Detonation Dampers for Ducts Transporting Gaseous Fuels.

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Abstract. The very serious problem connected with long distance transport of gaseous fuels is connected with the fact that detonation may occur inside the duct if some air leaks into it. Detonation is particularly dangerous for compressors which "push" the gas through pipelines. It is therefore necessary to use some "detonation dampers" to protect these compressors.

The commonly used detonation damper has a form of a matrix of narrow channels, placed across the pipe transporting gas. Detonation wave is supposed to be extinguished due to cooling by cold walls of these channels. To achieve efficient damping the channels should be very narrow. Our earlier simulations [1, 2, 3] indicate, that preferable widths should be of the order of 0.005mm. This is not acceptable for practical reasons – in real applications it is close to 0.5mm. In such channels cooling the gas by heat transfer is inefficient and cannot extinguish the flame (cooling effect is proportional to perimeter of the cross-section and amount of gas to be cooled to cross-section surface).

Rarefaction wave generated behind sharp increase of channel cross-section is an alternative phenomenon, which may be used to cool the burning gas [1]. In our earlier papers we tested several channel shapes with increase of cross-section [2, 3]. Here we compare channels 0.5mm wide, without and with sharp increases and decreases of cross-section. Such channels were found to be the best for practical applications.

Keywords: detonation waves, detonation damping, narrow channels.

1 Introduction

One of the serious problems connected with long distance transport of gaseous fuels is connected with the fact that detonation may occur inside the duct if some air leaks into it. Detonation is particularly dangerous for compressors which "push" the gas through pipelines. It is therefore necessary to use some "detonation dampers" to protect these compressors.

The commonly used detonation damper has a form of a matrix of narrow channels, placed across the pipe transporting gas. Detonation wave is supposed to be

extinguished by cooling with cold walls of these channels. To achieve good efficiency of damping the channels should be very narrow.

Our earlier simulations [1, 2, 3] indicate, that the width of the damper channels, preferable from the point of view of damping efficiency, should be of the order of about 0.005mm. Such width is, unfortunately, not acceptable for practical reasons. The width of the channels of real dampers is usually close to about 0.5mm. In such channels cooling the gas by heat transfer to the walls is relatively inefficient and cannot extinguish the flame (cooling effect is proportional to perimeter of the channel cross-section, the amount of gas to be cooled is proportional to the cross-section surface, proportional to square of perimeter).

Rarefaction wave generated behind sharp increase of the channel cross-section is an alternative phenomenon, which may be used to cool the burning gas [1]. In our earlier papers we tested several shapes of channels with increase of cross-section [2, 3]. We found, that channels of the shape shown in Fig.1 – bottom were the most favorable. Here we compare results for channels 0.5mm wide, without and with sharp increases and decreases of cross-section (Fig 1). Channels of such dimensions are most interesting for practical application.

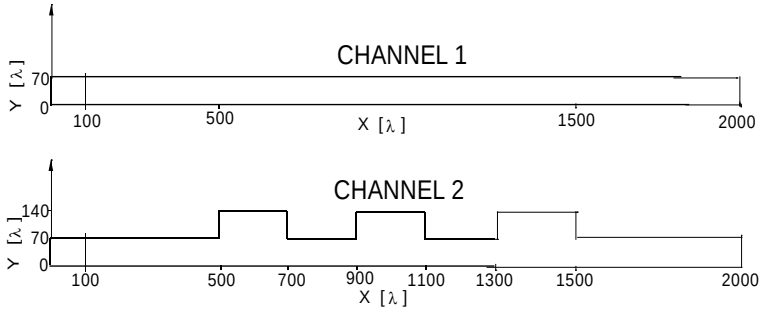

Fig.1. Shapes of the considered channels. (λ – mean free path at initial conditions).

There is one point, which should be noted here. The device for extinguishing detonation has a form of a thick steel plate (of the order of 50 mm thickness), with large number of holes of diameter equal to a fraction of a millimeter. It is impossible to drill large number of such holes in such plate. Instead, such device is usually manufactured from thin steel sheets, with narrow and shallow grooves, pressed firmly together. Such method of manufacturing makes it possible to produce channels of nearly arbitrary size and shape.

