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Large eddy simulation of bluff body flames close to blow-off using an Eulerian stochastic field method

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ABSTRACT

This paper reports on Large Eddy Simulation (LES) of turbulent premixed methane/air flames approaching blow-off. The study focuses on a stable flame, and on a flame just prior to blow-off, both stabilized by the Cambridge bluff-body burner. For turbulence-chemistry interaction, a model based on transported probability density function (TPDF) in conjunction with Eulerian stochastic fields is used. Velocity, species-concentration and heat release fields were first compared against experimental data showing good agreement. The results demonstrate that simulations of such complex combustion phenomena are possible and that the model is capable of reproducing the flame and the flow characteristics under both stable and close to blow-off conditions. A blow-off sequence was then examined and the results were used to evaluate some of the theories and mechanisms responsible for flame blow-off. It was found that the local extinction in the shear-layers had only minor impact on the flame blowing off and that the blow-off is a result of a series of events starting with the flame migrating into the recirculation zone. In the end, a mechanistic explanation is proposed for this series of events leading to full extinction of the flame.

1. Introduction

In combustion applications, where maintaining stable premixed combustion is difficult when the flame speed of any practical fuel is several orders of magnitude smaller than the flow velocity, a flame holding mechanism is required. Flame stabilization may be achieved by means of swirl or jet induced recirculating flow or by a bluff-body flame holder. Bluff-bodies as flame-holders are found in a wide range of high-speed reacting flow environments, e.g. ram-jets, scram-jets and turbojet afterburners. They may also be used in supplementary firing systems of industrial boilers and in heat recovery steam generators [1]. The idea with bluff body flame holding is to create a recirculation zone (RZ) behind the body, which entrains hot burnt gases acting as a heat source and thus ensuring continuous ignition of the fresh incoming fuel-air mixture. A low velocity region is thus created for the aerodynamic anchoring of the flame. Going towards low NOx systems, with lean premixed combustion at lower temperatures, the problem of keeping the flame anchored and stably burning becomes even more challenging.

The stability of bluff-body flames has been studied for several decades, stability here being defined as the range of equivalence ratios over which a flame can be maintained, keeping all other conditions constant. Traditionally, the focus has been on predicting at which conditions the blow-off occurs, and specifically on providing critical values and/or set of parameters such as equivalence ratio, temperature and velocity, responsible for flame blow-off, see e.g. Refs. [2–7]. Extensive physics-based correlations and critical values, all based on time-averaged characteristics, are discussed by Williams et al. [8,9], Longwell et al. [2] and Masri et al. [10]. It has also been studied during the *TNF-workshops* [11] under non-premixed conditions for detailed comparison of experiments with multiple modeling approaches.

In one of the first detailed studies, Spalding [6] correlated the occurrence of the blow-off to the length of the RZ. Winterfield [12] observed the onset of blow-off once the flame traverses the boundary close to the rear stagnation point of the RZ. In one of the earliest works, Zukoski and Marble [7] introduced critical values for chemistry and flow time scales. They determined the conditions where a stable burning flame can be maintained, defining a critical time τ_{cr} available for ignition, roughly the time of contact between the cold reactants and the hot RZ, defined as:

$$\tau_{cr} = \frac{L}{U_{B.O.}}. \qquad (1)$$

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In Eq. (1) L is the length of the recirculation zone and $U_{B.O.}$ the measured blow-off velocity. The same L is also often used as a characteristic length scale for the problem, and the correlation in Eq. (1) can be seen as a Damköhler, $Da = 1$, criterion, where blow-off occurs when the chemical time-scale becomes equal to the flow time-scale.

Conditions resembling those in modern practical applications were studied by Lefebvre et al. [13], among others. Based on studies with different sets of assumptions, a general conclusion regardfing blow-off was arrived, namely that the blow-off equivalence ratio (ϕ_{BO}) is a function of velocity, characteristic dimension of the flame-holder, pressure and inlet gas temperature [13]. For example, viewing the reaction zone of a bluff-body flame holder as a homogeneous chemical reactor, one can approximate the critical equivalence ratio as

$$\phi_{BO} \propto \left[\frac{U}{P^{0.25} T_0 exp(\frac{T_0}{150}) D_c (1 - B_g)} \right]^{0.16} \tag{2}$$

In Eq. (2) P is the pressure, T_0 is inlet gas temperature, D_c the characteristic dimension of the flame holder and B_g the geometrical blockage ratio [13]. The equation shows that the blow-off limit is mainly affected by the temperature, to a smaller extent by the velocity and weakly by the pressure.

