Application of acoustic oscillations in flame extinction in a presence of obstacle

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Abstract. Currently, a grooving body of research devoted to the potential use of acoustic waves in suppression of different flame types can be observed. However, all works related to this issue focus on flame quenching in open environment or inside resonator tube. When concerning the use of acoustic waves in a fire/flame extinction, one may expect that the closest environment of a flame would not be free of obstacles. Thus, the present work investigates experimentally how the acoustic screen – being the simplest model of a single obstacle affects the quenching process. To do so, the sound levels required to extinguish a gas burner flame were determined for both different distances between an acoustic screen and a waveguide outlet and different fuel loads. It was found that when decreasing distance between the acoustic screen and the waveguide outlet a higher sound levels are required to suppress the flame – what is quite surprising as the sound level alone also increases when the screen approaches the waveguide outlet. The physical interpretation of this feature formulated based on the present and earlier researches is also included in the present paper.

1. Introduction

Fire is one of the most common hazards and it is often accompanied by a variety of critical situations such as: environmental degradation, material losses or losses in human lives. That is why much efforts have been undertaken worldwide aimed at improving currently available and developing new fire extinguishing methods. In turn, a number of modern and effective technologies have been developed worldwide.

Among a variety of modern fire suppression technologies a few of them are worth mentioning as they have contributed to noticeable progress in the fire-safety discipline. Particularly interesting is the approach utilising a water mist as an extinction agent [1]. It has been proved that the water fog has an excellent extinction properties when droplets are of sufficiently small size (under 60 microns) and move with the proper speed [2]. This method allows to extinguish burning petrol, gas or oil
using a water/distilled water or an aqueous solution of inorganic compounds [3,4]. When the fog is produced from the distilled water it does not remain any sediments/precipitates after evaporation. Thus, it can be applied to extinguish fire of artworks, archives, libraries, museum halls and flats. The other interesting solution is the hot aerosol fire extinction technology. The main advantage of this approach over the other available methods is that the hot aerosol fire extinguishing agents do not have to be driven out by pressurised gases and can extinguish class A, B, C, D and K fires at 30 to 200 g/m$^3$ [5]. This technology is also available in the hand-held portable version (fire extinguishing grenade) suitable for extinguishing small scale fires close to an operator. A successive progress in the field of extinction powders can be observed as a number of new substances characterised by a high adsorption properties are developed [6,7]. Also an extensive research on the so-called clean extinction agents, i.e. extinction gases which are an alternative for already decommissioned halons. According to the standard of NFPA 2001 (National Fire Protection Association) the clean extinction agents include selected halogenated hydrocarbons and inert gases [8].

It should be stressed that all already mentioned approaches are at the high technological level, however, these methods suffer due to the following drawbacks. All of them are (more or less) invasive in nature and usually cannot be applied in hard-to-get areas/places and some of them are toxic due to their chemical compositions. A promising solution for such problems could be a technology utilising the acoustic waves. Such an approach could be used as an alternative or supplement to available methods. In order to do so a fundamental knowledge about extinction properties of acoustic waves must be accessible.

The available literature offers a useful information about experimental studies of a flame behaviour under an action of acoustic waves. A number of works are focused on the response of a gaseous burner flame to acoustic field which can be generally classified as linear or non-linear depending on the excitation frequency [9–15]. The latter one may lead to unpredictable flame behaviour as wrinkling [16,17] or bifurcation [18,19]. Some authors proposed to use an acoustic field in emission reduction of unwanted combustion products as soot [20] or NOx [21,22] which are a serious problem in a number of industrial applications [23–26]. There are also works related to numerical simulations [27,28] and theoretical consideration [29] of acoustics-flame interaction process.

