Evaluation of two models for the acoustic response of 2D laminar premixed flames

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Keywords: laminar premixed flames, $\mathcal{G}$-equation, thermo-acoustics.

Abstract

With the introduction of modulating boilers for domestic heating, severe noise problems have become apparent. It is thought that this phenomenon is related to the excitation of acoustic modes in the boiler system, where flames act as the driving sources of sound. This system is equivalent to a Rijke tube in which the heated grid has been replaced by a flame.

In this paper we will investigate the thermo-acoustic response of two-dimensional laminar premixed methane/air Bunsen-type flames which are subjected to an external acoustic field. This external field is applied in terms of an oscillatory flow velocity u'_u in the unburnt gas mixture. At low Mach numbers the acoustic response of the flame is governed by the fluctuation Q' in the heat release of the flame-burner system. For laminar premixed Bunsen-type flames, fluctuations in the total heat release are primarily caused by fluctuations A' of the total surface area of the flame. Flame temperature variations are probably negligible, except near the stabilisation point of the flame, where heat transfer to the burner might be important.

To determine A' as function of time, the unsteady flame motion will be studied by using two models. We start with the description of a very simple analytical model introduced by Fleifil *et al.* [1]. It will be shown that this model contains a number of shortcomings in the description of the physical situation. In order to get more accurate results and a better insight into the situation, the assumptions made in the derivation of this simple model are reconsidered. An improved numerical model is developed which is partly based on a flamelet model introduced by De Goey *et al.* [2]. These two models are described in more detail below.

In the analytical model [1], the flow field is described by a Poiseuille flow, which is assumed to be disturbed by a homogeneous velocity fluctuation $u'_u(t)$, and not influenced by the flame. Furthermore, for tracking the motion of the infinitely thin flame front due to acoustic disturbances, the $\mathcal{G}$-equation is used:

$$\frac{\partial \mathcal{G}}{\partial t} + \vec{u} \cdot \vec{\nabla} \mathcal{G} = s_L |\vec{\nabla} \mathcal{G}| \, . \tag{1}$$

The burning velocity s_L is assumed to be independent of flame temperature, flame curvature and stretch, i.e. $s_L = s_L^0$ where s_L^0 is the stretchless and adiabatic burning velocity.

A comparison of the flame shape with experiments shows that the model is able to describe the qualitative behaviour of the perturbed flame, but the quantitative behaviour is not accurately described. The assumptions made about the flame stretch and curvature, the interaction of the flame with the flow, the stabilisation of the flame at the wall and the flame thickness are therefore reconsidered.

The influence of flame stretch and curvature on the burning velocity can be taken into account by using the relation (see Peters [3])

$$s_L = s_L^0 - s_L^0 \, \mathcal{L}_M \, \vec{\nabla} \cdot \vec{n} - \mathcal{L}_M \vec{\nabla} \cdot \vec{u}_t \, , \tag{2}$$

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with $\mathcal{L}_M$ the Markstein length, $\vec{n} = \mathrm{sign}(\mathcal{G}_\mathrm{u} - \mathcal{G}_\mathrm{b})\vec{\nabla}\mathcal{G}/|\vec{\nabla}\mathcal{G}|$ the unit normal vector on the flame surface directed towards the unburnt gases, and $\vec{u}_t$ the component of the velocity field along the flame surface. In this way the flame tip resembles more closely the experimental flame tip in a steady state.

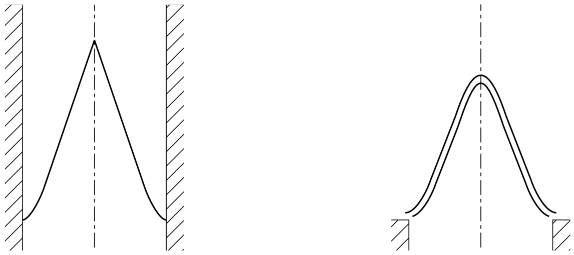

Figure 1: *Schematic representation of the stationary flame shape in the analytical model (left graph) and the numerical model (right graph).*

The interaction of the flame with the flow through density variations can be taken into account by solving the Navier-Stokes equations along with the $\mathcal{G}$-equation.

The physical stabilisation mechanism of the flame on the burner rim can be implemented by solving the enthalpy equation, which describes the heat transfer from the flame to the burner. The effect of heat loss on the burning velocity is described by

$$\frac{d\,s_L(T_b)}{d\,T_b} = \frac{Ze}{2}\frac{s_L}{(T_b - T_u)} \,, \tag{3}$$

with Ze the effective Zeldovich number of the mixture, determined from experimental or numerical results.

The flame can be given a finite thickness by solving the $\mathcal{G}$-equation not for the infinitely thin flame sheet, but for a set of iso-flame surfaces (e.g. isotherms) in the flame.

The numerical model incorporates these improvements and is therefore more physically accurate than the analytical model. Figure 1 shows a schematic representation of the stationary flame shape in the analytical and the numerical model.

Theoretical results will be compared with experimental data. These data are obtained from flame front visualisations using the natural emission of the flame, from Particle Image Velocimetry (PIV) experiments for the instationary flow field near the flame cone, and from integrated UV emission experiments for detecting the total fluctuating heat release of the flame. Figure 2 shows examples of various phases of the flame shape under influence of an acoustic field.

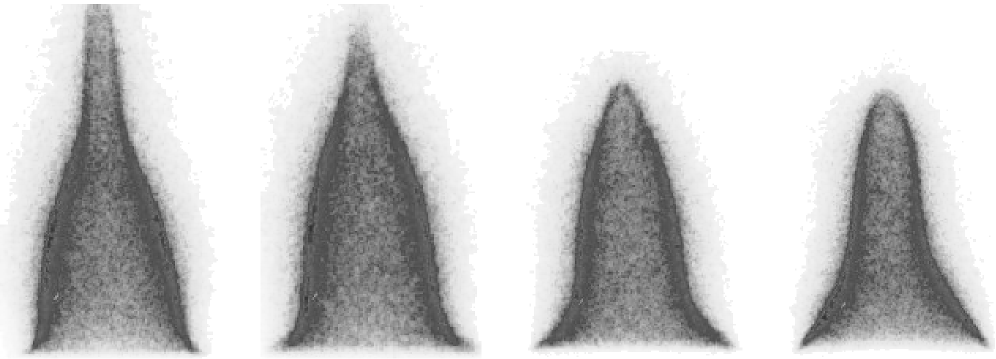

Figure 2: *Examples of various phases of a lean methane/air flame shape under influence of an acoustic field (85 Hz).*

The results of this study are used to evaluate the response of laminar premixed Bunsen-type flames to acoustic disturbances with varying frequency and amplitude. In this way it is possible to predict the acoustic behaviour of boilers in which premixed burners that contain slits and holes are used.

The institutes involved in the Centre for Noise in Boilers in the Netherlands are gratefully acknowledged for their support.

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