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Unsteady vortex breakdown in an atmospheric swirl stabilised combustor. Part 1: Chamber behaviour

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ABSTRACT

This paper presents the behaviour of three very different and unique flame and flow structures within an atmospheric swirl-stabilised dump combustor supplied with a lean premixed mixture of methane and air. The reactant flow was artificially perturbed with frequencies of 100 Hz, 200 Hz, and 400 Hz. Phase average behaviour and temporal dynamics were characterised using phase locked high speed CH chemiluminescence and high speed stereo particle imaging. The interaction between the flame and flow field, in particular the internal recirculation zone of the vortex breakdown, was determined to be responsible for differences observed in behaviour at the three forcing frequencies. The 100 Hz perturbation frequency displayed simple oscillatory motion. Higher perturbation frequencies of 200 Hz and 400 Hz gave rise to a second toroidal vortex ring which formed within the internal recirculation zone adjacent to the inner shear layer. This caused additional out of phase modulation of the heat release rate and flame area. Twin counter rotating vorticity structures attached to the annulus were formed as a result of the chamber geometry. The oscillating inlet flow and oscillating reversed flow region of the inner recirculation zone caused oscillations in vorticity magnitude which were responsible for flame wrinkling and stretch effects upon the flame front. Vorticity within the shear layers was found to be the source of harmonic frequency generation of the imposed perturbation frequencies. The data is presented in detail to facilitate CFD model comparisons, particularly LES.

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1. Introduction

The social and legislative demand to reduce the quantities of pollutants (NO_x and CO) and emissions of CO_2 associated with hydrocarbon derived electricity has led to the dry low NO_x approach that uses premixed fuel–air mixtures with lean equivalence ratios ($\varphi = 0.7$–0.9 typically). Lean premixed combustion (LPC) implementation has been hampered by self-sustaining combustion instabilities that couple the unsteady heat release and chamber pressure coinciding with one or more acoustic modes of the combustor. The inability to predict the onset, type, and behaviour of instabilities during the combustor design stage highlights the limits of scientific understanding of the phenomena.

Aerodynamic techniques over physical flame holders have become popular to stabilise high velocity combustion. Recirculation zones circulate radicals and hot burnt products back to ignite the fresh gas maintaining a constant reaction rate, improve mixing, and increase residence times. A dump plane, or sudden expansion, creates a toroidal vortex structure often referred to as a corner recirculation zone (CRZ) between the dump plane and chamber wall. Using swirl introduces a tangential velocity component and axial vorticity to the inlet flow. With strong swirl, $S > 0.6$, (ratio of axial flux of angular momentum and axial thrust [1]) off axis vortex breakdown is observed due to the tangential velocity component creating the internal recirculation zone (IRZ) of reversed axial flowing fluid located around the chamber centreline. The specific arrangement of the recirculation zones is highly dependent upon the combustor geometry, combustion type (premixed or diffusion), fuel injection method, swirler type and design, exhaust profile, and Reynolds and swirl numbers. Comprehensive reviews can be found in the literature [1–3].

The vortex breakdown is dependent upon the swirl number and the subsequent axial pressure gradient. This gradient forms as the flow moves away from the axial direction. Above a critical swirl number the kinetic energy of the flow will be unable to overcome the swirl dependent axial pressure gradient and flow reversal occurs [4]. Combustion chamber geometry also contributes to the strength of the pressure gradient and corresponding decrease of

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mean axial kinetic energy, such features include a bluff body which creates a low pressure focus at its tip [5], a sudden expansion – redirecting axial flow, and any flow restriction at the exhaust [6]. Once vortex breakdown has formed the behaviour is controlled by the ratio of axial and tangential velocity. In total, seven forms of vortex breakdown have been observed [7] based upon three types: the spiral, double helix, and bubble (axisymmetric) [8,9]. The spiral/helical types are characterised by the vortex core/cores adopting a spiral shape that persist for several revolutions before breaking up into turbulence [10]. The vortex core is wrapped around the boundary of reversed flow and can rotate (precess) around the centre axis, distorting the reverse flow region at acoustic mode frequencies [11]. The bubble type is described by an expansion that envelopes the reversed flow region and can develop from the spiral type or directly from swelling of the vortex core. The nature of the internal structure of the bubble is not fully understood. Bubbles with a single toroidal vortex ring [4,7,12] or two counter rotating toroidal vortex rings have both been observed with no clear explanation to account for the difference. Both the spiral and bubble type of vortex breakdown have been observed in computational fluid dynamics (CFD) simulations and measurements of combustors [3,13–20].

