EXPERIMENTAL RESEARCH OF ACOUSTIC-BASED FLAME SUPPRESSION FOR SPACE APPLICATION

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Fire suppression technology is a critical part of the strategy of spacecraft fire safety, which is introduced to satisfy the security of the crew and mission integrity. Several methods have been shown applicable in space missions. A water gun was designated for the secondary purpose of an emergency fire extinguisher in the Mercury and Gemini spacecraft. The Apollo spacecraft had extinguishers that generated a stable water-gas mixture propelled by inert Freon and nitrogen gases. Furthermore, extinguisher based on gaseous Halon 1301 and carbon dioxide was also used in space mission. However, the above-mentioned method may cause the emissions of unwanted materials which may affect the operation of electronic equipment as well as other payloads. Using the acoustic-based flame suppression mechanics, such problem can be solved. This paper concentrates on the underground experimental research on the acoustic flame suppression mechanics. Specifically, comprehensive introduction of underground acoustic flame suppression system is presented. The second part of this paper tackles parametric discussion of acoustic frequency and sound velocity on the homogeneous flame using orthogonal experimental method.

Keywords: Flame suppression, space application, low-frequency acoustics, underground experiment.

1. Introduction

With the exploration of outer space, the space program has wrestled with fire-fighting techniques. From Apollo 1 disaster to the more recent destruction of the space shuttle Columbia, controls of heat and combustion have been a primary concern. Despite extensive research, no new methods turn out for extinguishing or manipulating fire in almost 50 years. A water gun was designated for the secondary purpose of an emergency fire extinguisher in the Mercury and Gemini spacecraft. The Apollo spacecraft had extinguishers that generated a stable water-gas mixture propelled by inert Freon and nitrogen gases. Furthermore, extinguishers based on gaseous Halon 1301 and carbon dioxide were also used in space mission[1].Traditional fire-suppression technologies focus largely on disrupting the chemical reactions involved in combustion. Of the methods that do exist there are three widely accepted extinguishers: water-foam, carbon dioxide and Halons. While water primarily cools a flame, carbon dioxide suffocates it by diluting the surrounding oxygen. Halons work to disrupt the combustion process. These technologies suffer from limitations such as collateral damage to valuable property, environmental toxicity and limited effectiveness in different types of fire. DARPA theorises flames by using physics techniques rather than combustion chemistry, showing that it might be possible to control flames by electromagnetic and acoustic waves which will interact with the plasma in a flame.

The ideal of fire being affected by sound was discovered as far back as 1857 by John Tyndall. The phenomenon of sound interacting with flames exists in the study of combustion instabilities in aircraft engines[2, 3] and rocket propellant[4], flame manipulation[5], enhancement[6, 7] and extinction[8]. DARPA conducted its "Instant File Suppression" program to help extinguish fires in small spaces since 2008 after a shipboard fire on the USS George Washington which burned for 12 hours and caused an estimated $70 million in damage[9]. Through research, DARPA declares that two dynamics are at play in the acoustic fire suppression. Firstly, the increasing air velocity due to the acoustic field makes the flame boundary layer thin, leading it easier to disrupt the flame. Secondly, the acoustic field leads to higher fuel vaporization by disturbing the flame front, which widens the flame, but also drops the overall flame temperature. As a result, combustion is disrupted as the same amount of heat is spread over a large area. Through numerical experiments, DARPA found that the local air velocity imparted at the flame body is the dominant factor in the extinction of the flames. A threshold acoustic velocity (acoustic velocity at which extinction occurs) must applied to the flame in order to achieve extinction, rather than a specific frequency or acoustic pressure[10].

In 2005, Plarks found that there was one optimal frequency for maximizing the effects of sound waves on a flame through zero-g experiment in NASA C-9B aircraft under the Reduced Gravity Student Flight Opportunities Program. Specifically, experiments in one-g revealed that frequencies from 15Hz to 55Hz were most effective for extinguishing the candle[11]. In 2015, Tran and Robertson explored the impact of different frequencies of sound on small fires and found that sound with frequencies between 30-60Hz produced desired extinguishing effect[12]. Using Arduino-based sensor system, Beisner, et al. [13] analysed acoustic flame suppression in both normal(1g) and microgravity environments, showing that the suppression is more effective in the microgravity condition. Experiments suggest that there exists optimal surface interactions at two frequencies with methane gas , one low frequency at 30.6Hzand another higher frequency about 74Hz which is different from experiments of DARPA and Plaks, et al. [11] with 90Hz.

From the above mentioned research, present paper concentrates on the effects of acoustic frequency and amplitude on flames using orthogonal experimental method. Specifically, section 2 introduces experimental apparatus used in this paper. While section 3 gives detailed analysis of acoustic flame suppression, section 4 concludes this paper.

