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Evaluation of ammonia-hydrogen-air combustion in SiC porous medium based burner

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Abstract

Based on its well-known merits ammonia has been gaining special attention as a potential renewable energy carrier which can be replaced in power generation systems. Considering its low flame speed as one of the main challenges of combusting ammonia, flame stability is experimentally investigated. Focus is on premixed ammonia-hydrogen-air flames with high mixture fractions of ammonia (60-90% by volume) under standard temperature and pressure conditions. Silicon-carbide (SiC) porous blocks are used for stabilizing flame in a wide range of conditions. Upper and lower stability criteria are established for various mixture compositions. Also, combustion completeness is evaluated by analyzing measured and predicted temperature. The remarkable capability of the porous medium burners to efficiently operate at very high fractions of ammonia in a wide range of equivalence ratios provides a new achievability in more efficient combustion in power generation applications.

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Keywords: Ammonia combustion; Stability criteria; Flame speed; Flame temperature.

1. Introduction

As a potential fuel that can be used in various power generating systems, ammonia combustion has attracted many experimental and numerical studies especially in the last decade. Low flame speeds and fuel bond NO_x generation possibility are the two major drawbacks of ammonia as a potential fuel. There has been noticeable effort to figure out

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practical ways for addressing these challenges. Especially in the recent years, an astonishingly growing interest is observed aiming at creating effective methods to address the challenges associated with ammonia combustion.

A practical way to make ammonia operable in internal combustion engines as well as gas turbine combustors is to premix it with a vigorous fuel which acts as combustion promoter. Gross and Kong [1] combusted ammonia-dimethyl ether mixtures in a compression-ignition engine and Reiter and Kong [2] studied the combustion and emission characteristics of ammonia-diesel mixtures in the same type of engine. Past experience with ammonia fueled gas turbines by Solar Company [3] and UC Berkeley [4] in the 60's showed that acceptable levels of efficiencies were achievable in well-designed ammonia combustors. In a study by SPG Group, the feasibility of ammonia based fuels for environmentally friendly power generation in gas turbine engines was investigated [5]. Valera-Medina et al. [6] have examined combustion stability and emissions from gaseous ammonia blended with methane or hydrogen in a high pressure combustion test rig. Similar study by the same group [7] on ammonia-methane combustion in tangential swirl burners, evaluated potential of ammonia as a gas turbine fuel. With resulting weak flame stability and high emissions, stratified injection with low swirl was recommended as a possible way to burn the mixture effectively.

An inert SiC porous medium based burner was introduced as an effective means to burn high ammonia content flames in a previous study [8]. In the current study we focus on the flame stability criteria for a wide range of equivalence ratios and ammonia mixture fractions. Also we evaluate the combustion completeness of the mixtures with different ammonia contents on the porous medium based burner.

2. Methods

2.1. Experimental setup

A lab-scale combustion chamber is designed and applied for the study. Details of the experimental setup and related subsystems are presented in the previous study [8]. A premixed NH_3-H_2-air flame is formed in the burner which is enclosed by a stainless steel combustion chamber. A type R thermocouple with an accuracy of ±1.5 °C is used to measure the temperature 3cm downstream of the burner surface. Flame is stabilized by an inert SiC porous block burner with diameter of 7.62 cm, height of 7 cm, and a porosity level of 10 pores per inch. The porous block is enclosed by a stainless steel shell with the thickness of 0.5 cm improving rigidity of the burner as well as preventing air entrainment into the porous flame zone from the sides. Figure 1 depicts the burner, the ignitor plugs, and the thermocouple.

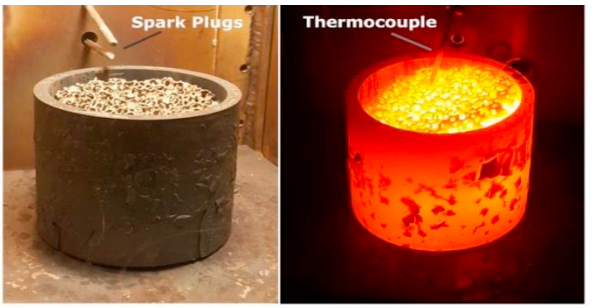


Fig. 1. SiC porous medium based burner.

2.2. Numerical predictions

Adiabatic flame temperature and laminar flame speed predictions in the following section are made using a reduced reaction mechanism established in a previous chemical kinetics study focusing on combustion characteristics of ammonia-hydrogen-air mixtures [9].

