Determination of a Correlation for Predicting Lean Blow Off Limits of Gaseous Fueled, Premixed Turbulent Jet Flame Arrays Enclosed in a Hexagonal Dump Combustor

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Abstract

The lean blow off limit (LBO) of a matrix of turbulent lean premixed jet flames in a dump combustor is determined from experimental investigations. The authors present their systematical approach to describe and scale jet matrix burners, beginning with the design of the combustion systems investigated, the derivation of a correlation based on Damkoehler number with corresponding interpretation and the design of experiment. The results show the applicability of the Damkoehler number based correlation to predict the effects of variation in geometrical and thermophysical parameter on LBO.

Introduction

The combustion of natural gas with air in premixed flames stabilized under turbulent flow conditions is a key technology for efficient energy conversion with low pollutant emission, which is technically applied in e.g. gas turbines [1] or furnaces [2]. Current technical concepts for fuel-lean premixed combustion, applied in stationary gas turbine combustors, rely on flame stabilization through recirculation of hot flue gas in swirling flows [3]. Swirl stabilized flames may be prone to combustion instabilities especially in lean premixed arrangements [4]. Therefore, the present study follows a different approach; the stabilization of a matrix of turbulent jet flames in a dump combustor.

In the development phase of a combustion system, one major parameter in the combustor characterization, in terms of flame stability, is the lean blow off limit (**LBO**) [5]. The lean blow of limit depends on several parameter, which emerge, for instance, from the combustor geometry and/or operating conditions (e.g. Air-to-Fuel ratio, preheating temperature, thermal load). This paper focuses on the systematical approach during the development of the combustion system and LBO-characterization. The technical design of the investigated combustion systems (**CS**) bases on a coherence between geometric features and derived geometric parameters, which are intended to be varied independently. The varied geometric parameter are the diameter of a single round channel (**d**) and the area combustor dump ratio (**DR**). The DR is defined in Eq. 1 as the ratio of the cross section area of the combustion chamber ($\mathbf{A_{Combustor}}$)to the free cross section area of the nozzle, in this case the sum of the cross section area of each round channel in a nozzle ($\mathbf{A_{Channel}}$).

$$\mathrm{DR}=\frac{A_{\mathrm{Combustor}}}{\sum A_{\mathrm{Channel}}} \qquad \text{Eq. 1}$$

The systematic design of experiment (**DOE**) bases on the independent variation of DR and d using three different CS. From consideration of chemical and thermophysical interrelationships from theory and their abstraction, a correlation based on a Damkoehler number [6], in the following referred to as **Da-correlation**, is derived and interpreted. In a first step, a Da-correlation is derived from experimental results of three CS (**CS1, CS3, CS6**). In a second step, the Da-correlation is used to predict the LBO of another CS (**CS4**). Through comparison to experimental results, the applicability of the derived Da-correlation in terms of LBO prediction is validated.

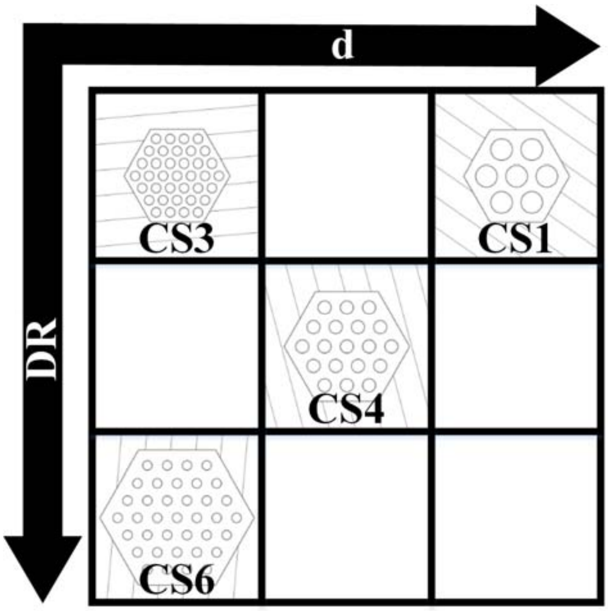

Figure 1: Schematic top view sketch of the channel arrangement of nozzles in the corresponding combustion chamber for CS1, CS3, CS6 and CS4

Figure 1 shows a sketch of the combustion systems CS1, CS3, CS6 and CS4. The CS are arranged in a matrix and arrows indicate an increase in the respective geometrical value. DR is varied by a factor of approximately 2.1 and d is varied by a factor of approx. 2.3. The matrix illustrates that the CS used for the correlation are select due to their characteristics of having either a maximum or minimum in DR and/or d respectively. Furthermore, *Figure 1* illustrates that CS4, which is used for validation, is situated between the other CS in the matrix. Therefore, the Da-correlation derived is validated against results of a CS considered to be an interpolation.