2. Apparatus setup

As present paper deals with the effect of acoustic frequency and amplitude on the acoustic fire suppression, experimental apparatus is composed of signal generator with adjustable frequency, adjustable power amplifier, horn and focusing waveguide as shown in Fig. 1.

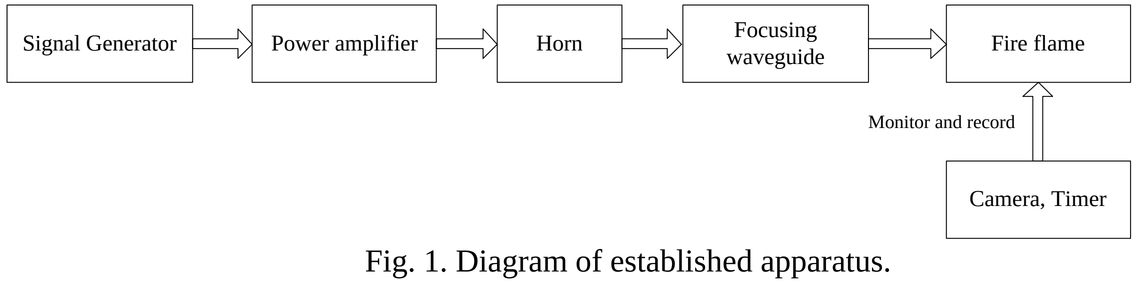

Fig. 1. Diagram of established apparatus.

Specifically, the signal generator provides a sine wave signal whose frequency can be changed freely. In the experiment, the signal generator is RS-800D made by Zefengsheng company in China as shown in Fig. 2. The produced signal is amplified by CE-1000 made by Spirit in China as shown in Fig. 2. The amplified electrical signal is transformed to mechanical acoustic wave through a horn as shown in Fig. 3. The acoustic signal is regulated in the cylindrical-conical waveguide to be focused as shown in Fig. 3. During the experiment, a camera is used to record the flame shape, meanwhile the time that the flame is extinguished is recorded for each excited frequency and amplifier.

Fig. 2. Signal generator and power amplifier. Left: signal generator. Right: power amplifier

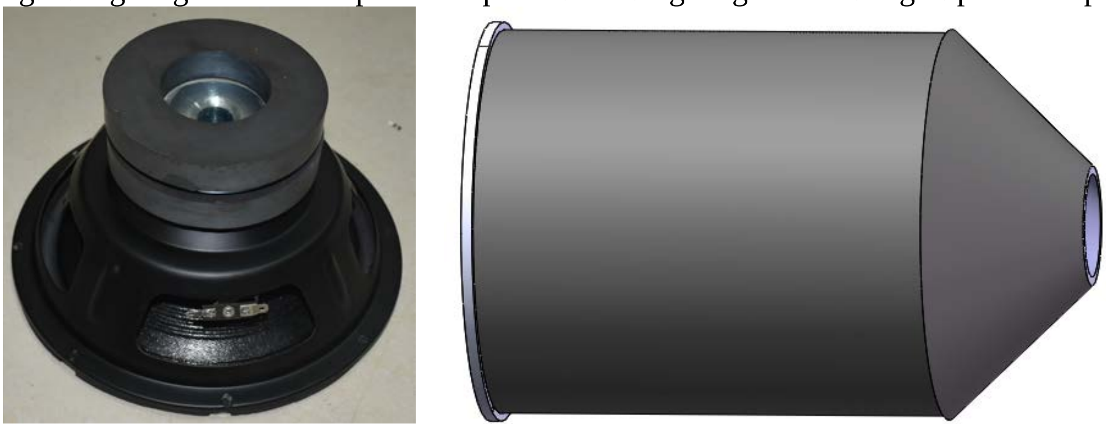

Fig. 3. Horn and focusing waveguide. Left: horn. Right: focusing waveguide

Fig. 4 shows the established experimental environment in the laboratory. Specifically, the alcohol fire is placed in a pan near the waveguide. The camera is used to record the experimental process. Fig. 5 shows the experimental records in the laboratory. In this experiment, the alcohol flame is imposed by the acoustic wave whose frequency and amplifier can be regulated by signal generator and power amplifier. Without acoustic interaction, the fire can keep the flame shape. In the presence of acoustic wave, the flame shape changes and becomes extinct in the end.

Fig. 4. The established experimental environment

During the experiment, the authors noticed that alcoholic fire cannot always suppressed by acoustic wave with any frequency even the amplifier is large. In the following experiment, the authors concentrate on the parametric analysis using orthogonal experimental method.

