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Thermal response of a turbulent premixed flame to the imposed inlet oscillating velocity

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ABSTRACT

Thermal response is known as thermal behavior of an unstable combustor. Such investigation, which has not been found in the literature, is important in terms of safety and prevention of the structural failure. In this study, the thermal response of a combustor with an inlet excitation is numerically investigated. Due to the geometry shape, two recirculating zones are found. Any change in the amplitude and frequency can affect these recirculation zones. At low fixed frequencies (below 50 Hz) and with a change in the amplitude, these two recirculation zones have no important influence on the heat release. Thus, at the low frequencies, excitation amplitude has no considerable effect on flame transfer function. For both adiabatic and convective cases, at fixed frequency, when amplitude increases, mass flow rate from cold to hot gases increases and this makes a reduction in the maximum temperature. Further, at a contestant amplitude, with increasing the frequency, the maximum temperature reduces, with a higher reduction for convective case. The physical interpretation of observed changes is sought in the relation between hydrodynamic and thermal field, relative length of combustor respect to the acoustic wavelength and so on.

1. Introduction

Combustion in gas turbines, for example in power plants and aircraft jet engines, produces NO_x emissions that cause air pollution. This should be reduced and controlled according to the current environmental policies [1]. Lean premixed combustion offers a means of reducing NO_x emissions [2]. Under such conditions, low emissions and high combustor performance can be achieved, but the reliability of such systems is a challenge, as they operate close to the lean stability limit and they are more susceptible to the damaging effects of combustion instabilities. Combustion instability is manifested by coupling of acoustic waves and unsteady heat release oscillations inside the combustor [3], which is often a consequence of multiple driving mechanisms [4]. Heat release rate fluctuations add energy to the acoustic field, leading to acoustic and velocity fluctuations that propagate through the combustor. These acoustic fluctuations then excite vortical structures and fuel/air ratio oscillations that, in turn, lead to further heat release fluctuations. This results in closing the feedback loop [5] and motivating combustion instability.

Due to the complex nature of combustion instability, its prediction and control at the early design stage of a gas turbine combustor are still challenging. Some experimental [6–10], analytical [11] and numerical [12,13] works have been carried out to study and predict combustion instability and pertaining phenomena. From numerical point of view, there exist two main methods of simulation strategies. The first is the direct method, in which acoustic wave and unsteady heat release from the flame are calculated simultaneously by Computational Fluid Dynamics (CFD) [14]. This means that the entire acoustic system (including the whole combustor and attached components) is simulated. Although such simulations are possible, they are impractical as an industry analysis tool.

Yet, a single model that may adequately incorporate unsteady combustion, acoustic waves, turbulence effects and heat transfer all together has not been fully developed. However, some alternative models that could capture the key mechanisms in combustion instability were presented, such as low order network combustor model [15–17]. A low order model describes the combustor system as a network of connected modules. The coupling between the unsteady heat release and the unsteady perturbations, i.e. the response of the flame unsteady heat release rate to perturbations, can be modelled via a flame model [18,19], which is the second

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Nomenclature

A	Amplitude
b	Progress variable
f	Frequency
h	Enthalpy
H	Flame transfer function
P	Pressure
Pr	Prandtl number
Q	Heat release
Re	Reynolds number
S	Stress viscous tensor
Sc	Schmidt numbers
T	Temperature
u_i	Velocity components
x_i	Direction components
Y	Mass fraction

Greek symbols

μ	Viscosity
ρ	Density
Δ	Filter width
Ξ	Wrinkling factor
$\overline{\dot{\omega}}$	Reaction rate
σ	Strain rates

subscripts

b	Bulk
i	Direction
SGS	Sub-grid scale
u	Unburnt mixture

method of simulation strategies [19]. The flame model is one of the key elements in the low order network modelling for combustion instability. This is because the flame model is the source of driving the instabilities. The flame model has been extended to the non-linear flame transfer function, defined as *H(f, A)* [20],

$$H(f,A) = \frac{Q'(f)/\langle Q\rangle}{u'(f)/\langle U\rangle} \tag{1}$$

where$\langle Q\rangle$ is the time-averaged heat release rate, $\langle U\rangle$ is the bulk velocity of the mixture entering the combustor, $Q'(f)$ and $u'(f)$ are their corresponding amplitudes at frequency f (i.e. the amplitudes of the Fourier transform of Q and U, narrowband filtered around f, and A is the magnitude of $u'(f)/\langle U\rangle$.

