combustor can be seen in Fig. 1. The prechamber is located where the combustor can necks down to join the swirlerhead.

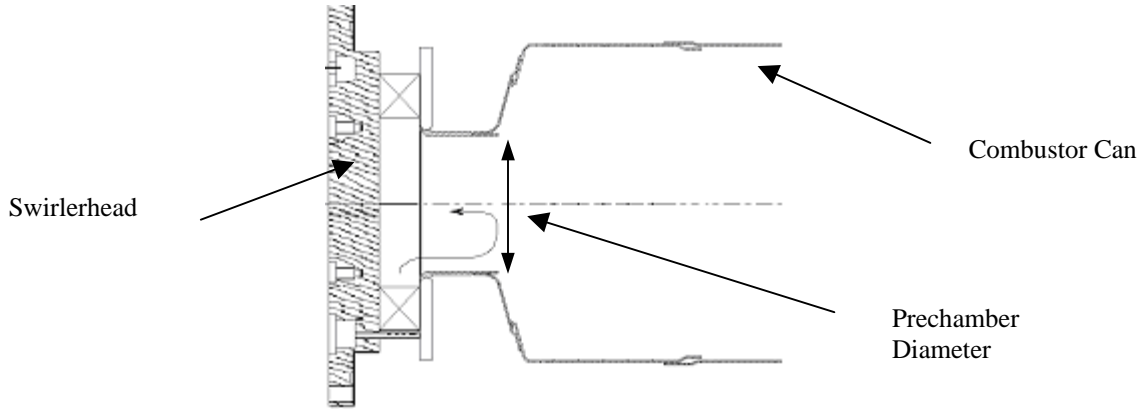


Fig. 1: Sketch of the combustor can and prechamber

### Characteristic Velocity

The characteristic velocity was assigned to be the average velocity through the prechamber. This velocity was calculated using the measured mass flowrate ( $\dot{m}_{PZ}$ ), a prediction of the density at the inlet of the combustor, and the area of the prechamber ( $A_{PZ}$ ). The following cycle diagram<sup>[2]</sup> (Fig. 2) was helpful in this analysis. The temperatures and pressures of the subsequent discussion are also labeled on the diagram.

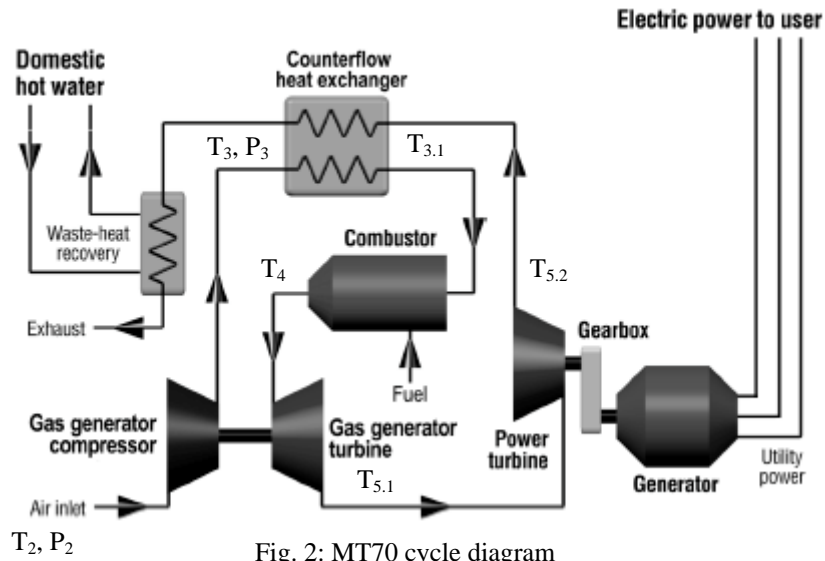


Fig. 2: MT70 cycle diagram

The density of air at the inlet of the combustor was predicted using the ideal-gas relation (Eq. 3)

