Investigation Singing into Conditions Enabling the Excitation of the Kinetic Flame

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Excitation of sound by hydrogen burning inside a vertical resonance pipe was observed by Higgins at the turn of the 18th century. It seems likely that Rayleigh was the first to methodically arrange the experimental material that had been accumulated by then and to draw the fundamental conclusions concerning the maintenance of the air column oscillation by heat using the singing flame. Even though the Rayleigh criterion was sufficient to account for the air column oscillation in a flow halfway into the 20th century, it was demonstrated at a later time that the oscillation could be maintained at significant phase differences, φ, between the heat release rate and pressure oscillations, the differences being as large as π. It was found that not only heat release, but also variations in the kinetic energy of the gas flow furnish the energy for the sound emission.

Here the object is to describe the present authors' experimental investigations into the contributions of a variety of mechanisms to the development of combustion instabilities in the case of the singing flame.

The experiments were conducted using resonance pipes, in which pre-mixed propane and air were burnt. In the course of the experimental investigation, different techniques were used to register the mixture flow rate, propane-air ratio, acoustic pressure, CH radiation intensity and to visualize the flame structure.

As is evident from the experimental findings, concentration-related excitation and silence ranges could be observed as the propane-air ratio was changed, the bulk of the variable heat release (as large as 80 per cent) occurring at the vertex of the flame cone. The availability of the concentration-related excitation and silence ranges could be accounted for by the variations in the phase difference, φ, at the vertex of the flame cone. It was found that for mixtures exhibiting peak pressure oscillations $\varphi = (\kappa + 1)2\pi$ for any of the concentration-related flame-cone-vertex excitation ranges, whereas $\varphi = (\kappa + 1.5)2\pi$ for any of the silence ranges, where κ is the sequence number of the respective excitation or silence range.

Images of the structure of developed singing flame oscillations obtained by different visualization techniques are shown in the figure 1, each series spanning a single oscillation period.

