Why the Standard Devices for Extinguishing Detonation in Pipelines can work

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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. Protecting these compressors with some kind of “detonation dampers” is therefore necessary.

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] indicate, that preferable widths should be of the order of 0.005mm. This is not acceptable for practical reasons – in real dampers the width of the channels is close to 0.5mm. In such dampers cooling the gas by heat transfer to the walls is inefficient and cannot extinguish the flame.

It will be shown in the paper, that such “real” detonation dampers may be efficient nevertheless. Detonation may be extinguished by cooling in the rarefaction wave, which is generated in the area behind the outlet from the channel.

Keywords: Transport of Gas, Detonation Waves, Detonation Damping.

4 Introduction

Modern societies need enormous amounts of energy for their existence. In the 20-th century the main sources of energy were natural fuels: coal, oil and natural gas. Combustion of these fuels produced large amounts of carbon dioxide, efficient greenhouse gas, which caused increase of the average temperature of the atmosphere and the problems connected with it. Presently we are trying not to use coal (as it produces the largest amount of carbon dioxide per unit of energy), however the natural gas, which is not as dangerous as coal, is still in use,

Natural gas must be transported from its source to the place of use. Pipelines are. pehaps, the most convenient devices for this purpose. Transport of natural gas through pipelines is, in principle, quite safe. Pressure in the pipes is much higher than atmospheric pressure, therefore if there are leaks in the pipe no air can get inside. However, under nonstationary conditions, (if the amount of flowing gas is decreased) pressure in the pipe may drop down below the atmospheric pressure and some air may get inside. Mixture of transported gas and air sooner or later will start burning and, eventually, detonation wave will be generated.

5 Earlier work on the problem

Detonation wave is a stong shock wave followed by a relatively thin layer of flame, supporting the shock. It is very dangerous for pipelines – in particular for compressor stations necessary to support the flow of gas.

The standard device protecting against detonation is a matrix of narrow channels, placed across the pipeline in front of the compressor station. Heat transfer to cold walls of these narrow channels is supposed to extinguish the flame and, eventually extinguish detonation.

The results of our early investigation indicated, that such detonation damper would work efficiently (i.e. at the outlet from the damper channel there would be no detonation wave – only weak shock wave remained), provided that the channels of the matrix were very narrow (of hydraulic diameter about 0.005mm) [1, 2]. Unfortunately such damper channels are technologically unacceptable. Hydraulic diameter of the channels of detonation dampers manufactured by the industry is usually close to about 0.5 mm. We suspected, that detonation dampers with such channels are, in fact, very inefficient and someting has to be done about it. We tried to replace the straight channels of the damper with channels of variable cross-section, hoping that this will enhance the heat exchange between flowing hot gas and cold channel walls [3, 4]. The results seemed promising: at the end of channel with variable cross-section the flame was extinguished (Fig.), however at the cost of increased resistance to the flow.

Quite recently we realized that the standard detonation dampers (with straight channels, of constant cross-section) are still manufactured and used. May it be that they are efficient nevertheless?

In our first paper on the subject [1] we have noticed, that there is an alternative tool for cooling the hot, burning gas – a rarefaction wave. Such rarefaction wave is always present behind the end of damper channel, where the flowing hot gas enters larger volume of the pipeline. Its presence might explain the high efficiency of standard detonation dampers. This suggestion needed confirmation – it is the subject of the present work.

Methodology used in the present investigation is the same as used earlier. However we will repeat here the main assumptions and describe the methods, following our most recent publications [8, 9], just for convenience of the reader.

6 Method of simulation

The simulations presented in this paper were performed with the standard Direct Simulation Monte Carlo (DSMC) technique [5]. 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 [6].

This, unfortunately, increases complexity of the computer programs and the necessary computing times. However, in the considered case considerable simplification is 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.

7 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 [1,2] 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. 1). The relative velocity of the molecules is then increased suitably.

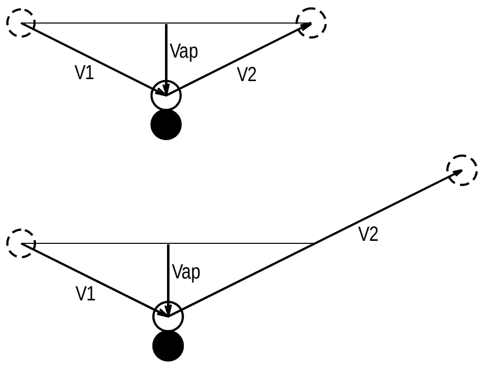

Fig.1. Collisions of two molecules in reference frame connected to one of them. Top – elastic, bottom – with energy release. V1 – relative velocity before collision, V2 – relative velocity after collision, Vap – "velocity of approach".