$$\rho_{3,1} = \frac{P_3}{R_{Air} T_{3,1}} \quad \text{Eq. 3}$$

where  $P_3$  was assumed to be constant across the recuperator,  $R_{Air}$  is the gas constant for air, and  $T_{3,1}$  is the exit temperature of the recuperator. In order to obtain a prediction for  $T_{3,1}$ , it was first necessary to assume the compressor was isentropic. This assumption (with  $T_2$ ,  $P_2$ , and  $P_3$ ) resulted in the following equation (Eq. 4) for the isentropic temperature  $T_{3,s}$

$$T_{3,s} = T_2 \left( \frac{P_3}{P_2} \right)^{\frac{k-1}{k}} \quad \text{Eq. 4}$$

where  $k$  is the specific heat ratio ( $k=1.4$ ). Once  $T_{3,s}$  was obtained, it was used with a prediction of the compressor efficiency to obtain  $T_3$  from Eq. 5. The compressor efficiency,  $\eta_c$  was calculated using the compressor pressure ratio.

$$T_3 = \frac{T_{3,s} - T_2}{\eta_c} + T_2 \quad \text{Eq. 5}$$

$T_{3,1}$  could then be solved using the recuperator effectiveness, the measured value  $T_{5,2}$ , and Eq. 6.

$$T_{3,1} = T_3 + \varepsilon(T_{5,2} - T_3) \quad \text{Eq. 6}$$

Once  $T_{3,1}$  was calculated, the density of air at the inlet of the combustor could then be solved using  $T_{3,1}$  and  $P_3$ . The average velocity of air through the prechamber was subsequently solved using Eq. 7

$$U_{ref} = \frac{\dot{m}_{PZ}}{\rho_{3,1} A_{PZ}} \quad \text{Eq. 7}$$

### Flame Speed

The first step in creating a correlation for the flame speed was to assume the form of the solution for the correlation. This assumption was based on calculations for flame speed performed using Sandia Lab's PREMIX<sup>[3]</sup> code along with CHEMKIN<sup>[4]</sup> and TRANSPORT<sup>[5]</sup>. The kinetic model used in these calculations is from GRI-Mech 2.11<sup>[6]</sup>. The model consists of 49 species and 279 reactions and was used to predict the combustion characteristics for methane. The model can also be used to predict the combustion characteristics of acetylene and ethylene. However, for this exercise, only the methane reactions were considered. The calculations were created over a range of pressures (2.5-4 atms) and temperatures (700-900K). These calculations suggested that the solution would take on the form shown in Eq. 8 (removed for proprietary reasons)

$$S_L = f(\phi, LHV, T_{3,1}, P_3) \quad \text{Eq. 8}$$

where the correlation depends on temperature, pressure, and the lower heating value of the fuel.  $\phi$  is the equivalence ratio of the mixture in the primary zone. The temperature range used in the correlation was 700 to 900K. The pressure range was 2.5 to 4 atm and the range of lower heating values was 240 to 802 kJ/mol.

Once the form of the equation was determined, the chemical kinetic data were used as the target for the fit. The form of the equation and its unknowns were adjusted using Excel's solver until the error between the target and the fit was minimized. The constants were recorded for each set of temperatures, pressures, and lower heating values. After these values were recorded, the regression tool in Excel was used to create equations that depended solely on the temperature [K], pressure [atm], lower heating value [kJ/mol], and the interaction of these properties at the combustor inlet.

The resultant equation for flame speed was compared with the kinetic data to validate the fit. The average error of the fit over the entire range of the calculations was ~4.6%. This value was deemed acceptable for this study. An example of the results can be found in Fig. 3.

