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# Influence of reactive species on the lean blowout limit of an industrial DLE gas turbine burner

Ivan R. Sigfrid [a,*], Ronald Whiddon [b], Robert Collin [b], Jens Klingmann [a]

[a] Department of Energy Sciences, Lund University, Sweden
[b] Department of Physics, Lund University, Sweden

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ABSTRACT

In order to achieve ultra-low emissions of both $NO_X$ and CO it is imperative to use a homogeneous premixed combustor. To lower the emissions further, the equivalence ratio can be lowered. By doing so, combustion is moved towards the lean blowout (LBO) limit. To improve the blowout characteristics of a burner, heat and radicals can be supplied to the flame zone. This can be achieved using a pre-chamber combustor. In this study, a central body burner, called the RPL (rich-pilot-lean) section, was used as a pre-chamber combustor to supply heat and radicals to a downscaled industrial burner. The flue gas from the RPL is mixed with the surrounding fresh mixture and form a second flame zone. This zone acts as a stabilizer for the investigated burner. The LBO limit was modeled using two perfectly stirred reactors (PSRs) in series, which allows the chemical influence on the LBO limit to be isolated. The resulting trends for the modeled LBO limit were in agreement with measured data. Increasing the equivalence ratio in the RPL section, thus increasing the energy supplied by the fuel, is a major contributor to combustion stability up to a limit where the temperature decrease is too large support combustion. For lean RPL combustion, the reactive species O, H and OH in combination affect the stability to a greater extent than the temperature alone. At rich equivalence ratios, the conversion of methane to hydrogen and carbon monoxide in the RPL section is a factor influencing the LBO limit. The results are compared with emission probe measurements that were used to investigate the LBO limit for methane and a generic syngas (10% $CH_4$, 67.5% $H_2$, and 22.5% CO). The syngas was also investigated after being diluted with nitrogen to a Wobbe index of 15 MJ/m$^3$.



## 1. Introduction

In order to achieve cleaner energy production and greater fuel flexibility when using gas turbines new burner configurations must be developed. Siemens Industrial Turbomachinery has developed a 4th generation dry low emissions (DLE) burner [1–3], which was investigated in this study. For gas turbines in general, the primary pollutant consists of nitrogen oxides ($NO_X$). These emissions can be reduced by premixed combustion at lower equivalence ratios [4–7]. Running a gas turbine at lower equivalence ratios will lower the turbine inlet temperature (TIT), reducing the efficiency of the turbine. Gas turbines can be optimized by increasing the efficiency through increasing the TIT, as in the Mitsubishi J-series gas turbine [8], where the TIT is close to 1900 K. Gas turbines can also be optimized with regard to robustness and high uptime, as for the SGT-750 [2], which is the gas turbine in which the full-scale version of the burner investigated here is operated. To achieve robustness a lower TIT is chosen. The nominal TIT for the SGT-750 gas turbine is 1420 K [2], which corresponds to a lean equivalence ratio of 0.33 for methane (the measured lean blowout (LBO) limit for the burner was 0.43) and 0.27 for the syngas investigated (the measured LBO limit for the burner was 0.26) [9]. The LBO limit for syngas is below the equivalence ratio that gives an adiabatic flame temperature corresponding to the nominal TIT for the SGT-750. Thus extending the LBO limit for syngas is applicable for part load only.

When the equivalence ratio is reduced, the stability will be compromised and carbon monoxide (CO) emissions will increase [10]. Reducing the equivalence ratio even further eventually causes the flame to blow out. Several theories have been proposed to explain the cause of blowout. Three of these theories, which affect the height of lift-off, which is a precursor to blowout, are the most common [11]. The first states that if the local flame speed is lower than the velocity of the approaching fluid, i.e. $v > S_T$, the flame will move downstream. The second theory considers the case when the local strain rate in the fluid exceeds the extinction strain rate [12,13] i.e., $\epsilon > \epsilon_{cr}$. This will cause the flame to be locally extinguished, which will lower the flame temperature and thus the

* Corresponding author. Address: Department of Energy Sciences, Lund University, PO Box 188, SE-221 00 Lund, Sweden.
*E-mail address:* ivan.sigfrid@energy.lth.se (I.R. Sigfrid).

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flame speed. The third theory considers the back-mixing of large-scale flow structures that supply hot product gases to fresh mixtures, causing them to heat up [14,15]. If the mixing time of the large-scale structures is shorter than the chemical time, i.e. $\tau_l > \tau_{ch}$, there will not be sufficient time for the fresh mixture to be ignited by the hot mixture. As a consequence of this, the flame temperature will be lowered locally, decreasing the flame speed. In addition to these three theories, the fuel composition has a significant effect on the flame speed and the blowout limit. It has been shown that fuels with high hydrogen contents have lower equivalence ratios at the LBO limit [5,9,16–19]. Experiments in which the swirl strength was varied have shown that this also affects the LBO limit [17,20]. Furthermore, other factors such as physical mixing and the operating conditions (e.g., pressure and temperature) could influence the limiting equivalence ratio at blowout [21].