A molecule which had lost its "internal" energy may regain it a collision with an "inert" molecule if their "velocity of approach" is higher than velocity corresponding to this "internal" energy. The relative velocity of the molecules is then decreased suitably.

The assumed "internal" energy of a single molecule was such, that the relative velocity of collding molecules was increased by the value of 10 times the most probable molecular speed. The "threshold velocity of approach" of colliding molecules, necessary to release the "internal" energy, was eqal to about 5.48 (exactly square root of 30) times the most probable molecular speed.

5 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 (the reflection close to diffuse) .

6 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 reflected diffusely to total number of molecules in the flow. Decreasing the number of molecules reflected diffusely (decreasing the assumed accommodation coefficient) it is possible to obtain, in a narrow channel, the flow picture similar to that in the channel of larger cross-section. The required value of accommodation coefficient is inversely proportional to required 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.

7 Details of simulation

We present here the results of simulation of formation and later behavior of detonation waves in two configurations:

Configuration 1 (Fig. 2 – top): channel of cross-section 70 x 70 units, 800 units long, attached to large volume of cross-section 360 x 70 units, 1200 units long.

Configuration 2 (Fig. 2 – bottom): channel of cross-section 70 x 70 units, 800 units long attached to large volume of cross-section 360 x 70 units and 700 units long, attached subsequently to next channel of cross-section 70 x 70 units and 400 units long, attached finally to next large volume of cross-section 360 x 70 units and 700 units long.

The applied unit of length was equal to 1 mean free path of the molecular motion at conditions in front of the detonation wave.

Interior of each channel was divided into cubic cells of dimension equal to 1 unit of length. Each cell contained initially, in average, 5 molecules in Configuration 1 and 3 molecules in Configuration 2.

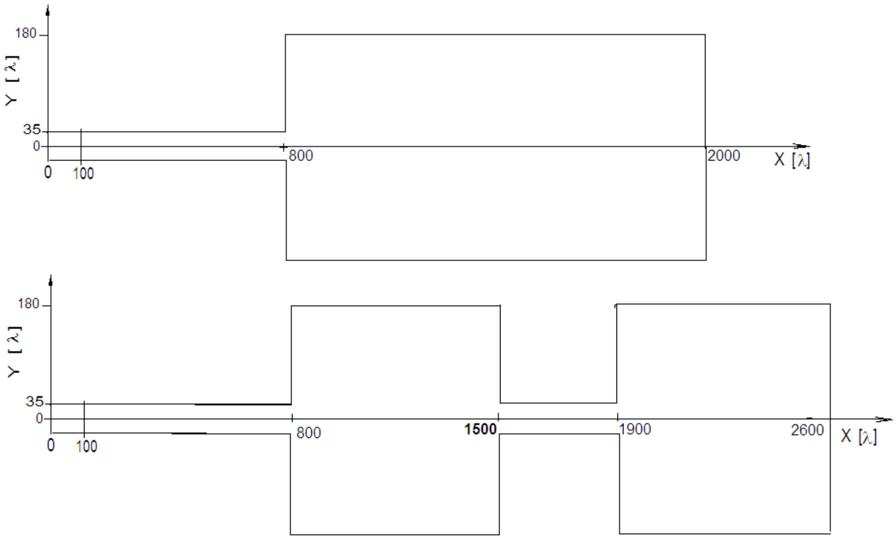

Fig.2. Investigated configurations: top – channel of cross-section 70 x 70 units, attached to volume of cross-section 360 x 70 units; bottom – channel of cross-section 70 x 70 units, attached to volume of cross-section 360 x 70 units, attached to next channel of cross-section 70 x 70 units and, finally, attached to second volume of cross-section 360 x 70 units.

In each channel, 100 units from its left end, there was a "diaphragm" separating the hot driver gas from the rest of the channel. Density of the driver gas was initially equal to density of the driven gas in front of the "diaphragm" and temperature was 20 times higher. Removal of the "diaphragm" produced a shock wave strong enough to be transformed sufficiently quickly into a detonation wave.