3. Results and Discussion

3.1. Combustion completeness analysis

Figure 2a and 2b demonstrate the effects of equivalence ratio and mixture fraction on adiabatic flame temperature and measured temperature, respectively.

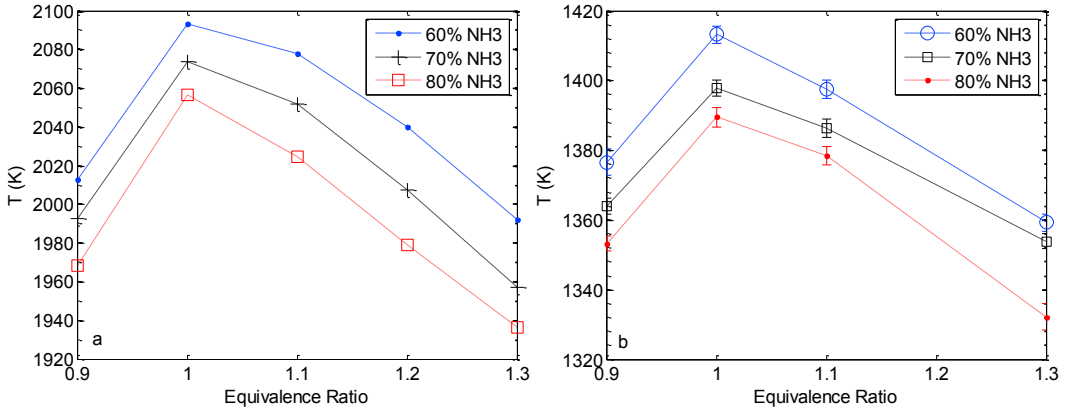


Fig. 2. Effect of equivalence ratio and mixture fraction on (a) adiabatic flame temperature and (b) measured temperature.

As expected, maximum adiabatic flame temperature takes place close to the stoichiometric condition for a certain mixture composition [9]. Following the similar trend, measured temperature profiles show a peak near the stoichiometric ratio. Also consistent with the numerical data, we observe a decrease in flame temperature with increasing ammonia content of the mixture. Although the overall trend is well captured by the experiments we are dealing with a noticeable difference between the experimental and chemical kinetics results. To have a better insight into the nature of the difference between the measured and the predicted temperature values, we consider a basic temperature index (T_{indx}) which is defined as the ratio of the measured temperature to the adiabatic flame temperature (T_{ad}), as shown in Eq. 1.

$$(T_{indx})_i = \left(\frac{T_{measured}}{T_{ad}}\right)_i \quad (1)$$

We tend to track the variation of the temperature index with respect to the equivalence ratio and ammonia mixture fraction in order to determine whether the source of deficiency is incomplete combustion or heat loss. Figure 3 demonstrates the relation between the measured temperature and the temperature index. The graph includes all data points from Fig. 2b.

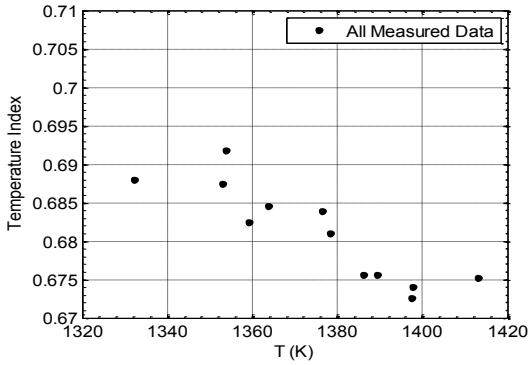


Fig. 3. Distribution of the temperature index with respect to the measured temperature.

The figure shows a slight decrease in temperature index with an increase in the temperature. Note that the amount of decrease through the complete temperature range is less than 2%. In an overall outlook, despite a major change in the chemistry, i.e. in the equivalence ratio and the mixture fraction, we obtain almost the same value of temperature index. Based on this observation we deduce that the combustion inefficiency is almost completely resulted from the heat loss and combustion incompleteness is not a major influential factor. We explain the slight decrease in temperature index as a result of relatively higher heat transfer level to the environment at higher temperatures. Once more, this confirms the heat loss as the dominant factor controlling the measured temperature drop with respect to the theoretical temperature.