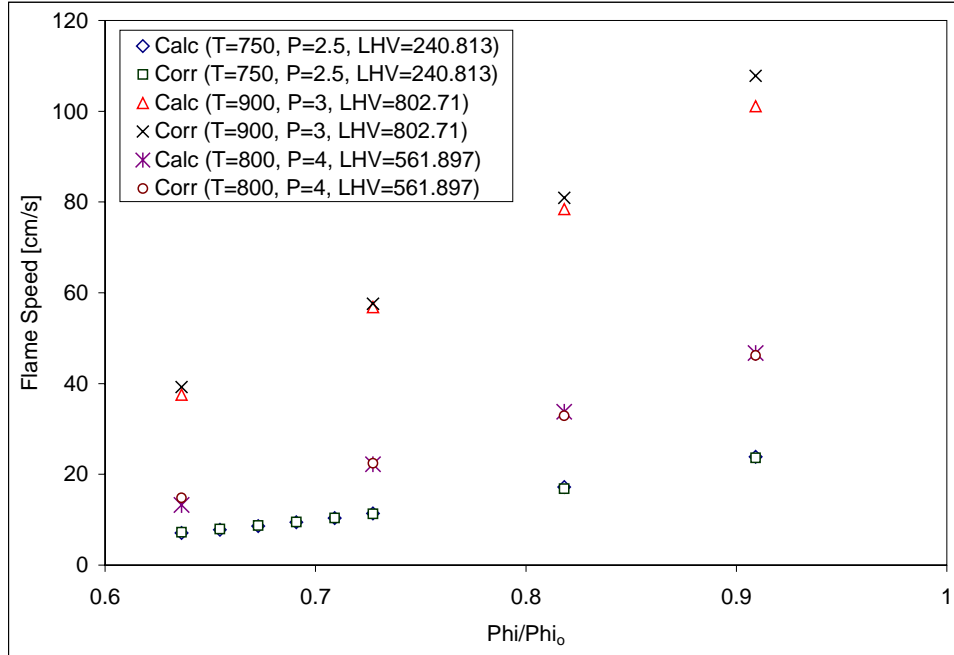


Fig. 3: Comparison between the correlation and calculated values for flame speed.

Fig. 3 shows that the correlation very accurately predicts the calculated values of the flame speed for a given temperature, pressure, and lower heating value.

#### Flame Thickness

The method used to create a correlation for flame thickness was very similar to the process used for the flame speed correlation. Sandia Lab's PREMIX code was again used to calculate the flame thickness. The calculations were used to identify the form of the solution for the correlation, which can be found in Eq. 9. (removed for proprietary reasons)

$$f_T = f(\phi, LHV, T_{3,1}, P_3) \quad \text{Eq. 9}$$

All the constants in Eq. 9 depend on temperature [K], pressure [atm], LHV [kJ/mol], and  $\phi$  is the equivalence ratio of the fuel mixture in the primary zone.

The coefficients for this function were again solved using the kinetics data as a target. The results from this equation were then compared to the kinetic code data for the flame thickness. A few typical results are shown in the Fig. 4 below.

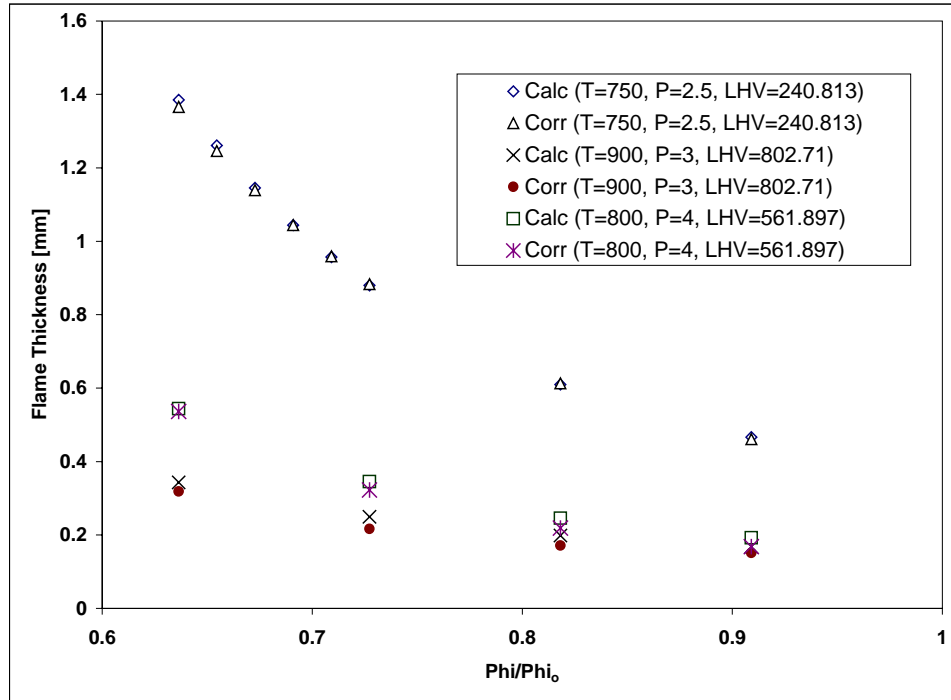


Fig. 4: Comparison between calculated and correlated values for flame thickness

Fig. 4 shows that the correlation very accurately predicts the calculated values of the flame thickness for a given temperature, pressure, and lower heating value. The average error of the correlation and the data was ~6.3%.

