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Effects of inert dilution on the lean blowout characteristics of syngas flames

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ABSTRACT

The paper presents an experimental study on the lean blowout (LBO) characteristics of inert-diluted syngas fuels. Real syngas fuels often contain inert diluents such as N_2 and CO_2. The diluents have negative impact on the syngas flame stability, which needs to be understood for the design and operation of gas turbine and industrial burners. In this work, effects of diluents on the LBO of premixed syngas flames were systematically studied under atmospheric pressure using a swirling flow model combustor. LBO limits, i.e., the equivalence ratio at which the flame blows out, were measured for syngas mixtures with various dilution ratios. Results show that the LBO limits generally increase with dilution ratio. In particular, inert dilution dominates the LBO behavior of syngas which has low H_2 content. Detailed analyses based on a well stirred reactor model reveal that the experimental data can be well explained by the thermal and chemical kinetics effects of diluents. A physics-based correlation, using Damköhler number and normalized flame temperature, is proposed for the prediction of LBO limits of inert-diluted syngas flames.

Introduction

The interest in fuel flexibility of gas turbines keeps increasing due to concerns over global warming, shortage of conventional fuels, and national energy independence. Syngas, or synthesis gas, is an attractive alternative to natural gas as gas turbine fuel because of its abundant availability and clean combustion characteristics [1]. Indeed, several IGCC (integrated gasification combined cycle) power plants have been successfully demonstrated operating on syngas. Syngas composition can vary significantly, however, depending on the feedstock (coal, biomass, petroleum coke, and landfill waste) and production processes (gasification, coking, and fermentation) [2,3]. In addition to combustible species (H_2, CO and CH_4), inert diluents (N_2 and CO_2) are common components present in real syngas, and their volumetric content may vary from 4 to 51% in different syngas fuels [3].

Inert diluents may undermine the flame stability, leading to flame extinction or blowout, due to its unfavorable thermal and/or kinetics effects [4,5]. This is potentially a serious problem towards its application in modern low-emissions gas turbine combustors, which usually employ lean premixed combustion technology and operate at equivalence ratios close to lean blowout for NO_x abatement [6]. Moreover, syngas and high-H_2 fuels in gas turbine applications often require N_2 dilution to prevent flashback and reduce NO_x [7]. As a

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promising technology for suppressing NO_x formation, preventing flashback and facilitating CO_2 capture, EGR (exhaust gas recirculation) has huge potential in future syngas turbines. To enable EGR applications, it is important to understand the effects of N_2 and CO_2 dilution on the lean blowout characteristics of syngas flames. This is critical in the design and operation of gas turbine combustors because their operation window is highly dependent on the lean blowout characteristics of the fuels.

Blowout refers to situations where the flame becomes detached from the location where it is anchored and is physically "blown out" of the combustor [8]. It is essentially flame extinction at flowing conditions. In gas turbine combustion, lean blowout (LBO) limit is a term referring to the equivalence ratio ($\varnothing_{LBO}$) at which flame blowout occurs when operated at fuel lean condition. Flame can only be stabilized above the LBO limit. It defines a very important boundary to keep off in gas turbine operation, because an LBO event usually requires a lengthy and costly gas turbine shutdown, purge and restart [8]. A higher LBO limit indicates the flame is more prone to blowout when decreasing the equivalence ratio.

