The Influence of Detonation Cell Size and Regularity on the Propagation of Gaseous Detonations in Granular Materials

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Introduction

Filters consisting of granular materials can be used to transform a detonation wave into a fast deflagration wave or to totally extinguish the flame of a detonation wave. Whether a detonation wave fails or not by a given filter type can depend both on detonation cell size and regularity. Failing of a detonation wave is expected to become more likely as cell size and regularity increase.

A research project for finding the limits for transmission of a detonation wave through a granular filter is completed. Both spherical glass beads and crushed rock were tested. Varying the initial pressure of the detonating gas mixture in the range 0.02 - 1 bara, controlled the cell size. Adding of argon was used to vary the detonation cell regularity. Eight piezoelectric pressure transducers recorded the pressure-time profile of the detonation wave. These pressure signals were used to calculate the detonation wave speed upstream, inside and downstream of the granular filter. To detect whether the flame of the detonation wave was extinguished or not, an ionisation probe was used in some experiments.

Experimental setup

The experimental setup used for the detonation testing is shown in figure 1. It is based on circular tubes with 100 mm inner diameter. The wall thickness is 1 cm. All joints and flanges are sealed to minimise leakage into the rig at sub-atmospheric pressure.

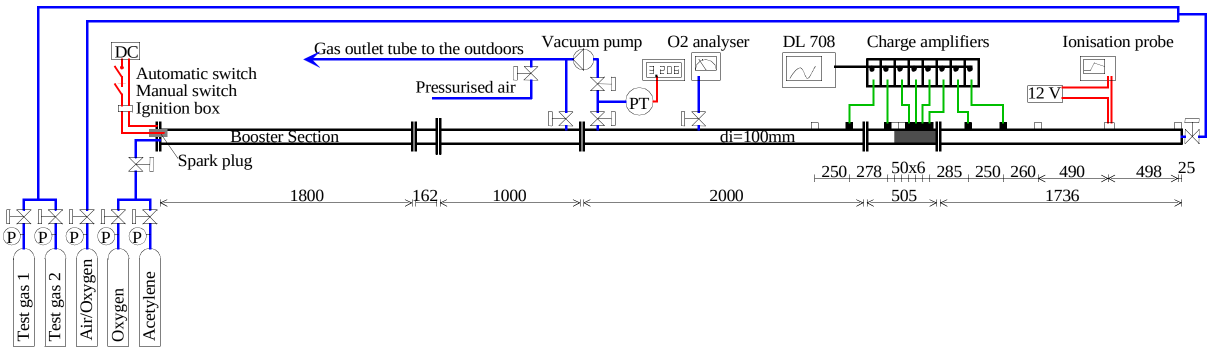

Figure 1 Experimental setup for detonation testing.

In experiments with granular filters involving detonation waves, the granular filter experiences a very high pressure-load. To avoid the granular filter from being destroyed, a very rigid construction is necessary. At the same time it must be possible to change the filter material and the flow area should be constricted as little as possible. The selected solution was a reinforced steel grid welded to the downstream end of the granular filter module. A finer steel grid was inserted on top of this to support the particles. At the upstream end of the granular filter, the same technique was used in addition to three guiding arms for pushing the reinforced steel grid in place. The design is shown in figure 2.

A problem with the horizontal design was the appearing of an opening at the top of the granular filter after some experiments. Compacting of the granular filter during impact of the detonation waves caused this opening. Refilling of filter material through the pressure transducer holes after a few tests minimized the problem.