Much less attention is devoted to the potential use of acoustic excitation in flame extinguishing. McKinney and D. Dunn-Rankin [30] utilised acoustic oscillations in quenching of methanol droplet stream flame. Authors analysed different droplets sizes, frequencies and acoustic pressures to identify flame extinction criteria. It was found that the acoustic pressure required to extinguish the droplet stream flame grows up with increasing both droplets diameters and frequency. In the work of Beisner et al. [31] a Zippo lighter was ignited in microgravity environment and then suppressed using a single tone acoustic wave. The results showed that it is easier to quench the flame in microgravity environment than in regular gravity field and at lower frequencies. In the study of Friedman and Stoliarov [32] a systematic study aimed at elucidating how acoustic waves affect laminar diffusion line-flames was conducted. In particular, authors analysed what conditions have to be meet to suppress such a flame type. The line flames were generated with the use of fuel-laden wicks and different liquid fuels including four alkanes and JP-8. Each experimental trial was performed using the same amount of fuel poured along the centre line of the wick. The acoustic frequency was changed within the range between 30 and 50 Hz, whereas the acoustic pressure ranged from 5 to 50 Pa. It was found that it is easier to extinguish the flame at lower frequencies as the minimum acoustic pressure required to cause an extinction grows with increasing frequency. Authors also observed that with increasing acoustic pressure the average mass loss rate of the fuels also increases. More detailed analysis showed that for the minimum speaker power required to cause extinction the ratio between the modified Nusselt number and the fuel's B number remains constant regardless of the acoustic frequency applied. Bennewitz et al. [33] determined extinction criteria for single droplets of three different fuels located in the vicinity of a velocity antinode of acoustic standing wave produced inside a closed waveguide. Similarly as in the previous works it was found
that the extinction pressure increases with increasing excitation frequency. Authors observed that extinction events were associated with temporal increase in the local rate of normal flame strain as the flame moved towards the droplet surface. Niegodajew and co-workers [34] used acoustic waves in suppression process of gas burner flame. The results showed a low impact of the burner power on the acoustic extinction pressure. However, with increasing burner power a substantial growth in critical speaker power (required to suppress a flame) was observed, what was even more pronounced when the distance between a flame and an acoustic source was increased. It was also found that regardless the changes in distance between a burner and a waveguide outlet the acoustic extinction pressure remains the same. The images obtained with Schlieren apparatus showed that the extinction process is caused due to the fuel stream deflection and flame displacement from its original position caused by cumulative effect of oscillatory perturbations and acoustic mean flow. Worthy noticing is also the paper of Hardalupas and Selbach [35]. Authors investigated an impact of acoustic perturbations, of frequency between 200 and 920 Hz, imposed on the coaxial air flow of a Swirl-stabilised burner fuelled with natural gas on the lean-flammability limits. The fuel was injected in twofold way, i.e. axially and radially in the centre of the flow. Also two different burner configurations were investigated, namely with and without diffuser located at the burner outlet. The lean-flammability limits were determined by reducing the gas flow rate until the flame extinction occurred. It was found that the lean flammability limits were noticeably and slightly improved with increased amplitude of acoustic oscillations and frequency, respectively for the case with radial fuel injection and without diffuser. For the other burner configuration a minor impact of acoustic oscillations on the lean flammability limits was observed.

To summarise the literature survey, one may notice that there are only five papers [30–34] strictly related to the study of a flame extinguishing with the use of acoustic waves. In all of these works the different flame types were suppressed in the open environment or inside a resonating tube. When concerning the use of acoustic waves in a fire/flame suppression, one may expect that the closest environment of a flame would not be free of obstacles. To the best of authors’ knowledge, there is no journal paper investigating the impact of obstacles on acoustically-driven quenching process. Hence, this work is aimed at investigating how the acoustic screen – being the simplest model of a single obstacle affects the quenching process, in particular the sound level measured at the flame location.

2. Experimental setup

Figure 1 illustrates the scheme of experimental setup used in the study of flame extinction phenomenon in a vicinity of acoustic screen. The test rig consist of the following components: generator GW INSTEK SFG-2110 synthesized function generator (1), power amplifier Mosfet MDD. 2108M (2), loudspeaker SONY 1-825-378-11 (3), steel waveguide with the length of 650 mm and inner diameter of 70 mm (4), precise traversing system (5), Bunsen burner (6), sound pressure level (SPL) sensor Volcraft SL-451 (7), acoustic screen (8) and gas flowmeter (9). Presented configuration of the loudspeaker and the waveguide allows to generate the traversing (progressive) longitudinal acoustic wave interacting with the non-premixed flame produced by the burner feed with the natural gas. The burner used is just a simple tube of inner diameter of 16.8 mm. The outlet of the burner was positioned on the axis of the waveguide both horizontally and vertically at a fixed distance of $L_0=30$ mm from the waveguide end. Three different fuel loads were investigated, namely: $q_f=0.02$, $q_f=0.04$ and $q_f=0.06$ m$^3$/h. The SPL was measured at the distance $L_0$ always located at the axis of the waveguide (see Fig. 1b). The sine signal was used to produce the acoustic wave of 50 Hz frequency. It was assumed that the extinction of the flame occurred when three instantaneous and consecutive quenching events took place.

The experiment was divided into two different parts. In the first one the measurements were aimed at determining SPL needed for three consecutive extinction phenomena to occur. Two different independent variables were analysed, i.e. fuel load and distance between the acoustic screen and the waveguide outlet. The second part was devoted to study of the acoustic field between the waveguide outlet and the screen in order to support the findings from the first experiment. To do so
the burner was removed from the setup and the SPL measurements were performed for various configurations of probe and the acoustic screen. The final part of the experiment was focused on the verifying whether and if to what extent the acoustic screen influences the SPL in its closest vicinity.

![Scheme of the experimental setup](image1.png)

**Figure 1.** Scheme of the experimental setup (a) and position of the outlet of the burner, the pressure sensor and the screen (b) with respect to the outlet of the waveguide

3. Experimental results
The first stage of the study was aimed at determining the sound pressure level (ESPL) required to cause three extinction events for varying wall distance \( L_S \) and different fuel loads. Measuring probe was inserted in place of the flame immediately after three extinction events occurred, so that \( L_P = L_B \). Results from this part are shown in Fig. 2. As can be clearly seen, the farther the acoustic screen is, the lower ESPL is needed for the extinction phenomena to occur. This dependence was measured for three different fuel loads to check its influence on the extinction. It is obvious that with the increase in fuel load, the ESPL must be higher also. As demonstrated all three measured curves are similar in character, the differences between highest and lowest ESPL are also similar, i.e. 8.4, 8.6 and 8.4 dB for \( q_1 \), \( q_2 \) and \( q_3 \) respectively. One may also observe that when exceeding a certain value of \( L_S \) (about 150 mm) the ESPL values reach constant levels.