2 Method of simulation

The simulations presented in this paper were performed with the standard Direct Simulation Carlo (DSMC) technique [4]. The DSMC technique makes it possible to simulate flows in various geometrical configurations and it also offers a possibility of taking into account relaxation phenomena and chemical reactions ([5], [4]).

This, unfortunately, increases complexity of the computer programs and the necessary computing times. However, in the considered case considerable simplifications can be made because in a detonation wave the medium is far from thermodynamic equilibrium, combustion proceeds very fast and relaxation processes at the molecular level may be disregarded. The factor of prime importance is the produced thermal energy.

3 Model of a detonating medium

In the present work we investigate only the influence of shape and size of the channel upon the flow inside it, and upon the process of extinguishing detonation. A very simple model of the detonating medium ([1], [6]) may therefore be used. All molecules of this medium are identical, hard spheres. Part of them, carry certain amount of "internal" energy, the remaining are "inert" – carry no "internal" energy and cannot accept it in any way. The "internal" energy of a molecule may be transformed into kinetic energy during collision with an "inert" molecule, if the colliding molecules approach each other with high enough "velocity of approach" (Fig. 2). The relative velocity of the molecules is then increased suitably.

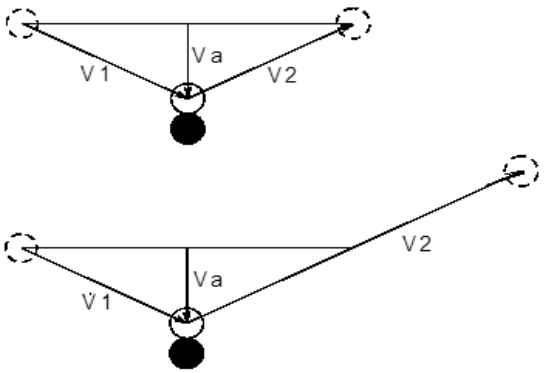

Fig.2. Collisions of two molecules in reference frame connected to one of them. Top – elastic, bottom – with energy release; V1 – relative velocity before collision, V2 – relative velocity after collision, Va – "velocity of approach".

The "internal" energy of a single molecule was such, that the relative velocity of colliding molecules was increased by the value equal to 10 times the most probable molecular speed.

4

4 Interactions with solid walls

Interactions of the molecules with walls were simulated with the simple model introduced by J.C. Maxwell [7]: molecules reflect from the walls either specularly (without exchange of tangential momentum and energy) or diffusely (molecules are adsorbed by the wall and re-emitted in directions selected at random, with energies corresponding to temperature of the wall). The "accommodation coefficient" α, (ratio of the number of molecules reflected diffusely to total number of reflected molecules) may vary from 0 to 1. The value $\alpha = 0$ (specular reflections) corresponds to no exchange of tangential momentum and energy, the value $\alpha = 1$ (diffuse reflections) – to maximum possible exchange (maximum friction and cooling). For majority of the so-called "technological surfaces" the accommodation coefficient is close to unity.

5 Simulation of flow in channels of larger cross-section

According to the Maxwell`s model of interactions, the walls influence the flow through diffuse reflections of the molecules only. The influence of walls upon the flow in channel depends therefore only on the ratio of the number of molecules reflecting diffusely to total number of molecules in the flow. Changing the number of molecules reflected diffusely (i.e. the assumed accommodation coefficient) it is possible to obtain, in the narrow channel, the flow picture similar to that in the channel of larger cross-section. The required value of the accommodation coefficient is then inversely proportional to hydraulic radius of the simulated channel.

The above does not apply to the narrowest channels, where the flow is close to free-molecular. The criterion is the Knudsen number, which should not be larger than 0.01 – 0.02.

6 Details of simulations

We present the results of simulations of behavior of the stationary flow and detonation waves in two channels:

Channel 1 (Fig. 1 – top) – of size 70 x 70 units and 2000 units long (the unit of length equal to 1 mean free path of the molecular motion at initial conditions).

Channel 2 (Fig. 1 – bottom) – also 70 units wide; other dimensions given in Fig. 1. The interior of the channels was divided into cubic cells of dimension equal to 1 unit. Each cell contained initially about 5 molecules.