Experimental setup

In an experimental campaign, the LBO is determined under a variation in CS and thermophysical

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parameters. The CS investigated consist of two parts; the nozzle and the corresponding combustion chamber. The nozzle consists of a certain number of parallel round channels in a hexagonal arrangement. The combustion chamber features an inner hexagonal cross section in order to realize a uniform minimum channel to wall distance. The intention behind the hexagonal inner cross section of the combustion chamber is the prevention of locally strong outer flue gas recirculation zones, between combustion chamber wall and jet matrix, becoming the dominating stabilization mechanism. The systematic design behind the channel arrangement in correlation to the inner wall of the combustion chamber is shown in *Figure 2*.

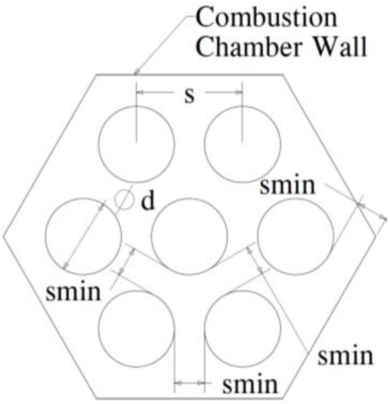

Figure 2: Schematic sketch of channel arrangement in nozzle with corresponding combustion chamber wall

Figure 2 illustrates that the distance between outer round channels and wall of the combustion chamber equals the minimum distance (**s_{min}**) between the edges of the channels. The variation in DR and d are conducted while the free cross section area of the nozzles is kept constant. Therefore, a variation in d corresponds to a variation in number of round channels in the nozzle and distances between channels and inner combustion chamber wall. A variation in DR corresponds only to a variation in distances between channels and inner combustion chamber wall while the number of round channels is kept constant.

The CS are mounted on a test rig described in detail in [7]. The setup allows precise control of mass flows of air and natural gas (**NG**), as well as preheating of the air flow to control the mixture temperature measured directly upstream of the nozzle. The experimental methodology is based on LBO detection from temperature measurement combined with flue gas analysis using an invasive probing system, both located at the combustion chamber outlet. Experiments are carried out at a certain air mass flow and under defined preheating temperature at an air to fuel ratio where stable operation close to the maximum temperature the combustion chamber material can withstand. NG is reduced stepwise until elevated carbon monoxide and unburned hydrocarbon emission indicate the LBO event for further reduction of NG. In this study, LBO refers to the event when the flame becomes instable, resulting in flickering of the flame in combination with a reduction in the mean flue gas temperature. The determination of LBO is repeated for various preheating temperature and air flows for the different CS. The ranges of experimental operating conditions for each CS are presented in *Table 1*, where T_0 is the measured preheating temperature and $\bar{u}$ the mean jet velocity in the nozzle, calculated from measured volume flow rate.

Table 1: Range of operating conditions in the experiments for investigated CS

Combustion System	T_0 in °C	$\bar{u}$ in m/s
CS1	50 – 400	27 – 106
CS3	50 – 300	29 – 51
CS4	50 – 400	49 – 125
CS6	50 – 400	46 – 126

Correlation

The Da-correlation used in this paper is derived from Eq. 2.

$$Da_t=\frac{\text{turbulent time scale}}{\text{chemical time scale}}=\frac{L_t\cdot S_L}{u'\cdot\delta} \qquad \text{Eq. 2}$$

In Eq. 2 **L_t** refers to the turbulent length scale which is known to be directly proportional to d for channel flow. While **u'** the fluctuating component of the velocity is proportional to the mean velocity component (**$\bar{u}$**). An expression for the laminar flame speed **S_L** is derived from laminar flame theory based on an enthalpy balance [8]. From this expression one can show that the thickness of the reaction zone (**δ_R**) is proportional to the temperature diffusivity (**a**) divided by S_L as shown in Eq. 3.

$$\delta_R \propto \frac{a}{S_L} \qquad \text{Eq. 3}$$

Through substitution of the thickness of the reaction zone, Eq. 4 is derived from Eq. 2.

