Acoustic Response of Burner-Stabilised Flat Flames

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Abstract

Since the introduction of low-NO_x premixed burners with a large modulation range, severe noise problems hampered further developments of modulating domestic heating boilers. It is expected that these problems are related to the thermo-acoustic phenomena like the "singing flame" reported by Byron Higgins in 1777. Two types of burners are generally used in these systems: burners with slits and holes on which Bunsen-type premixed flames stabilise and porous surface burners on which flat flames are anchored. Both types are sensitive to noise generation in boiler systems. The fluctuating heat release Q' of Bunsen-type flames is believed to be related to the fluctuating surface area of the oscillating flames (see G.R.A. Groot *et al.* [1]). However, the surface area of surface burners does not change as a result of acoustic disturbances. In this case it is believed that the fluctuating heat release is caused by fluctuations in the flame temperature, which on their turn are generated by a fluctuating enthalpy at the burner.

The acoustic behavior of burner-stabilised flat flames is studied in this paper. The study is divided in two parts. In the first part the complete set of 1D transport equations is solved numerically. The second part is an analytical model in which the most essential ingredients of the combustion system are taken into account. The analysis is used to provide a physical interpretation of the behavior of burner-stabilised flames in an external acoustic field. Both parts are described in more detail below. In the first part of this study, use is made of a numerical model of the system in which the complete set of 1D Navier-Stokes, energy and mass-balance equations is solved for the burner-stabilised lean methane/air flames. The burner is treated as an ideal sink of heat ($T = T_0$) and as inert to chemistry effects. Furthermore, non-reflecting boundary conditions are implemented for outgoing acoustic waves at both boundaries, to make sure that acoustic waves which interact with the burner and flame are not reflected back into the domain. The derivation of the boundary conditions is based on the theory of characteristic directions for traveling waves through a flow. Both skeletal and simple one-step models are used to treat the chemical kinetics. Starting from a stationary stabilised flame (for $t < 0$), the burner-flame system is distorted by an incoming acoustic wave u'_u at the unburnt boundary (for $t \geq 0$) and the response of the flame is studied in terms of the fluctuations in the mass burning rate, the total chemical heat release, the heat loss to the burner and the acoustic velocity in the burnt gases. The input signal at the unburnt boundary is a sweep, i.e. a sine-like signal in which the frequency is linearly increasing in the frequency domain. This signal and the output signal are then analysed to give the frequency dependence of the flame response. This method has proven to be valid because the acoustic disturbances are very small so that the system can be assumed to be linear.

A full theoretical analysis of this system was provided by the work of McIntosh *et al.* This theory is based on large-activation energy asymptotics (LAEA) and a low-Mach number approximation. In

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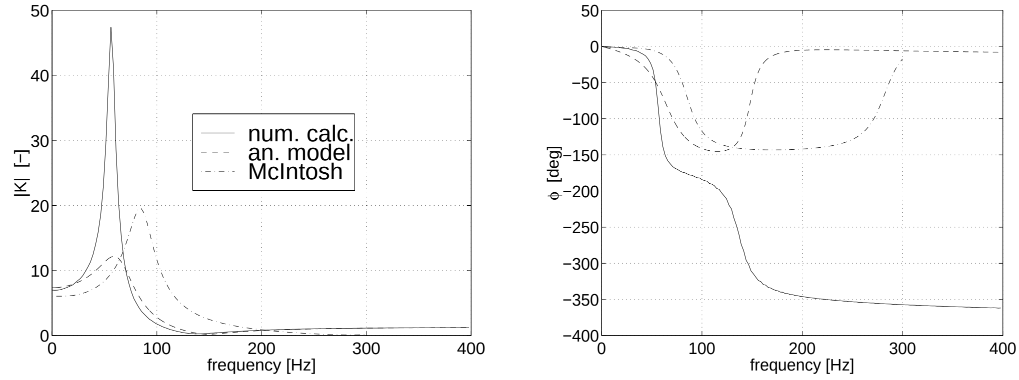

(a) Amplitude

(b) Phase shift

Figure 1: Acoustic response of velocity pertubations.

Figure 1, results are shown for the acoustic response in terms of the amplitude (Figure 1a) and phase (Figure 1b) of K, the response of the velocity perturbations in the burnt gases

$$u_b' = Ku_u' = |K| \exp(i\phi) u_u' \tag{1}$$

as a function of the frequency for a lean methane/air flame ($\Phi = 0.8$ at relatively low inflow velocity $u_u = 0.10$ m/s). A resonance is observed in both the numerical results using a one-step reaction model as well as in the result of McIntosh [2]. The physical background of this resonance, however, was first not understood. Furthermore, the rigorous theory of McIntosch did not give enough information for extracting the physical interpretation.

For this reason we developed a new and physically more transparent analysis. As a first step we restrict the analysis to a single step reaction, unit Lewis numbers and flame without flame stretch, which means that these 1D flames oscillate as rigid structures in the applied acoustic field. The motion of such a flame structure is described by the G-equation, which can be solved exactly under these assumptions. Due to the flame motion with respect to the burner, the *enthalpy* $J = c_p T + \Delta H Y_{CH_4}$ fluctuates at the burner edge. The resulting enthalpy waves propagate from the burner to the reaction zone with the gas velocity u_u, where they lead to variations in the flame temperature T_b' and lead to a fluctuating mass burning rate m'. Their relation is assumed to be given by the quasi-stationary equation

$$m' = \frac{Ze}{2} \frac{\bar{m}}{T_b - T_u} T_b' \tag{2}$$

with Ze the effective Zeldovich number. This relation is applicable if the frequencies are much smaller than the chemical frequencies in the system. From the analysis it is possible to formulate the relation between fluctuations in the mass burning rate m' and the gas velocities u_u' of the incoming acoustic wave. A resonant behavior is found when the resulting mass burning rate distortion amplifies the flame oscillation. Using this analyses it is also possible to formulate expressions for the fluctuations in the total chemical heat release, the heat loss to the burner and velocity perturbations in the burnt mixture.

Results of this analysis are also plotted in Figure 1. It appears that the results for $|K|$ agree well with numerical results and the results of McIntosh. For the phase, the agreement is less satisfactory. The reason for this is still under investigation and might be related to the fact that flame stretch has been neglected so far. The results will be compared with experiments in due time. We already performed first measurements with our experimental setup using UV emission to measure fluctuations in the heat release. Additional measurements, also with LDV, PIV and flame temperature measurements are underway.

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Bibliography

[1] G.R.A. Groot *et al.*. Evaluation of two models for the acoustic response of the 2D laminar premixed flames. *This conference*.
[2] A. McIntosh. Combustion-acoustic interaction of a flat flame burner system enclosed within an open tube. *Comb. Science and Tech.*, 54:217-236, 1987.