The combustion stability under lean operating conditions can be improved by adding a diffusion pilot flame to the burner [10]. However, this will also increase the $NO_X$ emissions. To reduce the $NO_X$ emissions while retaining the stabilization effect of a pilot flame, a premixed pre-chamber combustor can be used. Gussak et al. performed calculations to investigate the effects of specific combustion products on methane combustion [22]. They found that chemical activity was ranked in the following order: $H > HCO > O > CH_3 > OH > CH_2 > H_2CO > CO \gg H_2 > O_2$. Ionov states that for rich pre-chamber combustion the radicals arising from the products will aid the ignition of the main fuel–air mixture [23]. He also pointed out that the residence time inside the pre-chamber is important, due to the short-lived nature of the radicals involved in the ignition process. In later work, Levy et al. used the concept of a pre-chamber to lower the LBO limit in a conceptual combustor model [24,25]. They also showed that low equivalence ratios are preferable in a pre-chamber as this minimizes $NO_X$ emissions, although running the pre-chamber under rich conditions would result in lower LBO limits.

In a previous study, we investigated the emission from the DLE burner, and found that changes in the equivalence ratio in the RPL section strongly influenced the $NO_X$ emissions [7]. The highest $NO_X$ emission was observed at the highest the flame temperature in the RPL section. An exception to this was when methane was used as fuel, as combustion was not completed inside the RPL section. In this case, combustion was completed downstream of the RPL section where, together with the fresh mixture, a hot zone was created where additional $NO_X$ was formed, primarily through the Zeldovich mechanism [27]. A further investigation at elevated pressures by our group showed that a large proportion of the $NO_X$ emission originated from unmixed zones [28]. The increase in $NO_X$ production with pressure originated from higher contributions from thermal $NO_X$, arising from the unmixed zones and their higher temperatures.

We have previously found that the flow field did not vary significantly when changing the fuel [29]. Syred et al. [30] stated that, under strong swirl conditions, aerodynamic forces are so dominant that there is little change in the flow field as a result of chemical reactions in the flame. This means that it is possible to model the chemical kinetic aspects of the burner without having to perform time-consuming computational fluid dynamics calculations. We have previously measured the LBO limit experimentally, and found that the equivalence ratio at the LBO limit in the full burner could be decreased by increasing the equivalence ratio in the RPL section [9].

In this study the influence of reactive radicals in a central body pre-chamber combustor on the LBO limit was investigated. The LBO limit was modeled using a perfectly stirred reactor (PSR) to primarily estimate the equivalence ratio at which the flame will blow out, for a given fuel composition [9,21,31]. In the PSR model, fresh and burned gases are numerically mixed instantaneously, and the influence of the burner and fluid dynamics is neglected, apart from the residence time inside the PSR. For example, the effects of variations in mixing and strain due to different burner configuration are disregarded. The PSR equations are limited to zero-dimensional modeling of the conservation of energy, species and mass [32], which also removes the influence of diffusion on combustion.

## 2. Materials and methods

### 2.1. The DLE burner

The burner investigated in the present study is downscaled version of the 4th generation DLE burner manufactured by Siemens Industrial Turbomachinery (Finspång, Sweden). It consists of three concentric sections, as illustrated in Fig. 1. All sections have their own swirlers. The inner section, the RPL, produces heat and reactive species for the other two sections, to stabilize combustion [9]. The middle section is called the Pilot section, and connects the RPL section with the outer Main section. The fuel flow into the Pilot section can be adjusted to avoid unstable combustion and to minimize emissions [7,33]. Most of the mass flow, approximately 79%, passes through the Main section. This burner has been investigated by our group in previous studies [7,9,34–37]. The present study was carried out to investigate the potential of the RPL section as a combustion stabilizer.

### 2.2. Reactor model

To investigate the influence of the RPL section on the LBO limit, a model was used consisting of two PSRs in series, as illustrated in Fig. 2. The model of the individual PSR reactors solves the conservation equations for energy and species, as described by Kee [32], assuming steady-state conditions. PSR 1 is used as the stabilizing source, in the same way as the RPL section. During the calculations, the equivalence ratio in PSR 1 is varied to investigate its influence on the LBO limit in PSR 2.

The investigated fuel compositions are given in Table 1. The equivalence ratio was varied from 0.8 to 2.4 for methane ($CH_4$) and from 0.4 to 2.4 for the two syngas compositions. This corresponds to a total equivalence ratio in PSR 2 ranging from 0.5 to 1.3 for methane and from 0.3 to 0.6 for syngas. The residence time in PSR 1 was varied from 0.15 ms to 10 ms. The lower residence time was chosen as it marks the limit when combustion of methane is not possible at equivalence ratios of 1.6 and above in PSR 1. This agrees with the blowout limit for methane combustion in the RPL that was found by our group [9]. The higher residence time

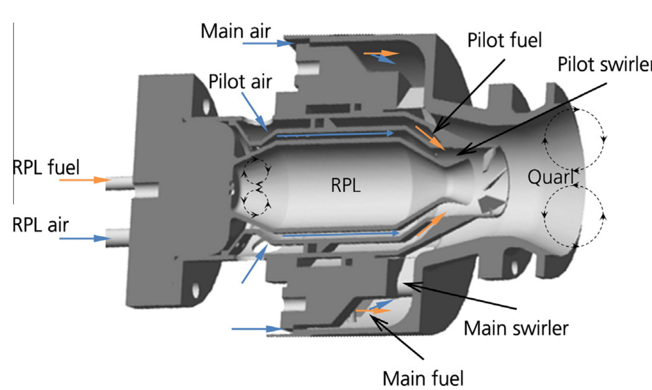


**Fig. 1.** The downscaled 4th generation DLE burner used in this study. The orange arrows indicate fuel flow and the blue arrows air flow.