In each channel, 100 units from its left end, there was a "diaphragm" separating the hot driving gas from the rest of the channel. Temperature of the driving gas was 22.5 times higher than temperature of the gas in front of the "diaphragm" and the number density was equal to about 0.9 of the number density in that region. Removal of the "diaphragm" produced a shock wave strong enough to be transformed sufficiently quickly into a detonation wave.

500 units from both ends of each channel the molecules were reflected from the walls specularly. Such region of flow without losses behind the "diaphragm" was necessary for the detonation to develop. At the other end of the channel it was assumed to enable checking whether the extinguished detonation would not reappear.

In the central part of each channel the molecules were reflected from the walls with accommodation coefficient $\alpha = 0.01$. At the dimension of the channel cross-section equal to 70 units, i.e. ~5μm, this corresponds to simulated channels acceptable technologically (dimension of the cross-section ~ 0.5mm).

Simulation consisted of two stages. During the first stage – generation of the stationary flow – the molecules were allowed to escape freely from the low-pressure end of the channel. The escaping molecules were then transferred to the place at low-pressure side of the "diaphragm", which created certain pressure difference between the ends of the channel and, after sufficiently long time (usually not less than about 150 hours of computing time) it led to establishing stationary flow.

Second stage of simulation was initiated by the "diaphragm" removal. It produced the shock wave, which was then transformed into a detonation wave.

7 Results

7.1 Stationary flow

Fig. 3 shows distributions of flow parameters along both considered channels, at accommodation coefficient $\alpha = 0.01$ in stationary flow. Fig. 3 – upper, left, shows the distributions of density, Fig. 3 – upper, right – velocity, Fig. 3 – lower, left – pressure, and Fig. 3 – lower, right – flow rate (product of local density and velocity). In all these figures density and pressure are related to their initial values (before beginning of the flow) and velocity – to the initial value of the most probable velocity of the molecular motion. All parameters are averaged over the local cross-section of the channel.

The presented variations of density, velocity and pressure along the channel in stationary flow are appreciable. The pressure drop along the straight channel 1 is smaller than that along channel 2 (Fig. 3, lower, left) and the flow rate is larger (Fig. 3, lower, right). This means, that resistance to the flow in the straight channel is smaller than that in the channel 2 (which was to be expected).

To make it more precise, the coefficients of hydraulic resistance were calculated from the standard formula:

$$\zeta = 2\Delta p/(\rho u^2)$$

where Δp – pressure drop along the channel, ρ – density and u – velocity in region $100 < x < 500$. The calculated coefficient of hydraulic resistance of channel 2 is about 5 times larger than that of the straight channel 1.

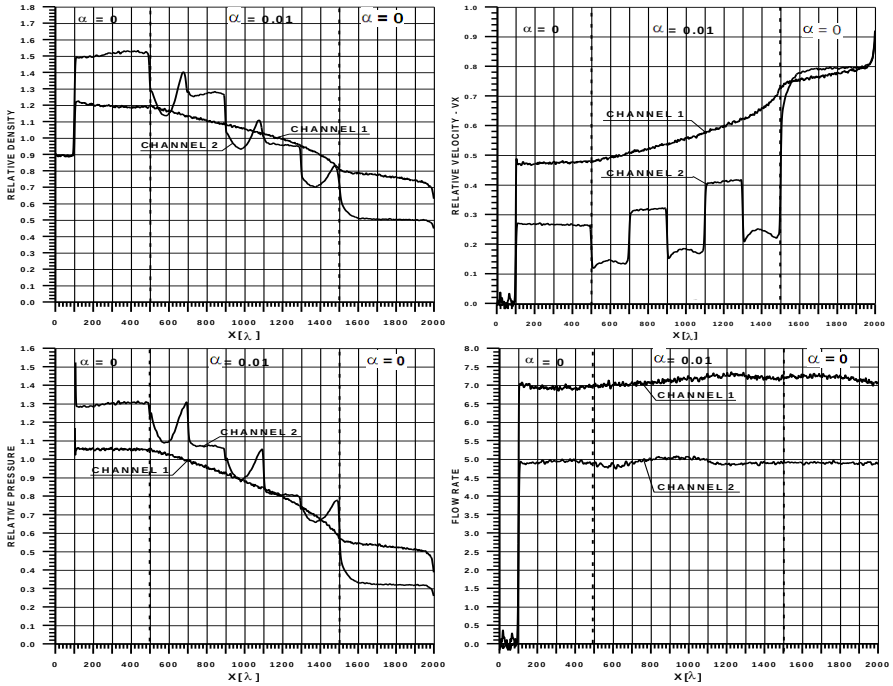

Fig.3. Stationary flow parameters in considered channels; accommodation coefficient α = 0.01. Upper, left – density, upper, right – velocity, lower, left – pressure, lower, right – flow rate.