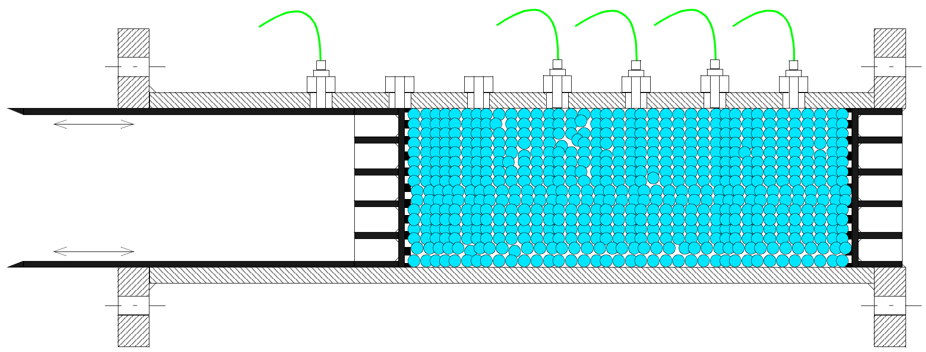

Figure 2 Mounting of the granular filter material in the detonation tube.

The measuring system consisted of eight Kistler 603B piezoelectric pressure transducers with 180 kHz charge amplifiers for detecting the detonation wave pressure. A Yokogawa DL 708 oscilloscope was used for logging of the pressure signals. A total of 10 000 data points were measured for each channel. An example of pressure transducer and ionisation probe output is shown in figure 3. During the first detonation experiments, only pressure transducers were used. Total quenching of the flame was expected in some experiments according to the findings of Makris et al. (1995), but this was uncertain to read from the pressure signals. Therefore an ionisation probe was used in addition to pressure measurements to confirm extinction of the flame. The ionisation probe consisted of two wires mounted into the tube wall. A 12 V battery was connected to the two wires. One of the wires was connected to an oscilloscope as shown in figure 5. If a flame was present in the channel, the oscilloscope would measure some of the battery voltage. The results from the ionisation probe were consistent with the pressure readings, and introduced a much more reliable method for determining flame quenching.

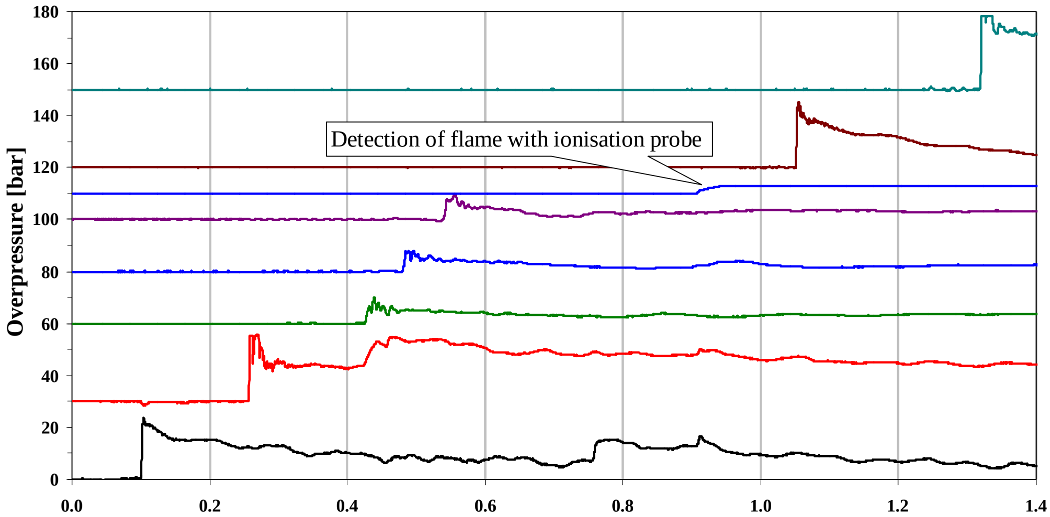

Figure 3 Detonation test with a 24 cm long granular filter consisting of 4 mm glass spheres with stoichiometric mixture of oxygen and propane diluted with 70% argon. An initial pressure of 0.89 bara was used. Values shifted up for better readability. Two pressure measurements upstream, three inside and two downstream of the granular filter are shown. The ionisation signal is indicating a flame downstream of the filter.