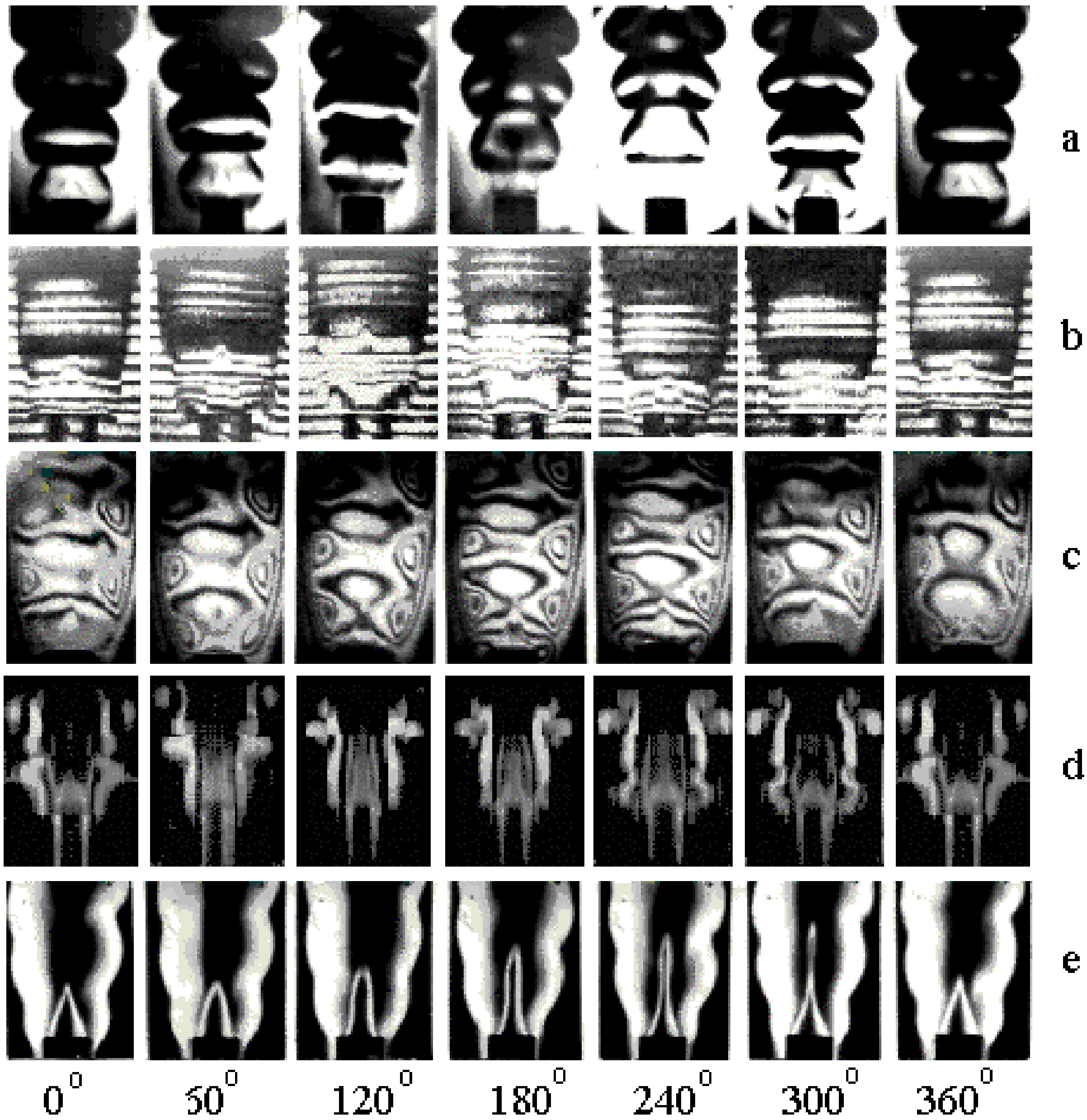

Figure 1. Series of photographs obtained by different visualization techniques, the images being phase-locked with respect to the pressure oscillation: *a* - stroboholographic images reconstructed from single-exposure time-averaged holograms; *b* - stroboholographic double-exposure interferogram; *c* - holographic interferogram with respect to a stationary flame; *d* - images obtained using the Mie scattering technique; *e* - shadowgrams.

As is evident from the figure 1, torroidal vortical structures are formed periodically outside the visible flame zone in the shear boundary layer at the burner outlet under the effect of acoustic oscillations. The vortices are carried away downstream by the flow and the Archimedes force, growing in size, and cause, by interacting with the flame front, the lateral surface of the flame cone to be periodically disturbed at the fundamental longitudinal frequency.

It can be readily seen that the periodicity of the sequence of the disturbances over the flame cone is defined by the frequency, ν, of the fundamental longitudinal mode of the gas moving inside the resonance pipe; the wavelength, λ, and the number of waves, n, are defined by the ratio of the average discharge velocity, υ, to the frequency and the ratio of the flame height, h, to the wavelength, λ, respectively, i.e.

$$n = \frac{h}{\lambda} = \frac{h\nu}{\upsilon} = St\,.$$

The last relation can be seen to correspond to the Strouhal number St taken with respect to the flame height rather than with respect to the burner diameter. The flame-cone-vertex phase relations will be favourable $\varphi \approx 0$ and the pressure oscillations will be intensified if an even number of half-waves fits over the flame height. If, on the contrary, an odd number of half-waves fits over the flame height, the fuel-air ratio will correspond to the silence range.

The occurrence of the concentration-related excitation and silence ranges as a function of St and the predictability of combustion stability by computing St without having to run experiments are demonstrated.

The variation in St can be estimated in terms of the formula

$$St = \frac{R \cdot c}{u \cdot l},$$

where R and l are the radius and length of the resonance pipe, respectively; c is the speed of sound; u is the normal burning velocity.

It was found that sound emission will occur at higher frequencies when the oxygen content is increased. The reason is that the flame decreases in height and long wave cannot fit over its height, which will result, due to the “self-organization”, in short-wave excitation.

It was demonstrated that combustion instabilities can be controlled by acting on the vortex formation conditions by moving a ring along the burner.

Also, the effect of the fuel mixture duct length on the conditions of the excitation of the kinetic singing flame was investigated.

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