Effect of Scale on the Onset of Detonations

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Abstract

Critical conditions for onset of detonations are compared at (1) two significantly different scales, (2) for a range of H_2-air mixtures diluted with CO_2, H_2O, and (3) for two types of geometry - long obstructed channel and room with relatively small aspect ratios. For the range of scales, mixtures, and initial conditions tested, the detonation cell size λ was shown to be a reliable scaling parameter for characterization of detonation onset conditions. A correlation is suggested for detonation onset conditions, which is applicable for a range of scales, mixtures, and geometrical configurations.

Introduction

Studies of the final phase of DDT - *the onset of detonations* - may be useful to gain data on limiting conditions for DDT. These conditions have been investigated in a number of experimental studies. One of their important findings is that the geometrical scale effects significantly the possibility of DDT. The larger is the scale, the less sensitive mixture is able to undergo DDT. A number of criteria have been developed which describe the effect of scale on the onset of detonations. They are based on detonation cell size λ as a chemical length scale or measure of mixture sensitivity. The cell size cannot be considered as a universal scaling or fundamental parameter characterizing mixture properties. Consequently, questions remain on the possibility of application of the cell size as a scaling parameter for detonation onset criteria over wide range of scales and in different mixtures under different initial conditions. The valuable answers should be obtained over a representative range of geometrical scales for practical applications

Objective of the present study is comparison of critical conditions for onset of detonations and details of the process (1) at two significantly different scales and similar geometry (scaling factor is 50), (2) for a range of H_2-air mixtures diluted with CO_2, H_2O at large scale, and (3) for two types of geometry - long obstructed channel and room with relatively small aspect ratios.

Experimental

At large scale, tests were made in RUT facility [1, 2]. Onset of detonations was studied in obstructed channel of the facility and in the room. Channel dimensions were 34x2.2x2.5 m. Different obstacle configurations were used with blockage ratio BR = 0.3, 0.6, and with no obstacles. Room sizes were 10.5x6x2.5 m. Tests were made with hydrogen-air (at 285K), hydrogen-air-steam (375K), and hydrogen-air-carbon dioxide (285K).

At small scale tests were made in MINIRUT experimental apparatus [3], which was similar to the RUT at 1:50 scale. Channel dimensions were 0.657x0.05x0.045 m plus additional flame acceleration section to ensure formation of choked flames. Room sizes were 0.201x0.125x0.05 m. Tests were made with hydrogen-air and $2H_2+O_2+\beta N_2$ mixtures at 293K initial temperature and normal initial pressure. High speed shadow photography was used in to resolve details of DDT processes.

Since main attention the study was focused on the *onset of detonations*, the development of sufficiently fast sonic or choked flames prior to DDT was considered as the necessary initial condition.

Results

Comparison of the critical conditions for the onset of detonations at large scale showed that critical compositions in obstructed channel or room are characterized by similar values of λ for a wide range of compositions and initial conditions. In the channel, critical cell sizes were λ = 0.7-0.9 m for H_2-air-CO_2 at 285K and $\lambda \approx$ 0.9 m for H_2-air-H_2O at 375K (see Fig. 1). In the room critical cell sizes were λ = 0.9-1.2 m for H_2-air-

CO_2 at 285K, $\lambda \approx 1.2$ m for H_2-air-H_2O at 375K (see Fig. 1), and $\lambda \approx 1$ m for H_2-air at 285K. Comparison of the critical conditions at two different scales showed that the ratios of the critical values of λ are indeed very close to the ratio of length scales (Table 1). Thus, for the range of scales, mixtures, and initial conditions tested, the detonation cell size was shown to be a reliable scaling parameter for characterization of detonation onset conditions. It is important to notice that this was shown in direct experiments without reference to any model or criteria for DDT.

Table 1. Critical values of detonation cell sizes for onset of detonations.

	RUT	MINIRUT (scale 1:50)	$\lambda_{RUT}/\lambda_{MINIRUT}$
	λ, mm		
Channel	900	18	50
Room	1200	21-25	48-57