#### Equivalence Ratio

After correlations for each variable ( $d$ ,  $U_{ref}$ ,  $f_T$ , and  $S_L$ ) of the Damkohler equation were created, a determination of combustor equivalence ratio was necessary. Since fuel flow is not directly measured, another approach to determining the equivalence ratio in the combustor was needed.

The details of the derivation of the equivalence ratio from the measured cycle parameters are considered proprietary and hence, will not be described here. However, the minimal amount instrumentation available in a microturbine limits the expected accuracy of this parameter. The authors believe that this calculation probably represents the largest uncertainty in the calculation process of the Damkohler number.

This correlation was compared with the measured equivalence ratio, which was found using a laboratory coriolis flow meter on a test MT70. This fuel flow meter was specially used in laboratory testing in Portsmouth as a validation of the correlation process. However, in fielded engines, this same measurement would not be typically available. An example of the results of this comparison can be found in Fig. 5 below.

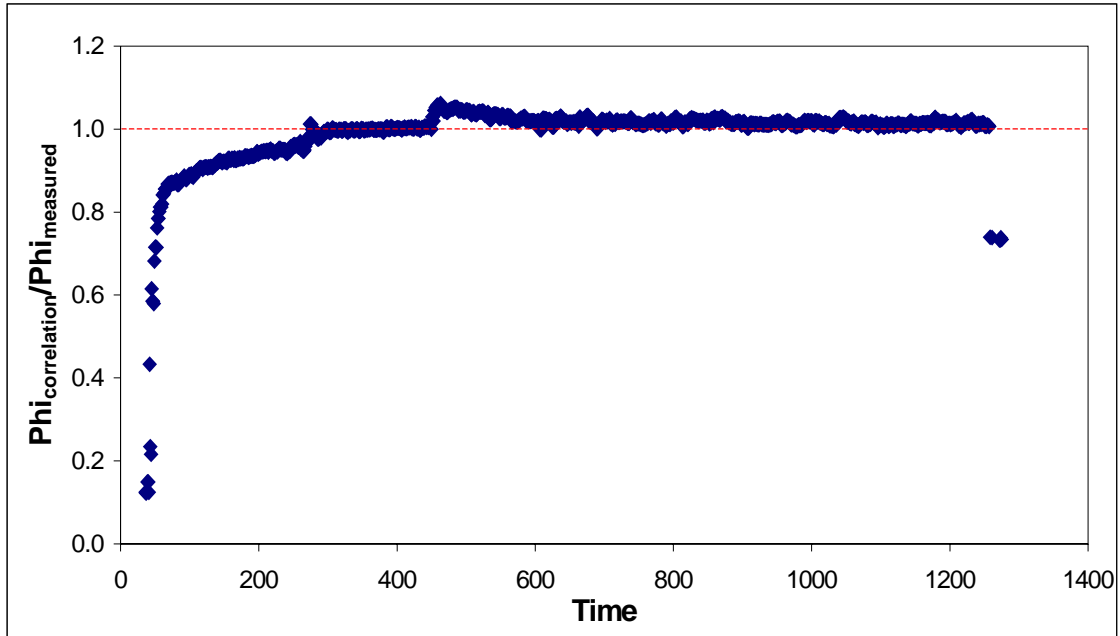


Fig. 5: Comparison of the ratio of the correlated and measured equivalence ratios for a range of  $\Delta T$ 's and an LHV of  $\sim 500$  Btu/ft<sup>3</sup>

Fig. 5 validates the correlation for this particular lower heating value and range of temperatures. The ratio of the correlation over the measured equivalence ratios doesn't deviate more than a few percent once steady state operation is reached. Similar results were found with different lower heating values over the range of temperatures of the correlation.