$$\frac{\bar{u}}{d}=C_{Da}\cdot\frac{S_L^2}{a}=\frac{C_{Da}}{\text{chemical time scale}} \qquad \text{Eq. 4}$$

This correlation can be interpreted based on a stability criterion shown in Eq. 5, where one assumes that the turbulent flame speed equals the magnitude of the local flow velocity at the point of flame stabilization, which is proportional to the mean flow velocity.

$$S_t=u_{local} \propto \bar{u} \qquad \text{Eq. 5}$$

The ratio of the length of a jet flame to jet diameter is known to be proportional to the ratio of the mean flow velocity to the turbulent flame speed as shown in Eq. 6.

$$\frac{L_{Flame}}{d} \propto \frac{\bar{u}}{S_t} \qquad \text{Eq. 6}$$

From substitution of S_t in Eq. 6 using Eq. 5, it is obvious that L_{Flame} is directly proportional to the jet diameter. Assuming that the volume of the flame (V_{Flame}) can be described by a cross section, which is proportional to d^2, times the flame length one can derive that the volume of a flame is proportional to d^3 (Eq. 7).

$$V_{Flame} \propto d^3 \qquad \text{Eq. 7}$$

$$P_{LBO}=\dot{m}_{Fuel}\cdot LHV=\dot{m}_{air}\cdot\frac{1}{AFR_{LBO}}\cdot LHV\propto\dot{m}_{air} \qquad \text{Eq. 8}$$

Eq. 8 shows a further consideration of the thermal power under LBO condition (**P_{LBO}**). P_{LBO} can be calculated from the fuel mass flow times the lower heating value, which equals the air mass flow divided by the Air-Fuel ratio at LBO (**AFR_{LBO}**) times the lower heating value (**LHV**). Therefore, P_{LBO} is proportional to the air mass flow. Calculation of the ratio of P_{LBO} to V_{Flame} results in an expression for the volume specific thermal power, which is directly proportional to the ratio of $\bar{u}$ to d, as shown in Eq. 9.

$$P_{LBO,spec}=\frac{P_{LBO}}{V_{Flame}}\propto\frac{\dot{m}_{air}}{d^3}\propto\frac{d^2\cdot\bar{u}}{d^3}\propto\frac{\bar{u}}{d} \qquad \text{Eq. 9}$$

Using Eq. 9, Eq. 4 can interpreted as the specific volumetric thermal power at LBO being described through the ratio of the Damkoehler correlation parameter to the chemical time scale.

Results

The results in *Figure 3* are illustrated in a diagram of the equilibrium temperature over a volumetric jet velocity, which is calculated from the volume flow of air divided by the free cross section area of each nozzle in a CS, at LBO.

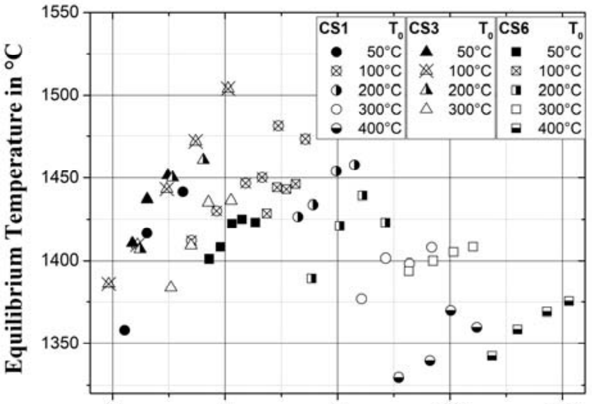

Figure 3: Equilibrium temperature over mean jet velocity for CS1, CS3 and CS6 at LBO for different preheating temperatures T_0

Figure 3 shows the LBO results from CS1, CS3 and CS6 for different preheating temperatures. For CS3 only the blank triangle symbols (preheating temperature of 300°C) deviate apparently from experimental results carried out at lower preheating temperatures for the same system. For the combustion systems CS1 and CS6 a clear trend to higher LBO velocities at lower equilibrium temperatures is observable for an increase in preheating temperature.

Based on these results the Damkoehler correlation coefficient is fitted in order to derive the Damkoehler correlation shown in Eq. 4.