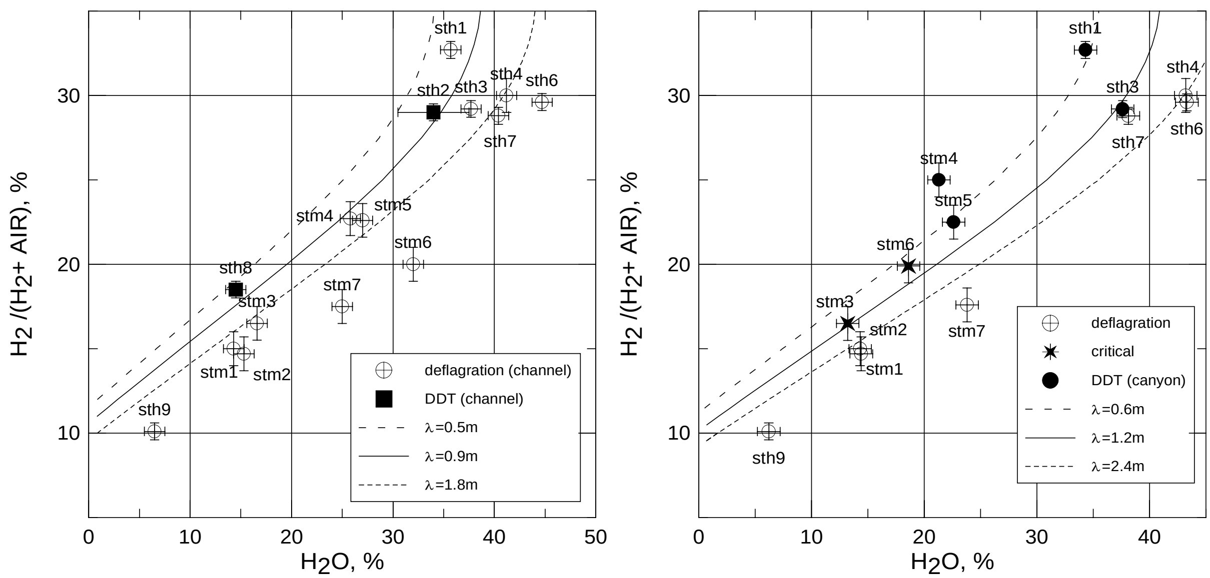

Figure 1. Detonation onset conditions for H_2-air-H_2O mixtures in obstructed channel (left) and room (right)

Correlations for onset of detonations

Available DDT criteria are based on comparison of *characteristic geometrical sizes* with chemical length scale of the mixture λ. Definition of characteristic geometrical sizes of an enclosure is necessary for formulation of necessary criteria for DDT. This size should be large enough compared to λ to make possible onset of detonations. One of DDT criteria [4-6] requires the minimum size of unobstructed passage in channel with obstacles $d > \lambda$ for onset of detonations. A different approach was also suggested, which requires the minimum distance L for detonation formation [1]. The size L should give a measure of possible macroscopic size of sensitized mixture where detonations might originate and develop. Originally, such a criterion was formulated as $L > 7\lambda$, where L was defined as a characteristic size of a room filled with combustible mixture (or size of a mixture cloud). Despite of a general agreement of $L > 7\lambda$ criterion with experimental data, definitions for characteristic size L used were not always quite clear, especially for practical applications. It was shown, that good correlations were observed for rooms (or mixture clouds), where the size L could be easily defined as a sort of average of corresponding geometrical sizes. An appropriate and clear definition of L for chains of connected rooms (or tubes with obstacles) was not derived. A large experimental data base on DDT conditions in obstructed channels and rooms give a basis to derive an appropriate L/λ-correlation which should address a range of geometrical configurations.

As a starting point, one can consider the channel with obstacle as a chain of connected rooms. It may be suggested that characteristic size L_1 for a single room is the average size from two maximum room sizes (H and S). Such a definition showed a good correlation in earlier analyses. Thus, for single room we assume:

$$L_1 = (S + H)/2. \qquad (1)$$

If a room 1 is connected with another room 2 through some opening, the characteristic size L of the system of rooms 1 and 2 can be defined as:

$$L = L_1 + \alpha L_2, \quad (2)$$

where L_1 and L_2 are characteristic sizes of room 1 and 2, α - is a parameter which describes the size of the opening between rooms. For long channels with repeating obstacles one should obtain instead of (2):

$$L = L_1 + \alpha L. \quad (3)$$

Thus characteristic size for the channel with obstacles appeared to be given by:

$$L = L_1/(1-\alpha). \quad (4)$$

Comparison with experimental data for DDT in channels and tubes was made assuming different definitions for α, namely, $\alpha = (d/D)^{1/2}$, $\alpha = d/D$, and $\alpha = (d/D)^2$, where d is unobstructed passage, and D is tube diameter (or channel height D = H). It was found out that the best correlation was observed for $\alpha = d/D$. Such a definition (Eqs. 1-4) for characteristic size L is qualitatively in accord with observations that detonation onset is facilitated in obstructed channels with increase of d/D (decrease of blockage ratio) and with increase of obstacle spacing. The critical ratio L/λ for DDT appeared to be nearly constant for different configurations of obstacles.

