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# Influence of a combustion-driven oscillation on global mixing in the flame from a refinery flare

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ABSTRACT

An assessment of the influence of strong combustion-driven oscillations on mixing rates and visible radiation in the flame from a full-scale refinery flare is reported. Importantly, the oscillations were generated naturally, with no external forcing, and at a high Reynolds number of $4 \times 10^6$. These conditions differentiate this study from those of previous investigations, which all involved some external forcing and were at a Re too low to ensure fully turbulent flow within the flame. A frame-by-frame analysis of video footage, providing good resolution of the instantaneous edge of each flame, was used to assess flame dimensions, and so to determine a global residence time. Since the flames are in the fast-chemistry regime, the visual imagers can be used to determine a global mixing rate. The analysis reveals a consistent picture that the combustion-driven oscillations do not result in a significant change to the global mixing rate, but do increase the visible radiation. This is in contrast to previous investigations, using externally forced jets, where forcing at the preferred mode has been found to increase mixing rates and reduce radiation.


## 1. Introduction

It is well established that acoustic excitation at, or near to, the preferred mode ($St = fd/u \approx 0.3$), will increase the size and coherence of the large-scale eddies in turbulent jets [1,2] and jet flames [3,4]. Here $f$ is the frequency of the oscillation, $d$ is the characteristic diameter of the jet and $u$ is the characteristic exit velocity of the jet, typically taken to be the bulk mean. Research of acoustic forcing has been driven by a variety of motivations, of which one has been the desire to increase rates of entrainment and mixing. It is established that acoustic forcing at the preferred mode can lead to significantly increased rates of entrainment [5]. In combustion, this can result in a significant reduction in flame length, $L_F$, and a width that is comparable with, or less than, the unforced case [6–9]. A shorter length and reduced width implies a smaller flame volume. Similarly, a range of investigations of fully-pulsed jet flames have also reported that pulsing results in a reduction of flame length. This is both for pulsing at frequencies (and hence $St$) that are orders of magnitude below the preferred mode [10], and at frequencies near to the preferred mode [7]. A decrease in flame volume implies a decrease in global residence time, $\tau_G$, [11], where $\tau_G$ is the flame volume divided by the throughput of the fuel. If it is assumed that these flames are in the fast-chemistry regime, the instantaneous reaction zone closely follows, and hence marks, the stoichiometric contour. On this basis, a reduction in flame volume implies an increase in the global mixing rate, $1/\tau_G$.

It is significant to note that all of these previous investigations have used external energy to drive the forcing, although some [7,8,12] also utilised a natural (organ pipe) resonance in the supply pipe to amplify the forcing. The amount of energy required to generate these increases in entrainment and mixing is significant. For example, Vermeulen et al. [5] found that the acoustic power required to double the entrainment of a turbulent jet is 32–72 times the power of the fluid in the unforced jet, depending on the jet diameter. This raises the question as to how important the external energy is on the result. That is, would the rates of entrainment and/or mixing would also be increased were the acoustic excitation to be derived entirely from the flow, as in a naturally-occurring combustion-driven oscillation?

The generation of a coupling between an acoustic resonance of the system (e.g. in a fuel supply pipe or combustion chamber) and the natural vortex shedding in the jet, is well known [5,13]. In some circumstances it can lead to the phenomenon of combustion-driven oscillations, which can be very strong when the fluctuating heat release from the flame matches the phase of the acoustic resonance [14]. Such occurrences are mostly undesirable, since they can lead to high levels of sound and vibration. Significantly, there are far fewer investigations of flames from these naturally-generated phenomena than those generated by externally forced ones. Indeed, no direct investigation of the effect of natural forcing on flame dimensions or mixing seems to have been reported. This is probably because the difficulty in establishing and controlling

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