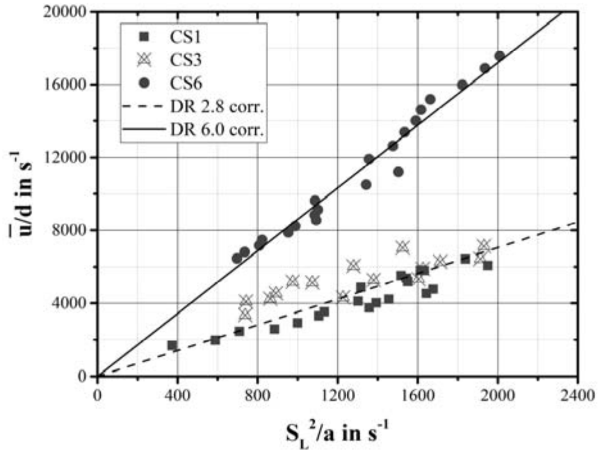

Figure 4 Volume specific thermal power at LBO over chemical time scale for CS1, CS3 and CS6 and resulting Da-correlation for DR2.8 (dashed line) and DR6.0 (solid line)

In Figure 4 the results from experiments are presented in dependence to the parameters from Eq. 4. The comparison of the results from experiments (symbols) to the derived Da-correlation (dashed and solid lines) indicates a sufficiently precise description of LBO using a constant Damkoehler correlation coefficient. It can be seen that the slope of the curves and therefore the Damkoehler coefficient is highly dependent of DR (compare CS1 and CS6), while the dependence of the diameter (compare CS1 and CS3) is much lower.

$$C_{Da}=1.41516^{DR}+0.57222 \qquad \text{Eq. 10}$$

The derived Damkoehler correlation coefficient is shown in Eq. 10. The Da-correlation is used to predict the LBO-behavior of the system CS4 where the chemical time scale is derived by using PREMIX for the calculation of the one-dimensional laminar premixed flame velocity using the GRI 3.0 chemical reaction mechanism.

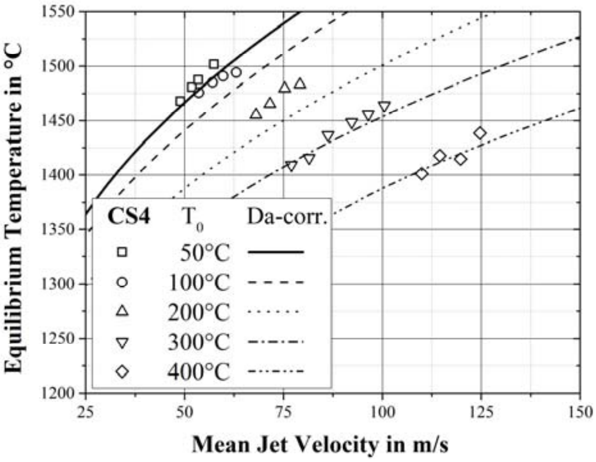

Figure 5 Equilibrium temperature over mean jet velocity for CS4 at LBO derived from experiment (symbols) and Da-correlation predictions (lines) for different preheating temperatures T_0

Figure 5 shows the results from the Da-correlation as lines in comparison to LBO measurements carried out with CS4. It can be stated that the results from Da-correlation predictions are in good agreement with values derived from experiments.

Conclusion

In this paper four combustion systems are experimentally investigated in terms of their LBO-behavior. The geometric design of the four combustion systems is based on the same systematic approach. The combustion systems differ in the area combustor dump ratio and the round channel diameter of their nozzles, while further geometric parameters are similarly scaled. The LBO-limit was determined for the four combustion systems under varying flow and preheating temperature conditions. The results show an expected trend as an increase in DR, d and preheating temperature leads to an increased flame stability.

In order to describe the LBO-behavior a Da-correlation is derived and theoretically interpreted. The result of the interpretation emphasizes that at LBO the Da-correlation correlates the flame volume specific thermal power to the ratio of a system specific Damkoehler number correlation coefficient to a chemical time scale.

From design of experiment, the results of three combustion systems, representing the minimum and maximum in variated geometrical parameter, are used to adjust the Da-correlation. The correlation is used to predict the LBO-behavior of a combustion system which represents an interpolation in the DOE matrix. The results derived from the correlation are compared to experimental data. The exceptional agreement between predicted and measured values validate the applicability of the Da-correlation approach for the type of combustion system evaluated. Furthermore, there is evidence that scaling of the combustion system in the range of the underlying DOE matrix by using the derived Da-correlation can be conducted.

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