The second part of the study was carried out to support previous findings and clarify the specific effect of acoustic screen on SPL. For this stage of experiment, the Bunsen burner was removed and SPL distribution was measured for different configurations of acoustic screen and measuring probe.

![Extinction sound pressure level](image2.png)

**Figure 2.** Extinction sound pressure level (ESPL) needed for three consecutive extinction phenomena to occur as a function of acoustic screen distance \( L_S \) for different fuel loads.
First, the dependence between $SPL$ near the tube outlet (at the previous location of the burner) and the distance of the acoustic screen (see Fig. 3) was determined. Measurements were performed in two independent runs (denoted as run 1 and run 2 in Fig. 3). For each run the power applied to the loudspeaker was fixed at a constant value and the screen location was changed.

The data clearly show, that the largest range of $SPL$ variation lies in the limit of 150 mm for acoustic screen distance $L_S$. Above this value one may observe strong flattening of the dependence and therefore only small changes in the $SPL$ value. Such relationship is observed independently from the power applied to the loudspeaker i.e. both curves presented in Fig. 3 have identical shapes. One may also speculate about the influence of used frequency on the appearance of a standing wave or on changing conditions due to interference effects between the generated and reflected (from the screen) waves. However, due to the used frequency of 50 Hz, the length of acoustic wave in the air is $\lambda \approx 6.8$ m and hence only one kind of interference may occur, which remains irrelevant for studied screen distances. In summary, the result is that above the distance of 150 mm, the screen has an insignificant impact on the $SPL$ at the probe location. Moreover, this support the findings from Fig. 2 where a similar dependence was observed.

![Figure 3](image)

**Figure 3.** Sound pressure level as a function of screen distance for two different starting $SPL$.

Next, to determine the effect of close proximity of the screen to the probe (and the burner) in isolation from the screen-tube distance, the dependence of $SPL$ as a function of probe distance was measured for two cases: when the probe location was varied along with the acoustic screen and without the screen for direct comparison (see Fig. 4).

![Figure 4](image)

**Figure 4.** Sound pressure level as a function of probe distance form tube outlet for two cases: when the screen was placed as close as possible to the probe (12 mm), and without screen.
By the analysis of Fig. 4 a clear picture of the impact of close vicinity between the screen and the probe emerges. Only one effect caused by the acoustic screen is observed, namely an increase in the SPL in the whole measuring range. Moreover, this increase remains constant independently from the distance between the tube’s outlet and the screen, what can be seen by comparing both curves.

Even more information can be acquired when changing the probe location between the waveguide outlet and the screen. Figure 5 illustrates changes in SPL with varying \( L_P \) for three different screen positions (100, 150 and 200 mm). When bringing the probe closer to the acoustic screen its impact becomes more evident. It is manifested by convergence of all three distributions when reducing probe distance. This means that in the close vicinity to the tube’s outlet the impact of the screen (if it is located sufficiently far) on SPL is of secondary importance. When analysing SPL distribution for case when \( L_S=100 \) mm and for \( L_P=20 \) mm a slight increase (about 0.2 dB) in SPL with respect to the other distributions. This suggests that the smallest analysed \( L_S \) lies very close to the critical distance above which the influence of the screen is negligible.

![Figure 5. Sound pressure level as a function of probe distance from tube outlet when the screen was fixed at \( L_S=100 \) mm, \( L_S=150 \) mm and \( L_S=200 \) mm.](image)

It should be stressed that the quenching process depends not only on the acoustic oscillations but also on the mean flow effect as it was elucidated in [34]. As it is also known, the normal velocity component decreases when the flow approaches the wall [36]. Therefore one may expect that when placing the wall just behind the flame will reduce the impact of the mean flow due to change in the momentum transport direction. Hence, the conclusion is that the mean flow for the given configuration and analysed parameters ranges has a dominative character on the quenching process. It is also manifested by increase in measured SPL at the flame position (due to the presence of the screen), which is still insufficient to suppress the flame.

4. Conclusions
The main conclusion resulting from the present study is that immediate surroundings has substantial impact on the ability to quench fire when utilising acoustic oscillations. If near a fire source (i.e. directly behind it) there is an object, flame extinguishing will be much more difficult, although the sound pressure in this area will increase. Moreover, the closer the object to the flame is, the higher acoustic pressure is required to cause an extinction event. This means that the increase in SPL itself is not sufficient to suppress the flame.

Based on present results supported by previous observations it was concluded that mean flow effect has significant impact on the extinction process next to the acoustic oscillations.

Obtained results allowed to determine the distance at which the impact of the screen on the flame quenching diminishes. This finding allowed to conclude that this distance is the same regardless the adopted fuel loads.
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