7.2 Detonation

In this section we present diagrams, uniformly distributed in time, of temperature and percentage of flammable component along both considered channels, resulting from simulation of the behavior of detonation wave in quiescent medium and in stationary flow inside the considered channels. The amount of "energetic" molecules in all channels is equal to 7%.

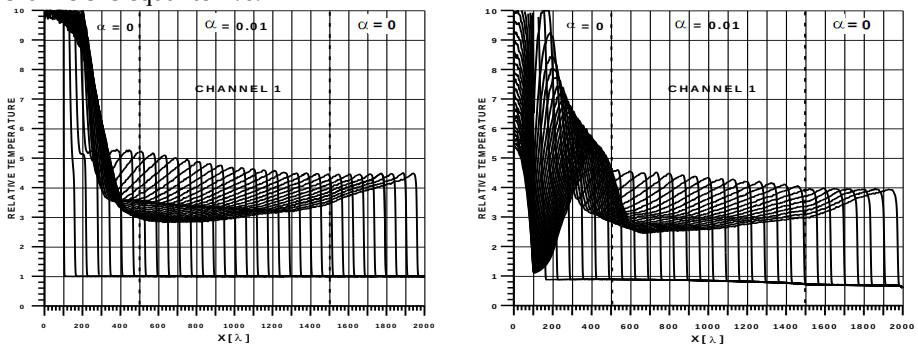

Fig.4. Temperature distributions in channel 1 at α = 0.01. Medium contains 7% of "energetic" molecules. Left: detonation in quiescent medium. Right: detonation in stationary flow.

In Fig. 4 – left, the diagrams of temperature inside channel 1 at α = 0.01 and no flow in front of detonation wave are shown. The detonation wave, fully formed in the initial part of the channel after "diaphragm" removal; in its central part it is affected very weakly – its amplitude decreases by about 9% only. In the end part of channel, where no friction and heat exchange are present, it begins regaining its intensity.

In Fig. 4 – right the diagrams of temperature inside channel 1, under conditions of stationary flow in front of detonation wave are shown. As before, the detonation is fully formed after "diaphragm" removal. In the central part of the channel the maxima of temperature decrease by about 30%. Still, the ratios of this temperature to the values in front of detonation wave increase, which means that intensity of detonation actually grows. This is result of density decrease along the channel in stationary flow (compare Fig. 3 upper, left).

