Self-excited combustion oscillations in industrial combustion systems can cause pressure pulsations with high amplitudes that lead to substantial noise and violent vibrations. In some cases the associated mechanical and thermal loads can severely damage the system concerned. The oscillations are generated by interactions between the sound pressure field in the system, the flow, and the heat released by the flame. This work explains how the involved effects are acting together in a closed loop: pressure fluctuations cause corresponding fluctuations in the flow which lead to pulsations of the flame, which in turn excite more pressure fluctuations. The chronological correlations that characterize the interactions and are crucial for the self-excitation mechanism are described, an abstract of existing approaches to model the oscillations is given, and possible counter measures are briefly outlined.

1 INTRODUCTION

In combustion systems of almost any kind – from domestic heating devices to industrial furnaces, jet engines and gas turbines – unexpected high-amplitude pressure pulsations at discrete frequencies have been observed in certain modes of operation. The pulsations are marked by very high noise emissions, violent vibrations, a noticeable increase of the heat transfer rate to the combustion chamber walls and, often, a rise in pollutant emissions. In large combustion systems the resulting dynamic loads may bring about excessive wear and premature failure of individual components or, in extreme cases, the complete destruction of the respective system.

The pulsations are caused by an interaction between the sound field in the combustor, the flow, and the flame and it is characteristic that a feed-back exists between these quantities which leads to instability and self-excitation. Pressure pulsations are maintained by fluctuations of the flame’s heat release rate which in turn is, indirectly, being triggered by the pressure pulsations themselves. According to the energy supply mechanism the phenomenon is usually referred to as "self-excited combustion oscillations" or "thermo-acoustic instabilities".

Having been discovered in the laboratory more than 200 years ago (Higgins 1802) the phenomenon remained of purely theoretical interest for another 150 years when it first became a problem in practical applications (Crocco and Cheng 1956; Putnam 1971). Since then, self-excited combustion oscillations in industrial systems have increasingly become important and a lot of effort has been put into the development of models to mathematically describe the phenomenon on the one side and counter measures to eliminate it in practical systems on the other.

2 PHENOMENOLOGY

The most striking feature of self-excited combustion oscillations are obviously strong pressure pulsations giving rise to a loud booming or screeching noise and to vehement vibrations which usually can be heard and felt even at considerable distance from the actual source. In contrast to combustion’s normal broad-band noise emissions, combustion oscillations are marked by high amplitudes at discrete frequencies with the amplitudes being substantially higher than those obtained for pure (non-fed-back) excitation of resonant modes.

Figure 1 shows the pressure frequency spectrum measured in the combustion chamber of a 137 kW burner for liquid fuel that is subject to self-excited oscillations. At the peak seen at 275 Hz the amplitude reaches about 1650 Pa, corresponding to a sound pressure level of more than 150 dB.

Even higher pressure amplitudes have been observed in large industrial furnaces or in charged combustion chambers of gas turbines. In Figure 2 pressure amplitudes measured in the combustion chamber of a 170 MW gas turbine are represented (static pressure about 17 bar). At $t = 30$ s the sudden onset of self-excited oscillations can be seen, with am-
Figure 1: Pressure frequency spectrum measured in the combustion chamber of an oscillating 137 kW burner (from Hantschk et al. 1996).

Figure 2: Pressure amplitudes in a gas turbine (170 MW, static pressure in combustion chamber approx. 17 bar): sudden onset of self-excited combustion oscillations (from Seume et al. 1998).

Figure 3: Self-excitation mechanism. The feed-back mechanism underlying self-excited combustion oscillations can vary greatly in its details. However, in the majority of cases where the oscillations turn up in industrial systems they are mainly based upon the following effects and variables, interacting with each other in a closed loop:

- The sound field in the system,
- The flow through it, and
- The energy released by combustion.

Figure 3 shows a simplified block diagram of such a loop: the pressure fluctuations excite a characteristic sound field in the system which causes fluctuations of the fuel and/or air mass flow rate entering the combustion chamber. When these are transported towards the combustion zone by the flow, the flame will be supplied with varying amounts of combustible mixture of fuel and air, thus modifying the combustion profile. The burnt gases exit the system which cause turbulence in the sound field in the surroundings.

The burner in question is shown in Figure 4. It consists of a pre-chamber linked via an orifice plate to the actual combustion chamber. Air is introduced laterally into the pre-chamber of the burner. Directly at the orifice plate, a centric nozzle is used to introduce fuel that will mix with the air passing through the orifice plate and burn within the combustion chamber. At its downstream end the burnt gases exit into the surroundings.