In figure 4 a soot film record from upstream of the granular filter for stoichiometric propane/oxygen mixture at 0.2 bara initial pressure is shown. Predicted cell size is 5.1 mm for this case. A soot film record from downstream of the granular filter is also shown in figure 4. Here something resembling a combustion jet from the granular filter can be seen below point A. At point B there are some vague detonation cells that interact with the combustion jet, resulting in a reinitiation to the right of point B. In area C this reinitiation fails, and in area D it propagates further downstream. Between these two areas, some very large detonation cells appear, and below point E a second reinitiation occurs. In area F the detonation is finally stabilised.

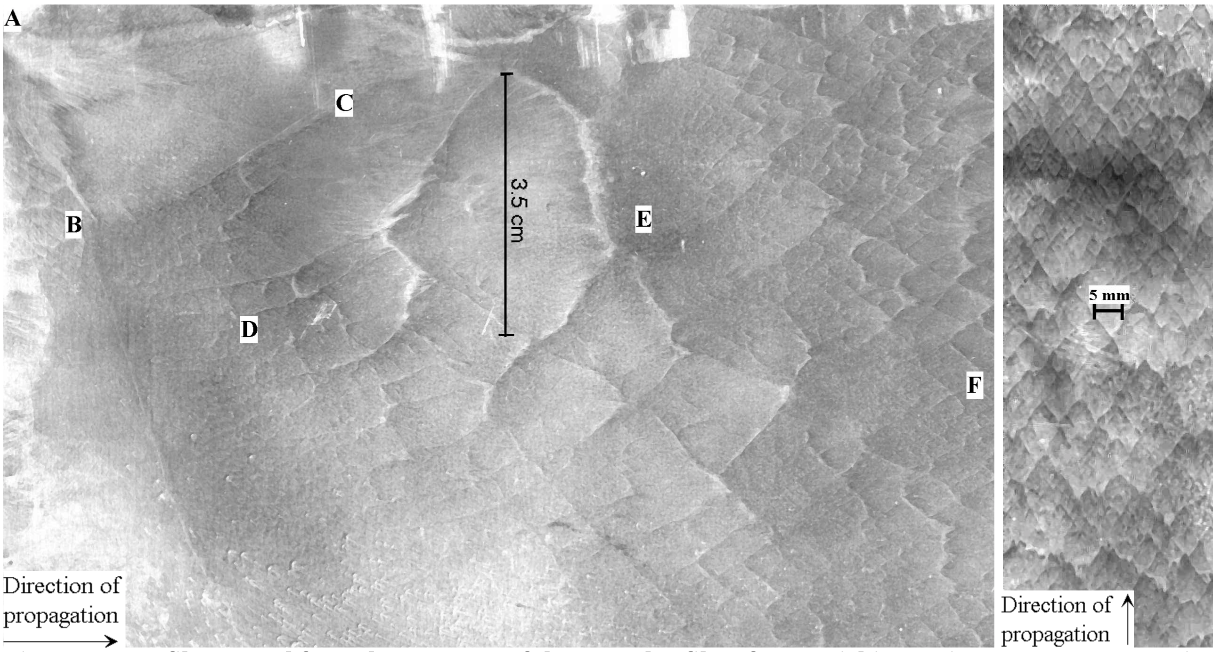

Figure 4 Soot film record from downstream of the granular filter for a stoichiometric propane/oxygen mixture at 0.18 bara initial pressure (left). This is close to a marginal case ($d_c/d_{ps} \approx 30$) for direct transmission of the detonation wave through the granular filter. Point A is about 5 cm from the granular filter. An example of a soot film record from upstream of the granular filter is also shown (right). It was recorded for a stoichiometric propane/oxygen mixture at 0.2 bara initial pressure.

