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Lean Blowout Limit Prediction in a Combustor with the Pilot Flame

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Abstract

One of the important combustion chambers characteristic is the lean blowout (LBO) limits. There are several ways to expand LBO limits. One of them is using pilot flame. The present research relates to LBO modeling inside the combustor with the pilot flame. The simplified version of a power plant combustion chamber was used. The experimental data was used to validate the model. Experiments were conducted at the inlet air temperatures ranging from 373 to 575 K, and changing the relative flow rate of the pilot fuel from 0 to 1. Methane was used as the fuel. It was found that the minimum value of the φ_{LBO} can be achieved even when a portion of the fuel enters the pilot zone, and not only when the fuel is fully supplied to the pilot circuit. So φ_{LBO} can be reduced up to 4 times compared to supplying fuel only to main circuit. It is also shown that there is a correlation between φ_{LBO} and fuel/air equivalence ratio averaged over the surface of the recirculation zone φ_{RF}, that can be obtained as a result of RANS simulations without combustion. To generalize the collected data the φ_{RF} value, obtained for an arbitrary fuel distribution, was scaled to φ_{LBO}, obtained for supplying the fuel only in the main circuit. In this case φ_{LBO} value was calculated using LES approach for each air flow rate, pressure and initial temperature. As the result of the work, the methodology that allows to determine LBO limits of combustion chambers with the pilot flame was developed. The presented method is based on a series of steady and transient 3D simulations.

Keywords: large eddy simulation; lean flame blowout; pilot flame, power plant, combustion chamber

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Nomenclature

φ_{LBO} – equivalence ratio at the combustion chamber outlet, during the LBO;
φ_{LBO_0} –equivalence ratio during the flame LBO when all the fuel is fed into the main circuit;
$\varphi_{LBO_{exp}}$–equivalence ratio at the combustion chamber outlet, during the LBO obtained experimentally;
φ_{RZ} – equivalence ratio average over the surface of recirculation zone;
φ_{RZ_0} equivalence ratio averaged over the surface of recirculation zone when all fuel is fed into the main circuit;

φ_{RZ_LES} –equivalence ratio average over the surface of recirculation zone obtained by LES;
φ_{RZ_RANS} –equivalence ratio average over the surface of recirculation zone obtained by RANS;
φ_{cc} – fuel-air equivalence ratio at combustion chamber outlet;
$\overline{\dot{m}_{pl}}$ – relative pilot fuel mass flow rate, $\overline{\dot{m}_{pl}} = \frac{\dot{m}_{pl}}{\dot{m}_{\Sigma}}$;
ΔP_{cc} – combustion chamber pressure drop;
RANS – Reynolds averaged Navier-Stokes;
CFD – Computational Fluid Dynamics;
LES – Large Eddy Simulation.

1. Introduction

In order to provide required nitrous oxides (NO_x) emission for gas turbine power plants, the combustion of lean premixed mixtures became the most prevalent. However, in this case, during the transient engine behaviour and at idle, the risk of flame blowout increases. The extension of the combustion chamber stable operation limits can be achieved by burning of partially premixed fuel-air mixtures, when the main part of the fuel mixes with the air before the combustion zone, and the rest fuel is used to create the pilot flame.

The following models are quite frequently used for LBO limits prediction during combustion chamber designing and development stages: semi-empirical models, modeling in a transient three-dimensional case and hybrid simulation. Semi-empirical models are approximate expressions, build on the generalization of experimental data on the basis of some theoretical assumptions. One of the first studies devoted to the generalization of flame blowout data was carried out by E. DeZubay [1]. A. Lefebvre made a significant contribution to semi-empirical models in his researches [2]. The authors of several works [3, 4] for a wider range of fuels, obtained the expression which considers its characteristics, for instance, H/C relation. All the studies presented above are related to the flameholders with two-dimensional flow downstream. Meanwhile, the swirled flow, which is the most common way to stabilize the flame in combustion chambers, has strong three-dimensional flow structure. The expressions to predict LBO limit in swirled flow are presented in papers [5, 6]. The presented expressions allow to quickly estimate LBO limits during the burning of premixed mixtures after the flameholders in the form of bluff bodies or vane swirlers, and also during the diffusion and homogeneous combustion in main combustion chambers. However, its applicability is limited by empirical coefficients, which were obtained in specific conditions.

In recent decades the use of methods of Computational Fluid Dynamics (CFD), at the combustor designing stage, had been widely adopted. For instance, the method of Large Eddy Simulation (LES) allows obtaining LBO limits directly from calculation results [7-11].

The existing semi-empirical methods were developed basically for diffusion and premixed combustion. The direct numerical simulation of the flame blowout in combustion chamber requires significant resources and is inappropriate in engineering practice. The combined method of LBO calculation, based on steady state three-dimensional simulations, might be the solution of the task.

The similar combined methods are presented in the studies, where the results of 3D calculations in a steady case were used to create reactor chains [12], in specific criteria equations [13, 14] or in modified already existing equations [15]. For instance, the modified semi-empirical Lefebvre's formula for combustion chamber LBO calculation [16] was presented in the study [17].

The shortcoming of most of the works devoted to the generalization of combustion chamber LBOs is its applicability only in cases of premixed mixtures or diffusion combustion. It is well known that the use of the pilot