In the following the effects involved in the feedback loop and their interaction will be looked at in more detail. Theoretical and experimental results for a comparatively small burner will serve to illustrate the process (Hermann 1997; Hantschk 2000; Hantschk and Vortmeyer 2002). However, the principal effects described are representative for many industrial combustion devices, independent of their respective output power.
wall) is characterized by a pressure anti-node, while there is a pressure node at the acoustically open outlet of the combustion chamber into the surroundings.

At the orifice plate separating pre-chamber and combustion chamber, the values for amplitude \( \hat{p} \) and phase \( \varphi_p \) of the sound pressure eigenmode change abruptly. This means that pressure oscillations immediately upstream and downstream from the orifice plate have different amplitudes and are also phase-shifted with respect to each other. This generates a fluctuating pressure drop across the orifice plate and therefore, during oscillations, the air passing through will alternatingly be accelerated or decelerated. In this way, a periodically fluctuating volume flow rate of air through the orifice plate and into the combustion chamber is generated.

### 3.2 Flow

The volume flow rate fluctuations induced at the orifice plate move downstream as a travelling wave, towards the reaction zone.

This can be read off Figure 6, where the axial flow velocity \( u_1 \) is plotted along the burner axis. The curves shown correspond to three moments in time selected at random but spaced with respect to each other by one quarter of the oscillation period \( T_f \) (= 1/\( f \)), as follows: \( t = t_1 \), \( t = t_1 + 1/4 \cdot T_f \) and \( t = t_1 + 2/4 \cdot T_f \). The “wave crests” and “wave troughs” proceeding along the \( x \) axis demonstrate the downstream movement of the flow rate fluctuations.

### 3.3 Combustion

When the flow rate fluctuations reach the reaction zone, the flame will be supplied with fluctuating amounts of combustible mixture. Consequently, the rate of fuel burnt in the flame will vary, resulting in fluctuating amounts of heat released by combustion per unit of time.

However, since the heat output of the flame causes the burnt gases to expand, any fluctuating heat release will lead to corresponding pulsations of the gases in the combustion chamber. Thus, a periodic pressure excitation (acoustic monopole source) is created and feedback into the sound pressure field will be established: the loop is closed.

### 4 Timing

The fact that pressure pulsations, flow and combustion interact with each other in a closed feed-back loop is not yet sufficient for self-excitation to occur. Pressure fluctuations in the combustion chamber will only be augmented and maintained if the heat addition by the flame takes place at the “right” instant.

A more precise definition of this criterion was formulated by Baron Rayleigh (1878, 1945) and later named after him. According to Rayleigh’s criterion oscillations can only be excited if the maxima of fluctuating heat release rate coincide with those of the fluctuating pressure, or are shifted less than one quarter of the oscillation period \( T_f \) against each other. Rayleigh’s criterion can thus be considered a criterion for instability.

That this instability condition is indeed fulfilled for the burner described here can be seen from Figure 7 which shows the pressure fluctuations in the combustion chamber \( p'_{cs} \) (solid line) and the total heat release rate of the flame \( \dot{Q}_{int,flam} \) (dashed-dotted line) versus time: the maxima of the two oscillating quantities are only about 0.14 \( \cdot T_f \) apart.

It is important to note that all of the phenomena involved in the feed-back loop have an influence on the fulfilment of the Rayleigh criterion. This is because the interactions described in sections 3.1, 3.2 and 3.3 between the associated parameters and effects are characterized by a precise chronological correlation which, in the last resort, also determines the shift between pressure and heat release fluctuations.

For instance, the volume flow rate fluctuations \( \dot{V}_{op} \) induced at the orifice plate will produce corresponding fluctuations in the heat release rate only after a
A certain characteristic delay or time lag. Figure 7 explains this convective time lag \( \tau_3 \) between \( V_{\text{Op}} \) and the total heat release rate of the flame \( Q_{\text{tot,react}} \), along with two further time lags encountered: time lag \( \tau_1 \) exists between the pressure fluctuations \( p_{\text{Cc}} \) within the combustion chamber and the fluctuating pressure drop across the orifice plate \( \Delta p_{\text{Op}} \). In its turn, \( \Delta p_{\text{Op}} \) is shifted by a time lag \( \tau_2 \) against the volume flow rate fluctuation \( V_{\text{Op}} \) caused by it. Overall, there will thus be a total time lag \( \tau_{\text{tot}} = \tau_1 + \tau_2 + \tau_3 = 1.86 \cdot T_f \) between the pressure oscillations in the combustion chamber and the fluctuating heat release rate of the flame.

