# Flame Quenching Performance of Ceramic Foam

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#### Introduction

In industries where flammable mixtures are present flame arresters are used to prevent flame propagation in the event of ignition. Different types of materials are used in flame arresting devices [1]. For example, wire gauze and sintered metal is commonly used in commercial flame arresters. Ceramic "foam" is typically used for gas filters or flame holders but also represents a novel material that can be used for flame arrester applications. The interconnectivity of the foam pores form a matrix of tortuous narrow passageways that the flame is forced to pass through, where flame extinction can occur. There is no flame quenching data for ceramic foams in the literature. Flame arrester design is typically based on the critical quenching diameter theory that considers the conduction of heat from the flame reaction zone to the confining channel walls. Zeldovich [2] showed that for a laminar planar flame the critical quenching condition corresponds to a critical Peclet number, defined as  $Pe_{cr} = S_u d_{cr} / \alpha$  where  $S_u$  is the burning velocity,  $d_{cr}$  is the critical quenching diameter and  $\alpha$  is the thermal diffusivity of the unburned gas. This basic thermal theory indicates that flame quenching occurs when the channel width is of the same size as the flame thickness. Spalding showed that this theoretical limit for a circular duct is given by a critical Peclet number of 60.5 [3]. By analyzing existing channel quenching data in the literature Rozlovskii and Zakaznov [4] showed that for the limit mixtures the Peclet number is roughly 65 with a large scatter in the results. The objective of this paper is to present experimental data on the flame quenching effectiveness of ceramic alumina foam with different pore densities. The quenching performance of the foam based arrester is compared to that of arresters consisting of a packed bed of ceramic spheres and a plate with circular channels.

#### **Experimental Setup**

The flame quenching tests were performed in a vertical tube assembly similar to the apparatus used by Coward and Jones [5] for measuring flammability limits. The tube assembly consists of two 90 cm long sections of 5 cm inner-diameter transparent Plexiglas tubes. The ceramic foam is sandwiched between the two tube sections inside of a larger diameter sleeve. The flame is initiated via an electric spark discharge across a pair of electrodes located 2.5 cm above the bottom edge of the lower tube. For the quenching experiments a standard automotive 12 volt DC induction coil ignition system is used to produce the spark. For the less sensitive mixtures near the flammability limit the spark is produced by the discharge of a 0.5  $\mu$ f capacitor charged to 5 kV. The test mixture is prepared by the method of partial pressures in a separate mixing chamber equipped with a pneumatic driven impeller. The fuel-oxidizer is thoroughly mixed by the impeller before transferring the mixture into the pre-evacuated Plexiglas tube assembly which is temporarily closed on both ends by rubber plugs. Just before ignition the bottom plug is removed and the pressure inside the tube is allowed to equilibrate with the atmosphere. The

interaction of the flame and the arrester is recorded using a standard digital video camera recording at 30 frames per second. For each arrester both the lean and rich quenching composition limits are obtained for mixtures of methane-oxygen.



Figure 1. Foam internal structure

The ceramic foams tested are 10, 20 and 30 pores per inch (PPI) manufacturer rated foams. The foam insert is 10 cm in diameter and 5 cm in height. Additional tests were performed with different arresters of similar gross size as the foam. They include an insert consisting of a packed bed of 3.2 mm diameter alumina spheres and an aluminum plate with channels made by drilling the plate with standard size drill bits. The channel diameters tested are 1.32 mm and 2.18 mm. The flame quenching is reported in terms of the lean and rich mixture composition where quenching occurs. The quenching material is characterized by the flow path size. For the drilled aluminum plates the flow path size is taken to be the channel diameter. For the packed spheres and ceramic foam an effective channel diameter is defined based on the flow path dimensions. For the spheres the effective diameter is taken to be 0.3 times the sphere diameter [6]. A photograph provided in Fig. 1 show that the basic structure of the foam material is a three-dimensional matrix of pores interconnected by holes distributed over the pore wall. The flame thus propagates from one pore to the next through a series of small holes in the pore wall, designated as a pore window in Fig. 1. The effective channel diameter is taken to be the average pore window size.