500 units from the left end of each channel the molecules were reflected from the walls specularly. Such region of flow without losses was introduced behind the "diaphragm" to accelerate formation of the detonation wave.

In the remaining 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, flow in such channel was similar to flow in the channel acceptable technologically (dimension of the cross-section ~ 0.5mm).

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

It was assumed, that the medium in front of the detonation wave was quiescent. Our earlier simulations [4, 8, 9] indicated, that the possible motion of gas in front of the detonation wave affects its behavior very weakly. This may result from the fact, that velocity of detonation wave is much higher than the speed of the flowing gas, which in this configuration is subsonic.

8 Results

In this paper we present results of simulation of detonation in channels of hydraulic diameter ~0.005mm, at accommodation coefficient at channel walls $\alpha = 0.01$. This way the picture for channel of hydraulic diameter ~0.5mm, (technologically acceptable), is obtained.

Each presented picture contains a series of diagrams of temperature averaged over the channel cross-section, evenly spaced in time.

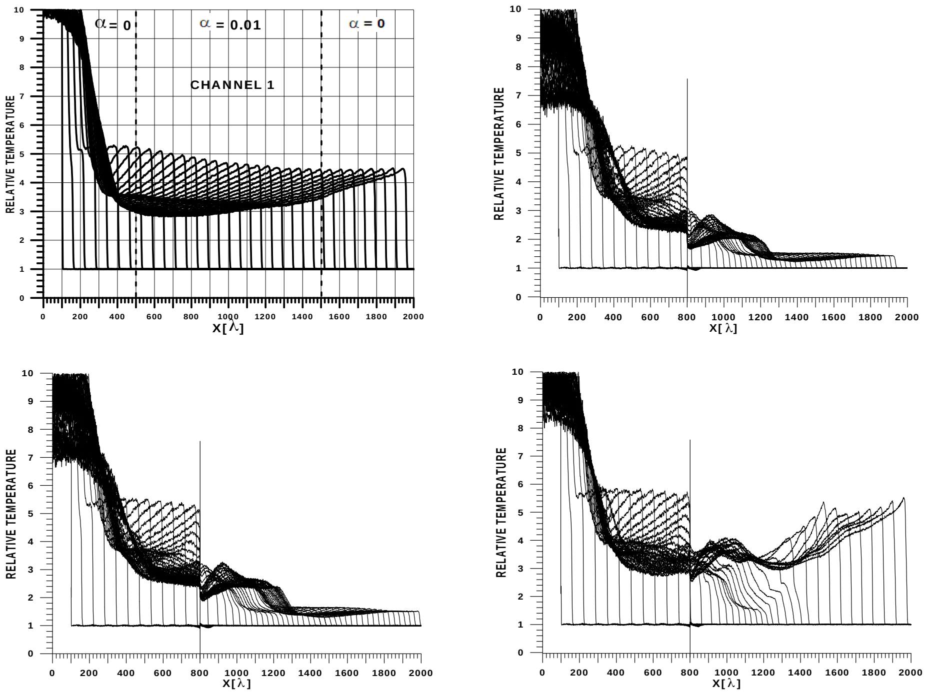

Fig.3. Temperature distributions in straight channel (upper, left) and in Configuration 1 (remaining pictures). More information in the text.

Fig.3 contains results for Configuration 1 and, for reference, one result for straight channel [9].

Result for straight channel (upper, left) was obtained for gas containing 7% of molecules "carrying energy". The detonation wave is fully formed in the initial part of the channel ($X < 500$). Later its amplitude decreases slightly because of heat transfer to the walls, tending to some asymptotic level.

Result for Configuration 1 and gas containing 7% of molecules "carrying energy" (upper, right) looks similarly to the previous case up to $X = 800$. At this point detonation wave enters the "large volume" – rarefaction wave is formed, flame is cooled down and extinguished and finally only weak shock wave remains. This shock wave is too weak to start detonation from the beginning.

Result for Configuration 1 and gas containing 8% of molecules “carrying energy” (lower, left) is similar to the case of 7%. Detonation is extinguished, only all waves are a little bit stronger

Result for Configuration 1 and gas containing 9% of molecules “carrying energy” (lower, right) – in this case detonation is not extinguished – rarefaction wave at the entrance to large volume is not strong enough to extinguish flame.