For ignition, a system originally designed for ignition of gas turbines was used. The electric circuit is shown in figure 5. This strong spark of about 10 J was required to ensure initiation of a detonation wave within the booster section when low pressure was used in the rig. With this ignition system a detonation wave could be initiated with an absolute pressure down to 0.02 bar in an equimolar acetylene oxygen mixture.

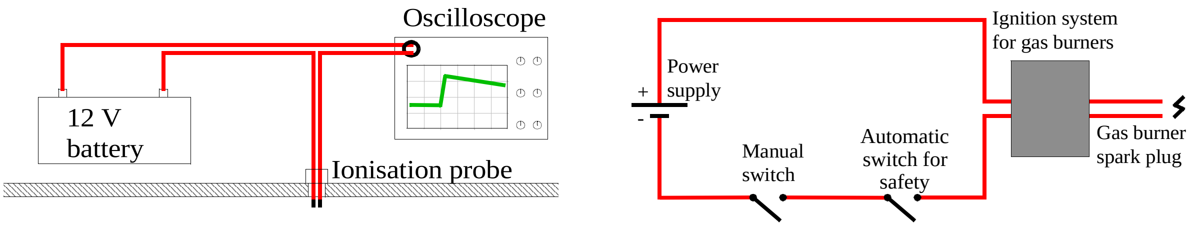

Figure 5 Mounting of the ionisation probe into the low-pressure detonation tube (left) and the ignition system (right).

The pressure in the rig was monitored using a Keller PAA-25/8735-1 pressure transmitter. Reading of this pressure was done with a Fluke 8050A digital voltmeter. Pressure lowering in the rig was achieved with a vacuum pump. A minimum pressure of about 0.01 bara could be reached within minutes. The lowest pressure used in the experiments was 0.02 bara due to the ability to initiate a stable detonation wave. Most experiments were performed above 0.1 bara. The accuracy of the pressure transmitter was ±0.0058 bara. The highest leakage allowed into the rig during experiments was about one Pascal pressure rise per second at 0.01 bara. This leakage was considered negligible.

Gas mixing was done with rotameters calibrated for each gas. An oxygen analyser was used to check the gas mixture composition in most experiments. An equimolar mixture of acetylene and oxygen was always used in the booster section. The two gases were not mixed before entering the rig due to safety reasons. Two or three different gases were mixed to create the test mixture. The fuel gas was mixed with the oxygen right before entering the rig. In the cases where three gases were used, the third gas was always argon and it was transported in the same tube as the fuel gas. In a few experiments, the oxygen was replaced with air. The gas filling was started with an evacuated rig and continued until atmospheric pressure was reached. Then filling was continued further in a flush through mode until the volume of the rig was replaced two to three times. Gas filling was then stopped, and the outflow was re-directed through the vacuum pump. Both test mixture and booster mixture was then pumped out until the right pressure was achieved in the rig. All operations on the rig during this pumping were remote controlled from a different room for safety reasons. The booster mixture was not separated physically from the test mixture, but as can be seen from figure 1, mixing of the two mixtures only occurred in a small region near the gas outlet. Since ignition occurred only a couple of seconds after gas pumping from the rig was stopped, this mixing region could be expected to be very short and not having any influence on the experimental results.

Theory on detonations in granular media

Basically three modes of combustion, or propagation mechanisms, also possible in a granular filter can be identified.

1. Detonation with typical three-dimensional cell pattern. This type of combustion will be achieved in free detonation propagation in smooth walled tubes with a large diameter compared to the cell size. The leading shock wave is here strong enough to ignite the mixture directly. If the cell size is small enough compared to the pore size in the granular filter, this detonation mode is also possible in a granular filter. The V/V_{CJ} ratio where V is the measured detonation velocity and V_{CJ} is the calculated Chapman-Jouguet detonation velocity, will be close to unity.