Fig. 5. Experimental test. Left: the fire flame before the acoustic suppression. Right: fire extinction after the acoustic suppression.

3. Experimental analysis

In the experiment, the effects of acoustic frequency and sound velocity on the acoustic fire with different shape size. Specifically, the acoustic frequencies used in the experiment are 25Hz, 30Hz, and 35Hz. During the experiment, the authors noticed that the alcohol fire cannot slake if the acoustic frequency is above 100Hz. As the selected horn cannot work properly under the low-frequency excitation (below 20Hz), the low-frequency experiment is not tackled. Furthermore, the output power of signal amplifier is selected to 1040W, 1560W, and 2080W. The flame area of fire to be put off is chosen to be 0.01cm^2, 0.03cm^2, 0.07cm^2. Table 1 represent s the experiment results under different parametric condition. It can be learned that under these frequencies, the fire can be suppressed with different time.

Table 1. Fire extinction and time under different parametric condition

Experimental number	Parameters			Extinction.	Extinction time(s)
	A	B	C		
1	25	1040	0.01	Yes	8.22
2	25	1560	0.03	Yes	8.30
3	25	2080	0.07	Yes	30.76
4	30	1040	0.07	Yes	25.94
5	30	1560	0.01	Yes	3.66
6	30	2080	0.03	Yes	5.42
7	35	1040	0.03	Yes	7.59
8	35	1560	0.07	Yes	21.17
9	35	2080	0.01	Yes	3.98

As shown in table 1, it is hard to distinguish the principle factor which affects the fire suppression. Luckily, the authors present the orthogonal experimental method to analyse different factors as shown in table 2.

According to orthogonal experimental method, the effect of parameters can be calculated by

$$K_1(A) = 8.22 + 8.3 + 30.76 = 47.28, k_1(A) = K_1(A)/3 = 15.76,$$

$$K_2(A) = 25.94 + 3.66 + 5.42 = 35.02, k_2(A) = K_2(A)/3 = 11.67,$$

$$K_3(A) = 7.59 + 21.17 + 3.98 = 32.74, k_3(A) = K_3(A)/3 = 10.91,$$

$$K_1(B) = 8.22 + 25.94 + 7.59 = 41.75, k_1(B) = K_1(B)/3 = 13.92,$$

$$K_2(B) = 8.30 + 3.66 + 21.17 = 33.13, k_2(B) = K_2(B)/3 = 11.04,$$

$$K_3(B) = 30.76 + 5.42 + 3.98 = 40.16, k_3(B) = K_2(B)/3 = 13.38,$$
$$K_1(C) = 8.22 + 3.66 + 3.98 = 15.86, k_1(C) = K_1(C)/3 = 5.29,$$
$$K_2(C) = 8.30 + 5.42 + 7.59 = 21.31, k_2(C) = K_2(C)/3 = 7.10,$$
$$K_2(C) = 30.76 + 25.94 + 21.17 = 77.87, k_2(C) = K_2(C)/3 = 25.96.$$

Table 2. Parametric analysis using orthogonal method

Orthogonal parametric	Parameters		
	A	B	C
K_1	47.28	41.75	15.86
K_2	35.02	33.13	21.31
K_3	32.74	40.16	77.87
k_1	15.76	13.92	5.29
k_2	11.67	11.04	7.10
k_3	10.91	13.39	25.96
The range	4.86	2.35	20.67
The primary order	$C > A > B$		
Optimal level	A_3	B_2	C_1
Optimal combination	$A_3B_2C_1$		

From table 2, it can be learned that the effect of flame area on acoustic suppression is the most important than the other two factors, while the second one is acoustic frequency and the acoustic velocity shows the third. This result shows that the acoustic frequency plays a more important role than the acoustic velocity. From the optimal level, it can be indicated that with the increase of acoustic frequency, the performance of fire suppression is better. In the case of smaller flame area, the time of fire suppression is shorter. However, the effect of acoustic velocity on fire suppression is complex.

4. Conclusion

Present paper concentrates on the experimental analysis of acoustic fire suppression in the underground for space application. To comprehensively analyse different factors (acoustic frequency, acoustic velocity and fire area) on the acoustic fire suppression, an experimental apparatus is established. Parametric tests are given based on different acoustic frequency, signal amplifier and fire area. The experimental data is analysed through orthogonal experimental method. Results show that the acoustic frequency on fire suppression is more dominant than the acoustic velocity. The work described in this paper is funded by the National Natural Science Foundation of China(No. 11404405, 11504427, 61601489, and 51675525), the Major Program of National Natural Science Foundation of China (No. 61690210 and 61690213) and by the National Innovation Training Project of Undergraduate Student(No. 20169002001). The authors gratefully acknowledge the funding.

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