Regarding the non-adiabatic nature of the experiments due to the discussed heat loss effect, to compare the temperature behavior with the adiabatic flame temperature trend, we use a scaled temperature. It is a non-dimensional quantity defined for adiabatic flame temperatures as well as the measured data points resulted by dividing the temperature by the maximum value, i.e. stoichiometric temperature value, obtained in the related chemical kinetics or experimental data set, respectively. The scaled adiabatic flame temperature and measured temperature behaviors with respect to the equivalence ratio for 60% and 70% NH_3 are shown in Figures 4.a and 4.b.

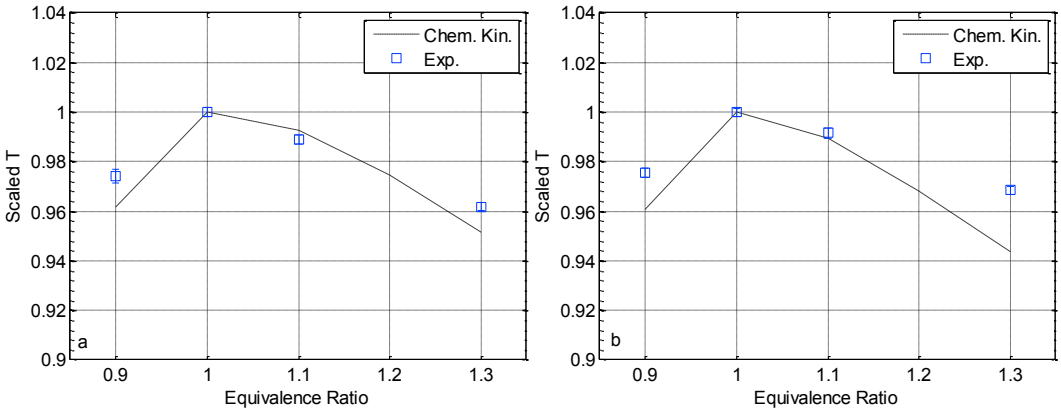


Fig. 4. Scaled temperature behavior with respect to the equivalence ratio for (a) 60% NH_3 and (b) 70% NH_3.

A general assessment of the results suggests that the measured temperatures for both mixture compositions have a satisfactory consistency with the predicted adiabatic flame temperatures. The trend is well captured with a maximum nonconformity of about 2% and the increasing-decreasing behavior is observed with respect to the equivalence ratio in measurements as well.

3.2. Stability criteria

Lower (upper) stability limit is obtained for each condition, i.e. certain equivalence ratio and mixture composition, by gradually decreasing (increasing) mixture exit velocity and finally approaching to a value at which flashback or extinction (blow-off) is observed. The lower and upper stability criteria for various conditions are depicted in Fig. 5.