According to Makris et al. (1995) this can occur in a granular material if $d_c/d_{ps} < 1$ where d_c is critical diameter and d_{ps} is pore size. If $d_c = 13\lambda$, where λ is the detonation cell size, is assumed to be valid, this means that if there is room for thirteen detonation cells across one pore diameter, the detonation wave propagates with no velocity deficit. d_{ps} can be estimated as $d_p/3$ where d_p is particle diameter.

2. The reflected shock wave ignition mechanism. In this case, the leading shock wave is attenuated by rough walls, repeated obstacles or a granular filter to such an extent that the leading shock wave is not strong enough to directly ignite the mixture. However, shock wave reflections, both single and multiple reflections, can give rise to hot-spots responsible for ignition. This means that it is still a shock wave driven propagation mechanism. This type of propagation is often denoted as a quasi-detonation.

3. The turbulent mixing mechanism. In this case even multiple reflected shock waves do not become strong enough to directly ignite the mixture. Turbulent mixing of hot combustion products and unreacted mixture which then ignites the unreacted mixture is the propagation mechanism. This type of propagation can be considered as a fast deflagration.

According to Makris et al. (1995) these two mechanisms are present when $1 \le (d_c/d_{ps}) \le 100$. The relative importance of each mechanism is supposed to be continuously changing from domination of mechanism 2 to domination of mechanism 3 as d_c/d_{ps} is increasing from 1 to 100. Due to the complex three-dimensional geometry in granular materials, no distinct change in propagation mechanism can be found. The global velocity is merely an indication of the relative fraction of pore volume experiencing detonative (mechanism 1 or 2) and deflagrative (mechanism 3) combustion. At $d_c/d_{ps} \approx 100$ total extinction of the flame is expected to occur. This extinction is assumed caused by turbulent quenching. For d_c/d_{ps} varying from 1 to 100 the corresponding global detonation velocity can be expected to vary from $V/V_{CJ} \approx 1$ to $V/V_{CJ} \approx 0.3$.
Makris et al. (1995) propose the empirical correlation:

$$V/V_{CJ} = [1 - 0.35\log(d_c/d_{ps})] \pm 0.1 \qquad (1)$$

which is supposed to be valid for most detonable mixtures.
According to Makris et al. (1995), there are indications of a regime with exclusively deflagrative driven combustion (mechanism 3) for the approximate velocity range of $0.3 \le (V/V_{CJ}) \le 0.5$. This is supported in my experiments by the fact that in this range, there is a deflagration downstream of the granular filter, and a detonation does not reinitiate before a certain acceleration or reflection at the tube end wall has taken place.

Experimental results

The experimental results compared to equation (1) are shown in figure 6. d_c as a function of pressure for the different gas mixtures was found from Moen et al. (1986). The pore size d_{ps} was estimated as $d_p/3$ where d_p is particle diameter. Soot films as shown in figure 4 indicate that as the pressure is lowered, reinitiation moves further downstream before it finally disappears at $d_c/d_{ps} \approx 50$. The flame is removed at $d_c/d_{ps} \approx 100$. For argon dilution, reinitiation disappears at $d_c/d_{ps} \approx 10$. The flame limit is not affected by argon dilution. The flame limit is only valid for an incoming detonation wave and not for an incoming deflagration. If the flame is extinguished, only a weak shock wave is present downstream of the granular filter.