Because of the highly turbulent environment in gas turbine combustor, LBO involves complex flow–chemistry interactions at transient conditions. The differential diffusion effect of multicomponent syngas adds more complexity to this problem. Given its importance in gas turbine operation, LBO phenomenon has attracted many studies. Noble et al. [9] and Zhang et al. [10] studied the effects of compositional variation on the LBO of premixed $H_2/CO/CH_4$ syngas fuels using a model combustor. They found that $\varnothing_{LBO}$ decreases significantly with H_2 addition. With the classical well stirred reactor (WSR) approach [11–14], this effect can be captured by a constant Damköhler number up to 50% H_2 content. Above that, however, the Damköhler number decreases sharply with H_2 content. The decrease was attributed to the preferential diffusion of H_2, which causes the local equivalence ratio to change upon flame wrinkling. Using an adjusted local equivalence ratio [15] to account for the preferential diffusion, they found that the constant Damköhler number correlation works again across the entire range of H_2 addition. Correspondingly, the (global) Damköhler number was replaced with a local Damköhler number based on local equivalence ratio. Lieuwen et al. [8] reviewed the lean blowout studies and suggests that the local flame extinction/reignition may be responsible for the inaccuracy of LBO prediction using the constant global Damköhler number approach. This point of view was supported by Zhang et al. [16], who characterized the local extinction pockets (flame holes) of premixed H_2/CH_4 flames using Mie scattering and OH chemiluminescence. They found that the constant global Damköhler number essentially predicts the onset of local flame extinction events and the local Damköhler number is more accurate for the prediction of flame blowout. Sayad et al. [17] also showed that for premixed $H_2/CO/CH_4$ flames stabilized by a swirling burner, molecular transport may affect the accuracy of the WSR model at low H_2/CO molar ratio.

The aforementioned studies suggest that molecular transport, particularly the differential diffusion effects, need to be considered for the prediction of LBO limit of syngas flames. This leads to the local Damköhler number approach based on local equivalence ratio. This approach, although more rigorous and accurate, involves lengthy calculation of multicomponent mass transfer. The calculation has to be performed at the *near-LBO limit*, *which is actually an unknown value and needs to be determined either experimentally or via modeling approach*. This is not straightforward in the prediction of LBO limit. It can be expected that adding diluents such as N_2 and CO_2 will further complicate this problem, given the strong coupling of thermal, chemistry, and differential diffusion effects on flame extinction/reignition when multiple inert species are present in the syngas. It is well known that CO_2 not only thermally decreases the flame temperature, but can chemically inhibit the flame by reducing H radicals [18–20]. Elkady et al. [21] and Evulet et al. [22] observed that for premixed natural gas flames in a gas turbine combustor, overdilution with EGR can cause near-LBO events, which was indicated by the high CO emissions. Sayad et al. [17] and Daniele et al. [23] found that for premixed syngas flames at gas turbine relevant conditions, N_2 dilution results in a higher LBO limit. Williams et al. [24] reported that CO_2 dilution causes higher CO emissions, a sign of near-LBO. Mo et al. [25] observed that for bluff-body stabilized syngas diffusion flames, CO_2 has stronger impact on the flame stability than N_2.

In spite of the many studies, effects of the *copresence* of N_2 and CO_2 on the LBO characteristics of premixed syngas flames are not fully characterized under gas turbine relevant conditions. In particular, the classical WSR model and Damköhler number approach are yet to be validated at the *copresence* of N_2 and CO_2, which is more representative of the environment of future syngas turbine combustors equipped with EGR. Furthermore, a simple, straightforward tool is needed in the industry for the prediction of LBO limit with satisfactory accuracy. Global flame properties are preferred over local properties for easy implementation.

In light of the knowledge gap and industrial needs, we present an experimental study on the LBO limits of premixed syngas flames upon inert dilution. The syngas, containing $H_2/CO/CH_4$, is diluted with both N_2 and CO_2 at various dilution ratios. LBO limits were measured for flames stabilized using a swirl burner in a model combustor at conditions relevant to gas turbine startup, i.e., ambient pressure and temperature. Air velocity at burner exit was also varied to study the effects of air flow velocity on LBO. Kinetics modeling was also performed for assisting the analysis of the experimental results. A physics-based correlation was proposed for the prediction of LBO limit by combining the global Damköhler number and another global flame property. We will further show that the correlation is a straightforward and yet satisfactory tool across a wide range of syngas composition.

Materials and methods

Syngas fuels

Composition variation of syngas is achieved by mixing two industrial process gases, A and B. Gas A is a low-heating-value fuel that contains 56.3% N_2 and 18.0% CO_2 and is used as the diluent. Gas B is a medium-heating-value fuel that contains 58.8% H_2. The syngas compositions are determined by an