For instabilities to become self-sustaining the unsteady heat release rate and pressure must be in phase, satisfying the Rayleigh criterion [21]. The consensus of the literature available is that there is no single fluid mechanical mechanism responsible for relating these two scalars. Experimental and CFD investigations have shown shear layer instabilities shed off the inlet lead to the periodic rippling of the flame front, thereby causing an unsteady heat release rate [15,16,18,22–24]. Coherent vortex roll up – the formation of a toroidal ring off the inlet – can cause large scale modifications to the flame structure or cause local extinction resulting in the undesired transport of fresh gas downstream to be consumed out of phase, both resulting in an unsteady heat release rate [25,26]. Recent attention has focused upon the precessing vortex core (PVC), the spiral shaped structure associated with strong swirl flame stabilisation. The vortex core rotates around the combustor centreline causing wrinkling of the flame front similar to the shear layer instability mechanism [16,27]. A thorough review of precessing vortex cores and vortex breakdown can be found in the literature [1,2,4,5,8,9,28]. In addition to fluid mechanical mechanisms, variations in equivalence ratio can also cause instabilities [29,30]. With respect to the vortex breakdown phenomena, only the PVC has been identified with a role in combustion instabilities. The range of potential mechanisms, dependency on combustor geometry and operating conditions, the coupling of thermo-acoustic processes, and interactions among these variables need to be better understood for instabilities to be mitigated and LPC to reach full potential.

Flame transfer functions (FTF) have become a popular choice to determine the response of a specific combustor when exposed to acoustic forcing, thereby identifying frequencies and excitation values which cause dramatic instabilities [31–36]. This allows combustor designers some indication of which frequency ranges could be susceptible to instabilities provided the geometries are similar. These investigations require some measure of the unsteady heat release rate and a measurement of the inlet velocity. Such measurements are typically performed using chemiluminescence (occasionally a PLIF technique has been used [37,38]) imaging and a calibrated pressure measurement. One dimensional acoustic analysis methods are also being developed to attempt to predict the FTF without experimentation and construction of the combustor. It has been shown that similar atmospheric combustors experiencing the same instability mechanism possess similar FTFs [39] but that this cannot be extended to instabilities experiencing different mechanisms [40]. The FTF itself however does not yield any information regarding the flame or flow field structure, nor the fluid mechanical mechanisms present. Provided the heat release was determined from an imaging method an analysis of the flame structure can be attempted although limited by the nature of data acquisition (phase locked or not). However behaviour of the flow field and fluid mechanical mechanisms will remain unknown. If a FTF is going to represent a particular combustors' response it is important to understand the physical mechanisms that underlie the FTF. This means investigations of the combustor physics subject to imposed perturbations are needed to understand why a particular FTF is what it is.

Additionally changes to the combustor geometry (or pressure regime [41] or fuel composition [42]) will cause changes to the combustor physics, particularly the vortex breakdown and swirling dynamics, which will require the FTF to be determined again. These changes of physics will be captured by the newly measured FTF but unless the physics are understood interpretation of the FTF is restricted as changes to the flow field physics will not be known. Understanding how vortex breakdown responds to geometry changes and how it behaves under unstable conditions are essential to allow the prediction of an FTF that is independent of combustor geometry. This knowledge will also improve FTF interpretation with respect to the fluid mechanics and therefore improve the FTFs applicability to real sized gas turbines.

Many of the investigations cited here were performed using large eddy simulation (LES). LES has become the most suitable CFD method to study instabilities and to develop design tools for gas turbine manufactures. This is primarily due to the resolving of temporal and spatial scales larger than an appropriate filter size, yielding instantaneous realisations of the flow. Still in its development stage, LES requires high quality validation data to gain confidence in it as a predictive development tool that requires little or no a priori experimental data. Such experimental investigations have been performed in atmospheric or low pressure combustors. Utilising optical access, these combustors have been probed non-intrusively, using precise optical diagnostics and sensory instruments, when experiencing instabilities (see experimental references above) [43,33,44–47]. The collected data are used for physical insight, typically of a single operating condition, and as LES validation data. Parallel studies of experimentation and LES have used the experimental data to gain confidence in the simulation, which was then used for an advanced analysis that could not be performed with the limited diagnostics [11,15,16,48,49]. Currently, the most comprehensive validation data set has been acquired by the German national laboratory, DLR [17,27,50–54].

This publication builds upon the work previously presented [55] where an atmospheric model gas turbine combustor designed for instability research and LES validation was introduced. A lean premixed methane/air mixture with an equivalence ratio of $\varphi = 0.8$ was artificially perturbed at 100 Hz, 200 Hz and 400 Hz, and the resulting flame dynamics were characterised with high speed CH chemiluminescence and stereo particle imaging velocimetry (SPIV). A full uncertainty analysis of the applied diagnostics was documented, and the ensemble average results were presented. This second publication details the phase locked averaged results and presents a global description of the instabilities. Rather than determine the FTF of the combustor this work seeks to investigate mechanisms present within the chamber during these perturbations through a more detailed investigation. Of importance is the observation of additional toroidal vortex rings forming adjacent to the flow reversal region upstream of their expected position during the instabilities. These additional vortex rings caused additional out of phase flame area modulation. To our knowledge this phenomenon has not previously been observed experimentally and is a newly documented fluid mechanical structure that can impact combustion instabilities. The actual mechanisms that affected heat