Control of Combustion Instabilities

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1 Physics of combustion instabilities

1.1 Background

Combustion instabilities are large amplitude flow oscillations that arise due to a feedback between acoustic (sound) waves and unsteady heat release. They can occur whenever combustion takes place inside an enclosed or partially enclosed volume (an "acoustic resonator"). They are almost always undesirable - the associated pressure oscillations and possibly enhanced heat transfer can deteriorate the system performance, and may be sufficiently intense to cause structural damage.

Combustion oscillations are of particular current concern as the new generation of low emissions gas turbines are proving to be particularly susceptible to them. This includes both industrial land-based gas turbines [1, 2, 3] and aero-engines [4, 5]. Operating gas turbine combustors under lean-premixed conditions reduces NOx emissions, but also makes combustors especially prone to combustion instabilities [6, 7]. Combustion instabilities also occur in aero-engine afterburners [8, 9, 10], rocket motors [11], ramjets [12], boilers and furnaces [13]. On a laboratory-scale, combustion instabilities can be generated in a simple open-ended vertical tube with a heat source in its lower half, known as a Rijke tube [14].

Combustion instabilities are caused by a coupling between unsteady heat release and the acoustic waves. Unsteady combustion is an efficient acoustic source [15, 16], and combustors tend to be highly resonant systems. Therefore when unsteady heat release generates acoustic waves, these partially reflect from the boundaries of the combustor to arrive back at the combustion zone. They then cause more unsteady heat release, for example through local changes in the fuel-air ratio [6] or hydrodynamic instabilities [17, 18]. Depending on the relationship between the unsteady heat release and acoustic waves, oscillation amplitudes may successively increase leading to instability. When instability occurs, the oscillation amplitudes initially increase exponentially; at some point some non-linearity in the system limits the amplitudes to give "self-excited oscillations".

1.2 Physical insight

Rayleigh was the first to provide some physical insight into combustion instabilities over a century ago [14]. In his now famous criterion, he states that oscillation amplitudes grow when heat is added in phase with pressure, but decay when heat is added out of phase with pressure. Chu [19] has since generalised this to incorporate the effect of boundary conditions, and this provides a useful insight into combustion oscillations and methods for controlling them.

Following Chu, a perfect gas burning within a combustor of volume V, bounded by a surface S is considered. For simplicity in this illustrative example, the gas is considered to be linearly disturbed from rest with no mean heat release (extensions accounting for mean flow and mean heat release can be made [20]). Viscous forces are neglected. The pressure, density, heat release rate per unit volume, particle velocity, speed of sound and ratio of specific heat capacities are denoted by p, ρ, q, $\mathbf{u}$, c and γ respectively, and a mean value is denoted by an overbar and a fluctuating value by a prime.

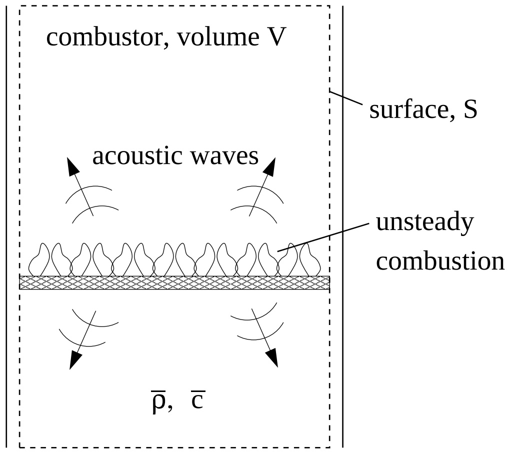

Figure 1: A control volume of perfect gas within a combustor.

The density change arising from unsteady heat release is due to both pressure fluctuations and changes in entropy.

$$\frac{\partial \rho'}{\partial t} = \frac{1}{\bar{c}^2}\frac{\partial p'}{\partial t} - \frac{(\gamma - 1)q}{\bar{c}^2} \tag{1}$$

Combining equation (1) with the linearised continuity and momentum equations, and integrating over the volume V, gives rise to an acoustic energy equation [19].

$$\frac{\partial}{\partial t}\int_V \left(\frac{1}{2}\bar{\rho}u^2 + \frac{1}{2}\frac{p'^2}{\bar{\rho}\bar{c}^2}\right) dV = \int_V \frac{(\gamma - 1)p'q}{\bar{\rho}\bar{c}^2}\, dV - \int_S p'\mathbf{u}.\, d\mathbf{S} \tag{2}$$

The term on the left hand side of the equation represents the rate of change of the sum of the kinetic and potential energies within the volume V. The first term on the right hand side represents