It should be noted that the time lag concept as outlined above is rather simplifying the real situation for most industrial combustion systems. For example, for long flames the time lag between heat release and pressure oscillation is not uniform across the flame front and the reaction zone comprises both regions for which Rayleigh’s criterion is fulfilled and others for which it is not. Whether self-excitation takes place or not will then depend on the overall balance among these regions.

In addition, it has to be mentioned that the fulfillment of Rayleigh’s criterion is a condition necessary but not sufficient for self-excited combustion oscillations to develop.

5 PREDICTION AND SIMULATION

It has been shown that even in the very simple case described here each of the individual effects involved in the feed-back loop can be crucial for the self-excitation mechanism. Consequently, a comprehensive model that is able to correctly predict and characterize self-excited combustion oscillations needs to take all of these effects into account.

An approach that comes close to this aim is to numerically solve the unsteady conservation equations of fluid dynamics together with appropriate models for combustion and turbulence. While simulations of this kind have been performed successfully, they are still out of reach for most industrial systems due to the enormous computational effort necessary (Menon and Jou 1991; Benelli et al. 1993; Smith and Leonard 1997; Steele et al. 1999; Murata and Ohtsuka 1999; Hantschk 2000; Hantschk and Vortmeyer 2002).

For practical applications models are sought for that yield results on average computing equipment and in reasonable time. Up to now, to accomplish this, simplifications have to be made.

An important group of models are based on the calculation of time lags and on Rayleigh’s criterion (e.g. Tsujimoto and Machii 1986; Lieuwen et al. 1999). For example, in case of the burner described in the previous sections, if the time lag \( \tau_{\text{tot}} \) could be predicted, it was possible to evaluate Rayleigh’s criterion for self-excitation.

Since the sound field plays an important role in the feed-back loop many models rely on solving the linearized acoustic wave equation with the unsteady heat release of the flame included as a source term. The representation of the latter is a crucial element in these approaches and various methods in different degrees of complexity have been developed ranging from purely analytical to semi-empirical and experimental approaches (e.g. Cuckl 1971; McIntosh 1987; Fureby and Lundgren 1993; Barr et al. 1988; Schuermanns et al. 1999; Dowling 1997).

In contrast to detailed and comprehensive numerical simulations, models which make careful use of simplifications and idealizations can be very efficient. However, they often require knowledge of important characteristics of the respective system and its dynamic properties which is not available in the planning stage. Thus they lack true predictive capabilities since they depend on input parameters which can usually be determined only at some later point, i.e. when a combustion system is already subject to unwanted oscillations (Dowling 1995).

6 COUNTER MEASURES

As indicated in the previous section, it is still impossible to date to reliably predict, during the design phase of a combustion system, whether it will be subject to self-excited oscillations or not. At the same time no generally applicable design rules exist that will guarantee oscillation-free operation under all relevant conditions. Consequently, it is still not uncommon that oscillations appear unexpectedly after a combustion system has been taken into operation. Counter measures to avoid or mitigate the oscillations can then become a crucial issue.

An arbitrary and rough division of counter measures can be made into those that only reduce the oscillation amplitudes without otherwise influencing
the process and into those that in some way "detune" the self-excitation loop so that unstable feed-back no longer occurs.

The first group comprises all sorts of devices that dissipate acoustic energy, e.g. mufflers, resonators or sound absorbing linings and insulations (e.g. Gysling et al. 1998). Due to the extremely high amplitudes associated with self-excited combustion oscillations it can be very difficult to achieve sufficient amplitude reduction that way. In addition, available space and process conditions may forbid installation of such devices.

Measures belonging to the second group can be aimed to influence any of the effects involved in the feed-back loop. Examples are geometric modifications which which lead to other acoustic eigenmodes/frequencies (e.g. Culick 1988), alterations of the flow field (e.g. DVGW Bonn et al. 1997; Straub and Richards 1999) or changes in fuel composition which will result in another location and shape of the flame. If successful, measures of this kind are very effective since they neutralize the instability of the feed-back loop and cancel out oscillations more or less completely. However, detuning of the self-excitation loop often only changes the stability regions of the system and oscillations surge up again under different operating conditions.

A special group of counter measures are so-called active measures which try to cancel out existing oscillations by superposition of anti-cyclical oscillations. These are generated by some sort of actuator device, e.g. loudspeakers. The correct phase and amplitude of the anti-signal is computed from a suitable sensor signal that monitors the system (e.g. Candel 1992; McManus et al. 1993; Seume et al. 1998). While this active control offers great flexibility it is usually rather costly and in large combustion systems it is often impossible to find suitable actuators that are powerful enough to level out the self-excited oscillations.

REFERENCES