### Results

Once the equivalence ratio, flame speed, and flame thickness were predicted using their respective correlations, the Damkohler number was calculated. Fig. 6 illustrates the predicted change in Damkohler as the power of the microturbine is turned down until blowout for an L2 LBTU combustor. The lower heating value of the fuel in this experiment was 600 Btu/ft<sup>3</sup>. The power (blue squares) was measured directly and is plotted along with the Damkohler number (green triangles). The power scale is on the secondary y axis (right axis), while the Damkohler number scale can be found on the primary y axis (left side). It is interesting to note how effectively the Damkohler number tracks the decrease in power. At flameout,  $\sim 1600$  seconds, both the Damkohler number and power move toward zero. In this particular case, flameout is predicted near a Damkohler of unity.

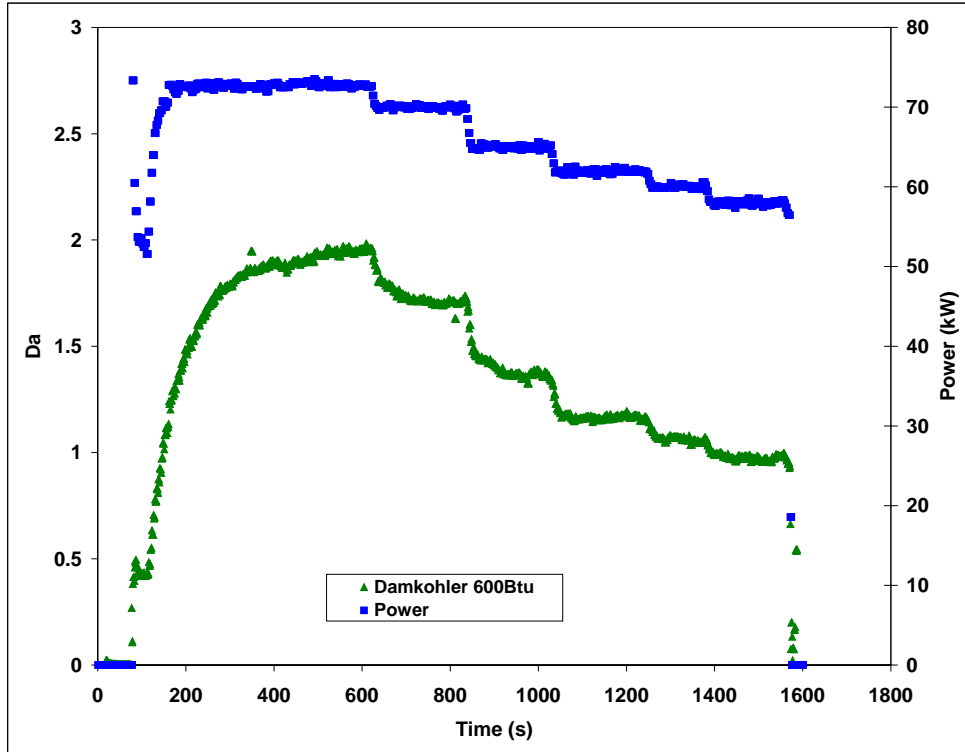


Fig. 6: The Damkohler prediction for an L2 LBTU combustor with a 600Btu/ft<sup>3</sup> fuel.

Damkohler predictions were made using blowout data with a variety of operating conditions. Fig. 7 illustrates the predicted Damkohler number at blowout (red squares) for a variety of lower heating values ranging from 500 Btu/ft<sup>3</sup> to 930 Btu/ft<sup>3</sup>. The Damkohler prediction at maximum power (blue diamonds) is also included. The red dashed line represents a possible minimum allowable Damkohler number before the pilot light ignites to prevent blowout.