Transfer functions have been determined by analytical models, experiments and CFD studies. For simple geometries, transfer functions can be derived analytically. Examples of this modelling are the work of Fleifil et al. [21], Ducruix et al. [22], Schuller [23] and Lieuwen et al. [2,24]. Fleifil et al. [21] used a theory model to calculate the (linear) transfer function between the heat release and upstream velocity modulation of a flame stabilized in a simple Poiseuille flow. Such arguments were extended to general axi-symmetric conical flames by Ducruix et al. [22], who assumed a uniformly one-dimensional velocity excitation along the flame and the calculated flame transfer function was observed to be in good agreement with experiment at lower frequencies. An extension to this linear theory was made by Schuller et al. [23] who replaced the uniform velocity excitation with a convective wave. Other works by Lieuwen and co-workers [2] have extended the Schuller et al. [23] transfer function, and suggested that the phase speed of the velocity disturbance should be considered as an independent variable.

Several experimental studies [20,24–29] have been conducted to determine the flame models needed for stability analysis. Palies et al. [17] experimentally measured transfer function for a turbulent premixed swirling flame, while Silva et al. [29] combined a measured transfer function for a premixed swirled combustor with a Helmholtz solver. These experiments suggest that the gain of transfer function tends to decrease as the amplitude of the applied velocity fluctuations increase [20,24–29]. Balachandran et al. [20] showed that the gain of transfer function varies nonlinearly above an inlet velocity forcing amplitude of 15%; the exact value of the transition to nonlinearity depends on frequency and mean equivalence ratio. It was also shown that the phase of transfer function may change with forcing amplitude. Swirl number fluctuations [30,31] and the relation between thermal and hydrodynamic field [20] may play important roles for variations of transfer function. The latter can arise from the effects of the exciting acoustic wave on the recirculating zones [32], which may then cause significant effect on the flame shape and location that, in turn, lead to a significant change in the overall heat release and transfer function of the flame [32]. Therefore, the recirculating zone, found behind a bluff body and over a backward-facing step, when an exciting acoustic wave is entered into the combustor, can be considered as crucial problems [2,32]. These are very commonly studied in the context of instability inhibition and flame structure (see Ref. [33] for the review). However, it seems that little effort has been placed for better understanding the fluid mechanical field when the flow is oscillating in a combustor with compound bluff body and sudden expansion configuration [32]. Further, the importance of temperature variation in conjugation with the recirculating zones in systems with acoustic excitation can be also important. Such studies can help to better understanding the reason of transfer function changes.

The flame response to an acoustic excitation is also found through a high-fidelity CFD simulation, rather than time-consuming and expensive experiments. Examples for such a procedure are given in Refs. [34–38]. CFD study offers the potential to further explore the flow field, the thermodynamic and kinematic response of the system to an acoustic excitation. The development of numerical methods for turbulent combustion has made it as a useful alternative tool to study the problem [39,40]. Large Eddy Simulation (LES) is capable of capturing unsteady flow and flame structure dynamics and is nowadays used more and more to investigate turbulent combustion problems [41,42,43]. The investigations show that LES can give accurate prediction of flame dynamics encountered combustion instabilities. As LES can provide abundant details about the full flow fields, LES-based method for combustion has been pursued by many researchers. Febrer et al. [44] used a hybrid approach for coupling acoustic wave effects with LES for the flame response. An acoustic network model for the whole geometry was coupled with LES at the combustor inlet plane, where the acoustic wave amplitude matched to a hydrodynamic inlet forcing. The flame response was obtained only at the known instability frequency, and the hybrid approach provided predictions in reasonable agreement with the experimentally measured amplitude. An LES solver was also used to study an