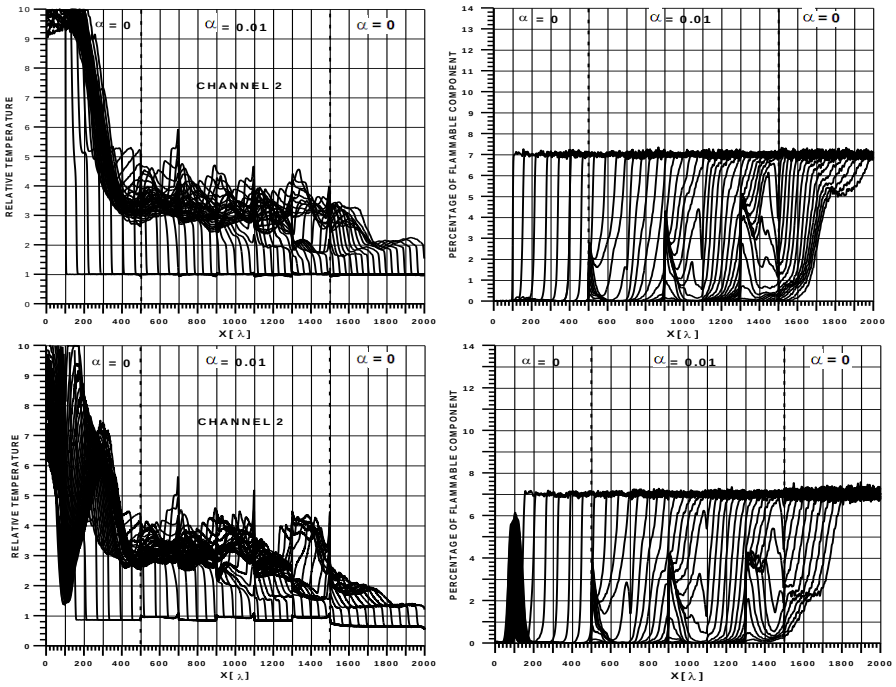

Fig.5. Distributions of temperature (left) and percentages of flammable component (right) in channel 2, at α = 0.01. Medium contains 7% of "energetic" molecules. Top: detonation in quiescent medium. Bottom: detonation in stationary flow.

In Fig. 5 – upper, left the diagrams of temperature inside channel 2 in progressing detonation wave at no flow conditions are shown. The detonation wave is fully formed after "diaphragm" removal and in the central part of the channel (where α = 0.01 and cross-section varies) its amplitude gradually decreases. Close to the end of channel (in region where α = 0) it transforms into weak shock wave followed by

some region of increasing temperature. Unfortunately, the strength of this shock grows with time.

Information on what actually happens there can be found in Fig. 5, upper, right. This picture shows distributions of percentage of flammable component of the medium, corresponding to distributions in Fig. 5, upper, left. Close to the end of channel (in region where $\alpha = 0$) the shapes of the curves suggest, that main part of the medium is not burning, however flame is still there and the burning area grows.

In Fig. 5 – lower, left the diagrams of temperature inside channel 2, in detonation wave, progressing into area of stationary flow are shown. Formation of the detonation and its behavior in the central part of the channel are here similar to those in the previous case. However, in the end section of the channel, where $\alpha = 0$, the strength of the emerging weak shock wave is nearly constant and its distance to the following area of temperature increase is growing with time. Fig. 5, lower, right (similar to Fig. 5, upper, right) does not show the flame there.

8. Conclusions

● The proposed method of DSMC simulation of flow in channels of a detonation damper was found to work also for channels of technologically acceptable dimensions.

● Presence of abrupt changes of cross-section of narrow channels used in detonation dampers generally increases efficiency of damping. In channels of technologically acceptable dimensions this influence seems to be much stronger, than influence of heat exchange with walls.

● In channels of technologically acceptable dimensions (~ 0.5 mm width, or more) the increase of flow resistance due to changes of cross-section is significant, however, taking into account the increased efficiency of damping, the net gain seems worthwhile.

References

1. Walenta Z.A., Teodorczyk A., Dabkowski A., Witkowski W.: Direct Monte – Carlo simulation of a detonation wave in a narrow channel, containing flammable gas. Central European Journal of Energetic Materials. 1(1), pp . 49-59 (2004).
2. Walenta Z.A., Slowicka A.M.: Extinguishing detonation in pipelines – optimization of the process, In: K. Kontis (ed.), Proceedings of 22nd Int. Shock Interaction Symposium, Glasgow, pp. 202-206. (2016).
3. Walenta Z.A., Slowicka A.M.: Detonation Waves in Narrow Channels of Various Shapes, Proceedings of 23rd Int. Shock Interaction Symposium, Skukuza, Kruger National Park, South Africa, pp. 135-140 (2018).

4. Bird G.A.: Molecular gas dynamics and the direct simulation of gas flows. Clarendon Press, Oxford (1994).
5. Larsen P.S.: Borgnakke C., Paper A7 in M. Becker and M. Fiebig (ed.), Rarefied Gas Dynamics 1. DFVLR Press, Porz–Wahn, Germany (1974).
6. Walenta Z.A., Lener K.: Direct Monte – Carlo simulation of developing detonation in gas. Shock Waves, 18, pp. 71-75 (2008).
7. Maxwell J.C.: In W.D. Niven, (ed.), The scientific papers of James Clerk Maxwell 2, 706. New York, Dover (1952).
8. Walenta Z.A., Slowicka A.M.: Optimization of Detonation Dampers for Ducts Transporting Gaseous Fuels. Proceedings of 32nd International Symposium on Shock Waves, Singapore, pp. 547-555 (2019).