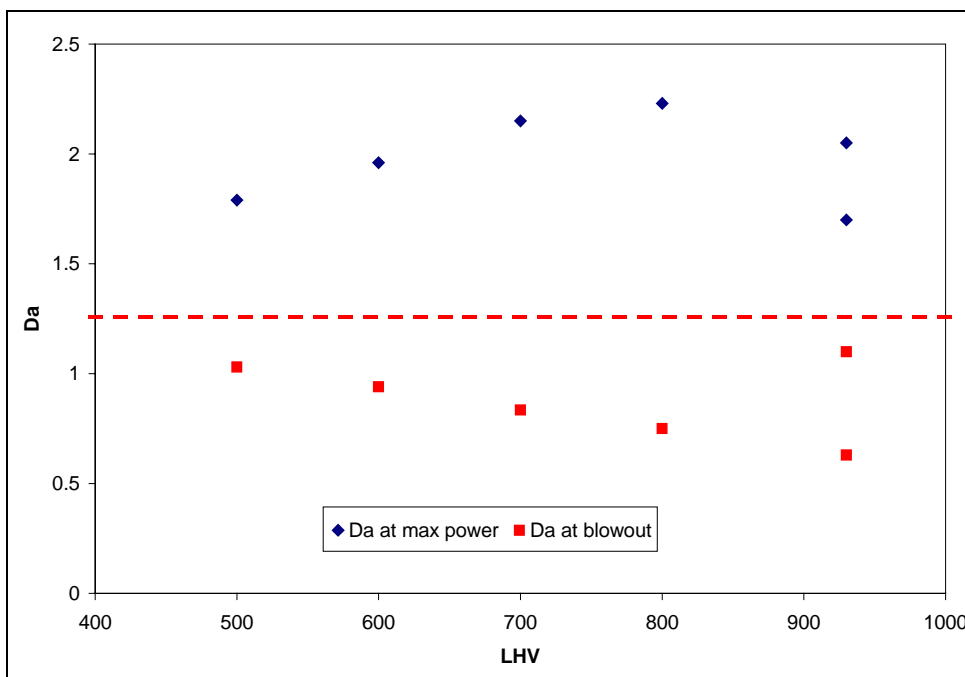


Fig. 7: Damkohler prediction at blowout and maximum power for different fuel types

Fig. 7 suggests that the Damkohler number could be used to predict a premixed lean blowout. All of the Damkohler predictions at maximum power lie above a Damkohler of 1.5, while the lean blowout predictions are near or below a Damkohler of unity. A universal minimum Damkohler number could be selected between 1.5 and 1, which once crossed, could signal the pilot light to ignite thereby preventing lean blowout. It should be noted that these particular Damkohler results are dependant on the selection of the characteristic diameter.

### **Conclusion**

The primary focus of this study was to correlate the premixed combustion lean blowout of IR's set of MT70 microturbines. It has been shown the correlation for the Damkohler number accurately predicts premixed lean blowout for a variety of microturbine conditions. Given the accuracy of the correlation, it is likely that premixed lean blowout can be avoided. Future work is suggested to further validate the range of the correlations.

### **References**

- <sup>1</sup>Noble, D. R., Zhang, Q., Shareef, A., Tootle, J., Meyers, A., Lieuwen, T., "Syngas Mixture Composition Effects Upon Flashback and Blowout," *Proceedings of ASME Turbo Expo 2006: Power for Land, Sea, and Air*, GT2006-90470.
- <sup>2</sup>Ingersoll Rand Power Works, "70LM Microturbine: Operating Manual," pg. 25.
- <sup>3</sup>Kee, R.J., Grcar, J.F., Smooke, M.D., and Miller, J.A., Sandia Report SAND 85-8240, Sandia National Laboratories, 1985.
- <sup>4</sup>Kee, R.J., Rupley, F.M., and Miller, J.A., Sandia Report SAND 89-8009B, Sandia National Laboratories, 1989.
- <sup>5</sup>Kee, R.J., Warnatz, J., and Miller, J.A., Sandia Report SAND 83-8209, Sandia National Laboratories, 1983.
- <sup>6</sup> Smith, G.P., Golden, D.M., Frenklach, M., Moriarty, N.W., Eiteneer, B., Goldenberg, M., Bowman, C.T., Hanson, R.K., Song, S., Gardiner, W.C., Jr., Lissianski, V.V., and Qin, Z, [http://www.me.berkeley.edu/gri\\_mech/](http://www.me.berkeley.edu/gri_mech/).