A number of experimental and numerical studies have been reported on the shear-layer and wake flow structure and the dynamics of bluff-body flames [14–19], among others, under different conditions. Dawson et al. [15], examining confined and unconfined axi-symmetric bluff-body burners, quantified the duration of the blow-off sequence and identified fresh reactants entering the RZ from the downstream stagnation region before BO occurred. In a recent review, Shanbhogue et al. [20] discussed recent advances in understanding the influence of the mixture properties on the spatio-temporal dynamics of the flow-field of a bluff-body burner. They hypothesized that simple Damköhler-number correlations contain the essential physics for describing the initial stage of blow-off; however, they do not describe the much more complicated flow and flame behavior associated with the actual blow-off process. The reason that these simple Damköhler and/or Karlovitz-number correlations do a reasonable job in identifying blow-off limits is that they describe the initial stage, at which flame extinction begins to occur (stage 1), rather than the blow-off physics itself [21]. Stage 1 with local extinction does not necessarily lead to blow-off but it is rather accompanied by change in the wake-zone dynamics (stage 2), with wake/RZ feedback causing additional stretch-induced extinction, or alternatively, it can also lead to ignition and flame propagation. Since a flame can withstand some extinction before the flame sheet is extinguished, the critical level of flamelet disruption and extinction is still not known [21].

The dynamics of the shear layer in reactive bluff body flows, e.g. vortex shedding and its impact on stable flames and the flames near blow-off, has been studied in Refs. [22–24]; but the underlining physics is still not well understood [25,26]. Thus, further studies are suggested on wake-zone dynamics, entrainment characteristics and flame-flow interaction under lean and close to blow-off conditions.

The focus in more recent studies has been shifted towards the dynamics of bluff body flames, with the goal of answering the question *why* the blow-off occurs, see e.g. Ref. [13], and not *when* it occurs.

Three main mechanisms for bluff body flame blow-off are suggested in the literature [20]:

- Large scale vortices entraining reactants into the RZ causing imbalance between the rate of entrainment and the burning rate of these reactants which is also seen as imbalance between the heat released by the reactions and the heat that must be supplied by the RZ for igniting the incoming mixture.
- The contact-time between the fresh unburnt gases and the hot gases in the RZ does not exceed the chemical ignition time. For the same inlet velocity, the shorter the RZ the shorter is the residence time.
- Local extinction, caused by excessive strain rate, giving rise to extinction holes in the flame surface sheet that allow cold unburnt fuel-air mixture to pass through, thus decreasing the temperature of the RZ.

Some of the recent studies suggest a combined view of the above-mentioned theories in a sequence of events, see for example the works of Chaudhury et al. [1,27–29]. The series of events starts with the extinction along the flame sheet causing large-scale RZ disruption. This large-scale wake disruption entrains the cold, unburnt gases, cooling the RZ and as a consequence, shrinking it, failing to reignite the shear-layers, leading in the end to a complete extinction. However, no general physical mechanism responsible for blow-off is identified and more research is required in the field.

The goal of this study is to examine in detail the dynamics of a bluff body flame under both stable flame conditions and close to blow-off. An unconfined methane/air flame set-up corresponding to the experimental investigation of Kariuki et al. [30], is chosen as a baseline case, since the provided experimental database contains both stable flames and flames very close to blow-off. LES are used in order to capture the unsteady characteristics and dynamics, computing directly the large scale energetic structures and modeling the effects of the unresolved ones, with a size smaller than the filter pdfwidth. Since the filtered chemical source term, representing the species formation, depends strongly on the unresolved sub-grid scales, modeling this term is of major importance. A variety of combustion models have been proposed, see e.g. [31–33], emphasizing the interaction between the turbulent flow, mixing and chemistry, especially in cases where local extinction and re-ignition occur as the case studied here. Here, we use a joint filtered probability density function (PDF) method for all scalar quantities necessary for a correct prediction of ignition/extinction for flames close to blow-off. The resulting joint PDF-equation, involving a large number of independent variables, is solved with a new stochastic solution method [34,35] based on stochastic Eulerian fields. These fields evolve according to stochastic partial differential equations (SDE) equivalent to the joint PDF transport equation and the method is often referred to as Eulerian Monte Carlo (EMC) approach. In LES the method has successfully been applied to non-premixed jet flames [36] and autoignition of lifted flames [37–39] but there are relatively few studies on premixed combustion [40,41]. One of the limitations of the PDF based methods is the long computational time required in the simulation, especially when a large number of species are involved. A recently developed method, Chemistry-Coordinate Mapping (CCM) [42–45] is therefore used to speed up the current calculations.

Based on the LES results, the paper critically assesses some of the modern theories of bluff-body flames approaching blow-off. The study also addresses a question raised in a recent experimental study of the current bluff-body burner [46], namely whether the large amount of CH_2O in the RZ can be predicted using LES with an appropriate SGS-model and what effect it has on the flame. Further, a detailed analysis of a blow-off sequence is performed demonstrating the capability of the current approach of predicting the flame and the flow under these conditions. In the end, the findings are summarized and a hypothesis on the sequence of events leading to blow-off is proposed.

The rest of the paper is organized as follows. First, the models and methods are described in Section 2 including the description