#### **Results and Discussion**

A preliminary series of experiments was performed without the flame arrester in place in order to measure the flammability limits. These limits are used as reference for the flame quenching experiments as well as for checking the equipment operation. For these tests the higher energy ignition system was used in order to get the widest possible flammability limits. The mixture sensitivity was varied by changing the mixture composition and flammability was determined based on the propagation of the flame over the entire length of the tube assembly. The measured flammability limits were found to be in good agreement with data in the literature. The flammability limits for methane-air were found to be 5.5% and 14% methane by volume compared to 5.4% and 14.3% found by Coward and Jones [5]. And the flammability limits for

methane-oxygen were found to be 6.0% and 61.3% methane by volume compared to 5.15% and 60.5% found by Coward and Jones [5].

Experiments were then performed with the ceramic foam in place. High-speed video taken at 4000 frames per second shows that for more reactive mixtures the flame propagation is very unsteady, propagating in a pulsating manner. This is caused by the coupling of the reaction rate and the axial acoustic pressure oscillations within the tube. In tests performed with methane-air mixtures flame quenching was only observed for the 10 PPI foam. For this particular foam, mixtures within the composition range of 7.5% and 10.5% methane resulted in flame transmission through the foam. For methane-oxygen mixtures flame quenching limit data was obtained for all three foam porosities, see Table 1 for a summary of the results. The effective channel diameter is provided in the table for the different quenching material. Recall for the foam the effective diameter is taken to be the average pore window size. Window size measurements were made for each foam, the average value and standard deviation is provided in Table 1. The ceramic foams with greater pore densities, corresponding to a smaller pore and window size, result in the narrowest quenching limits and thus are considered to have a superior flame quenching performance. The 30 PPI foam was able to quench the most reactive mixtures compared to the other foams, i.e., 8.5% to 46.5% methane, a stoichiometric mixture is 33% methane in oxygen. The quenching limit data obtained for the packed spheres and the aluminum plates are also provided in Table 1. The quenching limit data provided in Table 1 is plotted in Fig. 2 in terms of the effective channel diameter versus methane mole fraction. The error bars shown with the foam data points corresponds to the standard deviation in the pore window size measurements. The data is limited to mixtures away from stoichiometric conditions due to the limited strength of the Plexiglas tube. Also provided in Fig. 2 is the quenching data obtained by Harris et al. [7] using the flash back technique in a circular tube, and Blanc et al. [8] based on flame kernel quenching between flanged electrodes. The data from the present study follows closely the trend for the Blanc et al. data. The quenching data obtained for the porous material, which includes the foam and spheres, overlap the data obtained for the drilled aluminum plate for fuel rich mixtures. This finding indicates that the flow path effective channel dimension is the governing parameter and the quenching phenomenon is independent of the details of the flow path through the porous media. For the lean mixtures the aluminum plate appears to perform slightly better than the porous material since more reactive mixtures can be quenched for the same effective channel diameter.

The foam is a three-dimensional matrix of pores interconnected by holes distributed over the pore wall through which the flame propagates from one pore to the next. Quenching can occur as the flame passes through the pore window. The flame thickness is generally smaller than the channel length, i.e., pore window depth, which for the foams tested is in the range of 0.6 to 1.2 mm. Heat loss from the reaction zone to the ceramic can potentially lead to flame quenching. After the flame propagates through the short channel it propagates through the adjacent pore. This process can result in a high degree of flame curvature causing flame stretching that can lead to flame quenching. Therefore there are two quenching mechanisms, the thermal mechanism or the flame stretch mechanism. In experiments performed with a closely packed bed of spheres, of different material, diMare et al [6] found that the material of the spheres did not have an effect on the quenching limit. Therefore, they hypothesized that the key mechanism for flame quenching was flame stretch not thermal effects.