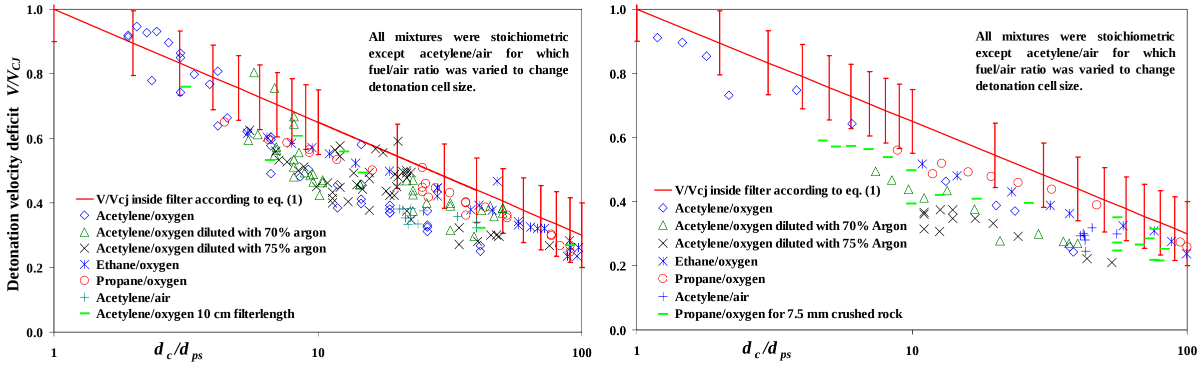

Figure 6 ***V/V_{CJ}*** **averaged over a 10 and 20 cm long granular filter consisting of glass spheres with 8 mm diameter (left).** ***V/V_{CJ}*** **averaged over a 24 cm long granular filter consisting of glass spheres with 4 mm diameter, and a 25 cm long granular filter consisting of crushed rock with 7.5 mm volume average diameter (right).**

Conclusions

The correlation from Makris et al. (1995) is verified to be fairly accurate for both spheres and irregular crushed rock. There is, however, some scattering of the data. The critical tube diameter d_c present in the experiments may have been slightly different from the calculated critical tube diameter. This again can have been caused by inaccurate correlations, inaccurate pressure in the tube or inaccurate gas mixing. Interpreting of the pressure measurements to calculate detonation velocities may have introduced some additional inaccuracies. Finally there are uncertainties in the effective pore size.

Measured detonation velocity upstream of the granular filter tends to be slightly lower than the calculated Chapman-Jouguet velocity V_{CJ} used for finding the detonation wave velocity deficit. A measured detonation wave velocity ratio V/V_{CJ} of 0.97 to 1.00 upstream of the granular filter was found in most experiments. If using the measured incoming detonation velocity instead of the calculated value, all values in figure 6 are shifted somewhat upwards. This effect is too small to change the overall trend of lower values than predicted by the correlation.

Very regular detonation wave structures as achieved by argon dilution were found by Moen et al. (1986) not to follow the $\lambda = d_c/13$ correlation. This can lead to the idea that the correlation in equation (1) neither is valid for regular structures. There are indications in figure 6 that values are especially low for argon dilution, and pressure measurements show that regular cell structures will fail at a lower d_c/d_{ps} ratio. Ionisation measurements, however, show that the flame is no easier to quench than for other mixtures. This can be expected since cell structure might be of no importance in a deflagrative driven combustion wave, also described as the turbulent mixing mechanism. This result is interesting as it shows that in contradiction to critical tube diameter tests where detonation wave extinction seem to be influenced by cell regularity, granular materials need to both destroy the detonation wave structure and to quench the deflagrative driven combustion wave possible in tubes with repeated obstacles or granular materials. This is consistent with the work of Makris et al. (1994) who investigated detonation transmission through an orifice placed on top of a granular filter consisting of spheres of equal diameter.

The present results confirm the $d_c/d_{ps} \approx 100$ rule for total flame extinction from Makris et al. (1995). In addition $d_c/d_{ps} \approx 50$ is found as an approximate value for direct transmission of detonation waves with irregular cell structure. For argon dilution resulting in regular detonation cells this is changed to $d_c/d_{ps} \approx 10$. In the direct transmission range where $d_c/d_{ps} < 50(10)$ the detonation wave regain full velocity of $V/V_{CJ} \approx 1$ immediately downstream of the granular filter. For $50(10) < (d_c/d_{ps}) < 100$ there is a fast deflagration downstream of the granular filter with the possibility of deflagration to detonation transition (DDT) depending on geometry.

References

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