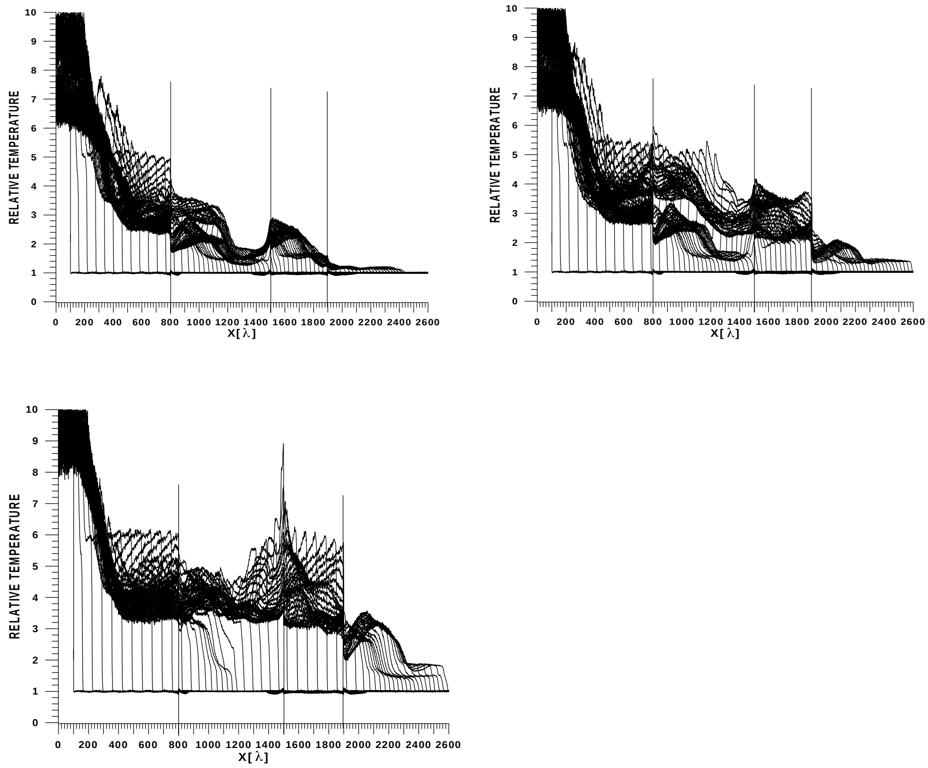

Fig.4. Temperature distributions in Configuration 2. More information in the text.

Fig.4 contains results for Configuration 2. The first picture of Fig 4 (upper, left) was obtained for gas containing 7% of molecules “carrying energy”. As it can be expected, up to X = 1500 the process is similar to the case of Configuration 1, gas containing 7% of molecules “carrying energy” (Fig.3. upper, right). In the range between X = 1500 X and X = 1900 (second narrow channel) we can see some increase of temperature (which could be expected) and finally, in the range X > 1900, temperature drops down to nearly the ambient temperature level.

The second picture (upper, right) obtained for gas containing 8% of molecules “carrying energy” may be compared with Fig.3, lower left. As expected, these pictures are nearly identical up to X = 1500. In the area X > 1900 of Fig.4 the temperature is lower than that in corresponding part of Fig.3 lower left.

It should be noticed, that identification of the primary detonation wave in Fig.4, upper left and upper right is difficult because of presence of many waves reflected from the changes of flow cross-section.

The third picture of Fig 4 (lower, left) for gas containing 10% of molecules “carrying energy” suggests, that detonation damper of Configuration 2 may be most efficient as far as detonation damping is concerned. The gas temperature in the exit part of this damper channel, although higher than in other dampers, is still not very high and does not seem to incrase with time.

9 Conclusions

● The proposed method of DSMC simulation was found to be a convenient tool for solving certain fundamental problems of flow in a detonation damper.

● Question formulated in the title of the present paper: “Why the standard devices for extinguishing detonationin pipelines can work“ has been answered. The answer is: “Because behind the exit from each narrow channel of the detonation damper a rarefaction wave is formed. Such rarefaction waves have strong cooling effect, usually much stronger than cold channel walls.”

● It follows from our simulations, that if efficiency of the standard detonation damper is insufficient it may be worthwhile to put two dampers into the pipeline at some small distance from each other.

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