Figure 2: Quenching distance for methane-oxygen mixtures

The Peclet number for the quenching limit mixtures, based on the effective channel diameter reported in Table 1, is plotted as a function of the methane mole fraction in Fig. 3. The limit mixture thermal diffusivity and laminar burning velocity are obtained by the chemical reaction program Cantera [9]. There is a large disparity between the measured quenching limit Peclet numbers and the theoretical value of 60.5 predicted by the thermal quenching theory. However, this large deviation of + 65% and - 45% of the theoretical value is well within the data spread found in the literature [4]. In general the lean quenching limit data lies below the critical thermal theory Peclet number of 60.5 and is concentrated around a value of 20. The rich quenching limit data lies above the critical Peclet number and is more scattered than the lean limit data.



Figure 3: Calculated Peclet Number for the quenching limit mixtures

Clearly the deviation of the flame quenching data from the one-dimensional laminar flame theory prediction for the aluminum plate with straight circular channels indicates even for this simplest flow path flame dynamic effects are important. For example, at the limits as the flame propagates in the channel heat loss to the walls causes the flame front to take on a parabolic shape, convex towards the fresh mixture. Since methane is a much lighter gas than oxygen, preferential diffusion effects can amplify the distortion leading to curvature and flame stretch effects that can cause flame quenching [10]. This flame dynamic mechanism is even more prominent for the foam and sphere arresters where strong velocity gradients in the unburned gas can exist due to the tortuous flow path. To isolate this factor a limited number of experiments were performed with ethylene-oxygen mixtures to measure the quenching limits in the same drilled aluminum plates. Since the molecular weight of ethylene is close to that of oxygen the flame in this mixture is considered to be more stable in terms of preferential diffusion compared to flames in methane-oxygen mixtures.

Flame Arrester	Mixture	Pore Size (mm)	Effective channel diameter (mm)	Lean Limit	Peclet Number	Rich Limit	Peclet Number
10 PPI foam	CH <sub>4</sub> -O <sub>2</sub>	4.8	2.4±0.4	6.5	16	50.5	117
20 PPI foam	CH <sub>4</sub> -O <sub>2</sub>	3.3	1.4±0.3	7.5	18	48.5	92
30 PPI foam	CH <sub>4</sub> -O <sub>2</sub>	1.7	0.9±0.2	8.5	18	46.5	76
Spheres	CH <sub>4</sub> -O <sub>2</sub>	-	0.95	9.0	23	45.5	90
Plate w/holes	CH <sub>4</sub> -O <sub>2</sub>	-	1.32	9.5	38	47.5	99
Plate w/holes	CH <sub>4</sub> -O <sub>2</sub>	-	2.18	7.5	28	49.5	124
Plate w/holes	$C_2H_4-O_2$	_	1.32	5.5	54	55.5	170
Plate w/holes	$C_2H_4-O_2$	_	2.18	4.5	49	50	218

 Table 1: Measured quenching limits for methane-oxygen mixtures

The flame quenching limit data obtained with ethylene-oxygen is summarized in Table 1. The lean limit data for the two ethylene-oxygen mixtures tested lie closer to the thermal theory critical Peclet number of 60.5 compared to the methane-oxygen data obtained in the same arrester. This trend in the data is supported by the preferential diffusion mechanism due to the expected negligible affect for the ethylene-oxygen mixture. However, the rich quenching limit for the two ethylene-oxygen mixtures lie substantially above the methane data and thus the improved agreement with the thermal theory postulated for the lean limit mixtures is fortuitous. That is, it is the result of a general upward shift in the quenching limit Peclet number for the ethylene mixtures.

## Conclusions

This study has shown that the quenching performance of ceramic foam is less effective than a packed bed of spheres with the same effective flow path and circular channels with an equivalent diameter machined into a metal plate. The results also indicate that the quenching phenomenon cannot be explained solely based on thermal effects. Other possible effects include flame stretch and preferential diffusion.

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