It should be noted that the definition for L (Eq. 4) has a singularity for $\alpha = 1$. It can be easily avoided by limiting the range of application of Eq. 4 to the cases with large enough values of blockage ratios BR, e. g., BR > 0.1. In cases BR ≤ 0.1, the system of connected rooms can be considered as a single room with L defined by Eq. 1.

Experimental data on DDT conditions were collected for a wide range of fuel-air mixtures, scales and geometrical configurations. A brief description of data is given in Table 2. L/λ-correlation for these data is presented in Fig. 2. A good agreement is observed for $L/\lambda \approx 7$ as the necessary condition for DDT within the accuracy of the cell size data over a wide range of scales. The minimum ratio of $L/\lambda = 5.6$ for few cases of DDT can be found among the general borderline of $L/\lambda \approx 7$ in Fig. 2. This is just 20% deviation which is much smaller than inaccuracy of the cell size data, which is about a factor of 2.

The data presented in Fig. 2 show that quite good L/λ-correlation is obtained for a variety of different geometrical configurations. This correlation can be used as necessary criterion for onset of detonations in practical applications (within the range of mixtures, initial conditions and scales used in this correlation). The accuracy of corresponding estimates is limited by the accuracy of the cell size data.

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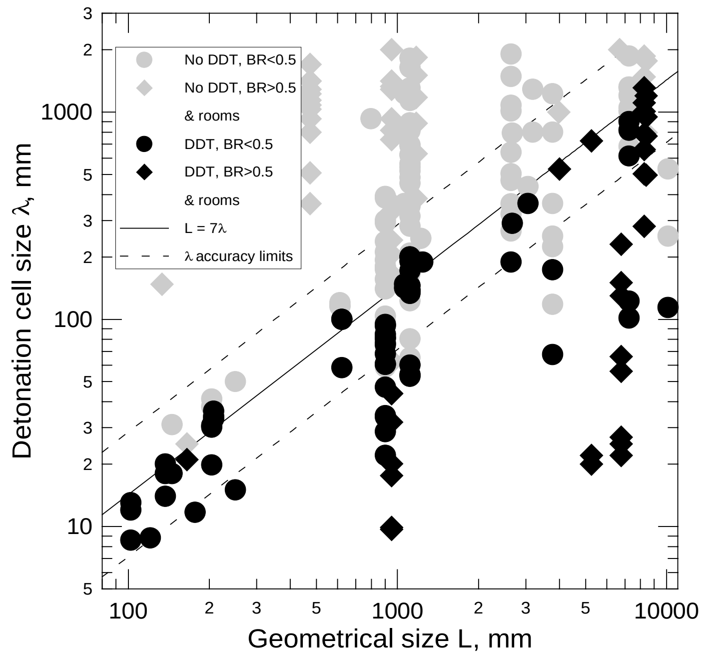

Figure 2. Combustion regimes (DDT or deflagration) as a function of characteristic size L, and detonation cell width λ. Black points - DDT, gray points - deflagrations.

Table 2. Experimental data used in L/λ-correlation for onset of detonations

Reference	Blockage ratio	Tube, channel, or room sizes, mm (m)	Initial T, K	Mixture type	Equivalence ratio, ϕ
1, 2	0.3, 0.6	2250	285-375	H_2/air/H_2O, H_2/air/CO_2	<1
1, 2	room	10.5x6x2.3 m	285-375	H_2/air/H_2O, H_2/air/CO_2	≤1
1, 2	room	15x6x2.3 m	293	H_2/air	≤1
3	0.3	46	293	H_2/air	<1
3	room	210x120x50	293	H_2/air	<1
4	0.44	16x57x50	293	H_2/air	<1
4	0.44	16x57x100	293	H_2/air	<1
5	0.43	50	293	H_2, CH-fuels/air	<1
5	0.43	150	293	H_2, CH-fuels/air	<1
5	0.43	300	293	H_2, CH-fuels/air	<1
6	0.44	65x52x32	293	H_2, CH-fuels/air	<1
6	0.44	65x52x64	293	H_2, CH-fuels/air	<1
6	0.44	65x52x128	293	H_2, CH-fuels/air	<1
7	0.31	280	373	H_2/air/H_2O	<1
8, 9	0.1 - 0.9	80	293	H_2/air	<1; >1
8, 9	0.1 - 0.9	174	293	H_2/air	<1; >1
8, 9	0.1 - 0.6	520	293	H_2/air	<1; >1
8, 9	0.3, 0.6	350	293	H_2/air, H_2/air/CO_2	<1; >1
10	0.43	273	300-650	H_2/air, H_2/air/H_2O	<1
11	0.33	1830	293	H_2/air	<1

11	0.33	150	293	H_2/air	<1
12	0.3, 0.6	406	383	H_2/air	>1