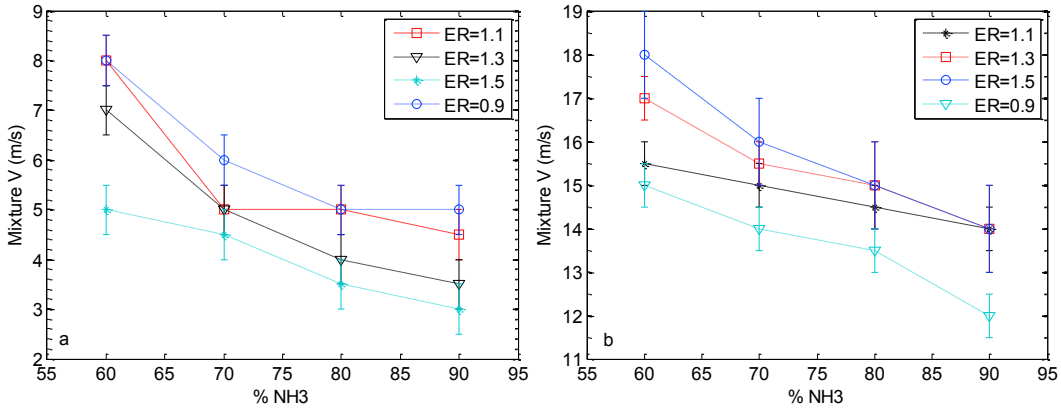


Fig. 5. Lower (a) and upper (b) stability limits for various mixtures

For all equivalence ratios, we observe a decrease in low stability limit with increase in ammonia content in the mixture. It is directly related to the lower flame speeds of the mixtures with high ammonia percentages. In a more detailed analysis, two conditions can occur in the vicinity of the low stability limit. When the burning speed exceeds the mixture jet velocity flashback happens. This is usually observed in the near-stoichiometric and lean conditions for which relatively vigorous flames are formed and propagated. Other behavior detected near the low stability limit is extinction. Due to the noticeable heat losses to the tube walls and the ambient gases, flame extinguishes in the flame holder, lifts off, and finally extinction occurs. The latter behavior is observed mostly in the case of the rich flames through which some fuel remains unburned due to the extreme heat losses near the tube rim and the burner. In a more detailed point of view we can associate the flame extinction to two parallel mechanisms. Remarkably reduced heat release at low mixture energy input is unable to compete with the substantial heat loss to the burner wall and environment. On the other hand, as the flame gets closer to the upstream edge of the burner as the mixture inlet velocity approaches to the lower limit, the preheating length for the incoming unburnt mixture becomes shorter. Therefore, the limited heat recirculation from the solid walls to the unburnt gases cannot compensate the large heat losses anymore. To ensure that the lower stability limit is not affected by quenching phenomenon in the feed pipe, quenching distances are estimated for the flames using Eq. 2 based on the flame speed (S_l) and thermal diffusivity (α) of the mixtures [10]. Figure 6 illustrates the variation of the laminar flame speed and the quenching distance with the equivalence ratio for various mixture compositions.

$$d = \frac{2\alpha}{S_l} \qquad (2)$$

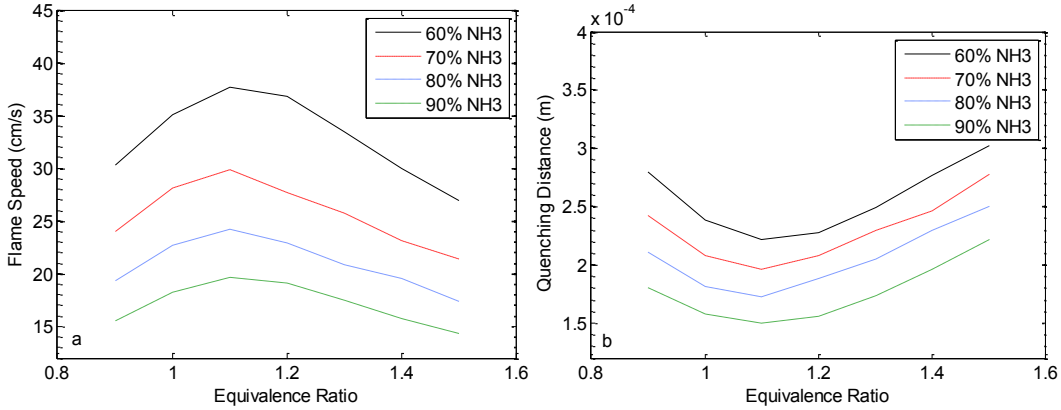


Fig. 6. Effect of equivalence ratio on (a) flame speed and (b) quenching distance, for various mixture compositions.

The figures indicate that the extrema happen around $\phi=1.1$ for the flame speed and accordingly for the quenching distance. Based on the calculation results the quenching distance is two orders of magnitude smaller than the feed tube diameter. Therefore, at least theoretically, a flame can be absorbed into the feed pipe and quenching in the pipe does not apply in studied cases.

The upper stability limits presented in Fig. 5b are specified as the points at which unstable behavior in the form of erratic oscillations in the flame structure starts. The upper stability limit has a direct correspondence with the insufficient residence time for the incoming mixture flow in the burner due to high velocity of the mixture. It is noteworthy that the flames stabilized within the matrix of a porous medium have higher burning speeds than open flames due to the internal feedback of heat from the combusted gases to the unburnt gases by radiation and conduction through the porous medium. Based on this mechanism the burner is able to operate at high mixture flow rates and hence extending the flame blow-off limit even compared to many conventional flame holding methods [8,11].

4. Conclusion

Ammonia-hydrogen-air premixed flame is stabilized in an inert SiC porous medium based burner in a wide range of equivalence ratios and ammonia mixture fractions. Measured temperature profile captures the adiabatic flame temperature trend with an acceptable level of accuracy. Combustion completeness evaluation proves that heat loss is the primary mechanism responsible for lower measured temperatures. Also, considered as an important challenge in ammonia doped mixtures, stability of ammonia-hydrogen-air premixed flame is investigated. Upper and lower stability criteria are determined for various mixture compositions. A decrease in the both limits occurs with increasing ammonia mixture fraction which is mainly resulted by lower flame speed of mixture with higher ammonia fraction.

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