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Out of Equilibrium Dynamics

Progress and challenges in swirling flame dynamics

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ABSTRACT

In many continuous combustion processes the flame is stabilized by swirling the injected flow. This is the case for example in aeroengine combustors or in gas turbines where aerodynamic injectors impart a rotating component to the flow to create a central recirculation zone which anchors the flame. Swirling flame dynamics is of technical interest and also gives rise to interesting scientific issues. Some of the recent progress in this field will be reviewed. It is first shown that the swirler response to incident acoustic perturbations generates a vorticity wave which is convected by the flow. A result of this process is that the swirl number fluctuates. It is then shown that the flame response is defined by a combination of heat release rate fluctuations induced by the incoming acoustic and convective perturbations. This is confirmed by experimental measurements and by large eddy simulations of the reactive flow. Measured flame describing functions (FDFs) are then used to characterize the nonlinear response of swirling flames to incident perturbations and determine the regimes of instability of a generic system comprising an upstream manifold, an injector equipped with a swirler and a combustion chamber confining the flame. The last part of this article is concerned with interactions of the precessing vortex core (PVC) with incoming acoustic perturbations. The PVC is formed at high swirl number and this hydrodynamic helical instability gives rise to some interesting nonlinear interactions between the acoustic frequency, the PVC frequency and their difference frequency.

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1. Introduction

In the 1970s Clavin was well aware of the pioneering work of Zeldovich (see Zeldovich et al. [1]) and anticipated the revolution which was to come from activation energy asymptotics (AEA). In his work he perceptively emphasized the multiscale and nonlinear nature of combustion problems where thin reactive layers propagate in a flow featuring a broad range of spatial scales. This was exploited in analytical investigations of combustion waves by making use of asymptotics, a feature which has been extensively advocated in studies of laminar flames. AEA takes advantage of the fact that the activation energy of kinetic steps controlling the combustion process is quite high, so that the ratio $E/(RT_u)$ is a large parameter. AEA has provided a modern view of laminar flame structures as exemplified in the work of Liñán [2], Clavin (see [3] and [4,5] for reviews), Sivashinsky [6] and monographs by Buckmaster and Ludford [7] and Kapila [8]. Many examples are treated by Williams [9], Law [10–12], Matalon [13,14] and in a collective review of this topic [15]. Activation energy asymptotics has

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provided considerable information on the structure and properties of many types of flames and on fundamental combustion processes like ignition and extinction, effects of strain and curvature on the laminar burning velocity, flame instabilities and response to various types of flows or external perturbations. Williams underlines the remarkable progress made in combustion theory during the twenty years separating the two editions of his book [9], a progress in which Clavin was one of the major actors.

Much of his theoretical work and much of the experimental work carried out by his colleagues (most notably G. Searby and L. Boyer) has concerned flame structures and their dynamics generally in fundamental aerodynamic configurations. While the list of issues which have been tackled is long it does not include questions raised by swirling flames which are considered in what follows from a dynamical point of view. It is, however, worth noting that important issues may be examined with tools derived from combustion theory. Swirling flames are by no means of minor interest. In jet engines and gas turbines and in many other applications the flame is anchored by imparting an azimuthal component to the flow usually by passing the air stream in a swirler or a set of swirlers. The rate of rotation defined by these devices generates a central recirculation zone (CRZ) which is filled with hot combustion products serving to continuously ignite fresh reactants introduced in the combustor. The swirling flow is confined by the lateral walls which in most cases has an annular cross section and by the flows originating from lateral injectors. The presence of the side walls and of neighboring injectors has a significant impact on the flow structure which complicates the analysis. A single injector placed in a sector or in an axisymmetric configuration will only approximately represent the practical situation. It is, however, natural to examine such configurations to identify the main dynamical features. It is also logical to examine annular geometries comprising multiple injectors to examine possible coupling by azimuthal modes.

Much of the recent work on swirling flames has been carried out in relation with the design of advanced premixed combustion technologies with the objective of reducing NO*x* emissions from gas turbines. These new systems have successfully achieved low pollutant levels but their operation has been hindered by dynamical phenomena. Premixed flames are more compact and more sensitive to external perturbations. Also damping in premixed systems is diminished because the perforated liners found in classical designs are for the most part eliminated in modern combustors. For these reasons, combustion dynamics has become a major issue in this field and it has been intensively investigated. This paper begins with a brief review of the state of the art in combustion dynamics. It then focuses on selected issues in swirling flame dynamics:

- The first problem concerns the swirler response to incident acoustic waves. It is shown that the interaction generates a vorticity wave characterized by azimuthal velocity fluctuations convected by the flow.
- The second issue is that of the response of the flame formed by a swirling injector. This may be described by a flame transfer function (FTF) which defines the relative heat release rate fluctuations ($\dot{Q}'/\overline{\dot{Q}}$) as a function of incident relative velocity fluctuations ($u'/\bar{u}$):

$$\mathcal{F}(\omega) = \frac{\dot{Q}'(\omega)/\overline{\dot{Q}}}{u'/\bar{u}} \tag{1}$$

  It is shown that the mode conversion process taking place at the swirler has a marked influence on the flame response. It is also important to deal with the nonlinear response of the flame when it is submitted to a broad range of oscillation amplitudes. The response changes with the input level and one may then use an extension of the linear concept of transfer function and define a flame describing function (FDF) which depends on frequency and on the amplitude of the input:

$$\mathcal{F}(\omega, |u'|) = \frac{\dot{Q}'(\omega, |u'|)/\overline{\dot{Q}}}{u'/\bar{u}} \tag{2}$$

  This nonlinear dependence of the flame with respect to the input level leads in many cases to the nonlinear features observed in practice as already shown in a range of previous studies and as will be confirmed in what follows.
- The third issue is concerned with the analytical determination of the transfer function of swirling flames. It is shown that this can be determined by making use of a level-set framework which describes how the flame is perturbed under the combined effect of incident acoustic waves and azimuthal velocity fluctuations induced by the swirler.
- The fourth issue is linked to the use of the FDF to predict regimes of oscillation of a generic system. It is shown that by combining an acoustic network representation with a description of the flame response in terms of the FDF one obtains suitable estimates of frequencies and amplitudes of limit cycles observed experimentally.
- The final issue has to do with the precessing vortex core (PVC) a helical instability of rotating flows. Perturbations induced by the PVC have a frequency which is of the order of the rate of rotation of the swirling flow. When this flow is submitted to incident acoustic perturbations, or when the system develops a thermo-acoustic oscillation, the PVC frequency combines with the acoustic perturbation to produce a component at the difference frequency which has a characteristic "yin–yang" spatial structure and rotates at a rate equal to the difference frequency.

2. Background on combustion dynamics

Combustion dynamics raises difficult practical issues and constitutes a challenging area in combustion research. Under normal operating conditions, turbulent flames generate heat release rate fluctuations which are essentially incoherent and

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