CHEMICAL ENGINEERING TRANSACTIONS

VOL. 31, 2013

Guest Editors: Eddy De Rademaeker, Bruno Fabiano, Simberto Senni Buratti
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ISBN 978-88-95608-22-8; **ISSN** 1974-9791

A publication of
AIDIC
The Italian Association
of Chemical Engineering
Online at: www.aidic.it/cet

DOI: 10.3303/CET1331103

Quantification of the Static Equivalent Pressure of Gas Phase Detonations in Pipes at the DDT, in the Region of Stable Detonation (if any) and at the Reflection Point

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In order to establish guidelines for detonation pressure proof pipe design, experiments in 48.3x2.6 and 114.3x3.6 pipes (outer diameter [mm] x wall thickness [mm]) were conducted, in which deflagrative explosions of stoichiometric C_2H_4/air-mixtures at 20 °C underwent the transition to detonation. Initial pressures were chosen high enough to produce detonation pressures that caused significant bulging of the pipe walls. Hydraulic tests were carried through with all pipe material charges to determine the diameter increase as function of internal pressure. These results were compared to the diameter increase produced by the detonation experiments, enabling to assign static equivalent pressures (p_{stat}) to the detonations in the C_2H_4/air mixtures. P_{stat} can be regarded as the effective pressure "seen" by the pipe when exposed to the highly dynamic load. When, under application of the conventional (i.e. developed for coping with static loads) pressure vessel guidelines, the pipe is designed for this static equivalent pressure, it will withstand the detonative pressure pulse.

For gas phase detonations in pipes 8 different pressure scenarios can be distinguished. All scenarios were realized experimentally with stoichiometric C_2H_4/air-mixtures at 20 °C and for each one p_{stat} was determined. This includes also the worst case detonation pressure scenario, in which the DDT occurs within approximately one pipe diameter of the blinded pipe end.

When switching to stoichiometric $C_2H_4/O_2/N_2$-mixtures with O_2 concentrations between 21 vol.-% and 30 vol.-% the ratio between p_{stat} at the DDT and p_{stat} for the stable detonation decreases with increasing O_2 content. Whereas the ratio between p_{stat} at the reflection of the stable detonation and p_{stat} of the stable detonation will remain constant at about 2.49 for all detonative gas mixtures, the ratio between p_{stat} at the DDT and p_{stat} of the stable detonation must be expected to be strongly influenced by the reactivity of the gas mixture (increasing the reactivity will reduce the ratio).

1. Fundamental problems in establishing design rules for detonation pressure proof pipes

When investigating the pressure/time/space profiles associated with gas phase detonations in pipes it is necessary to distinguish between long and short pipes (Figure 1). In each pipe type four different pressure load scenarios may occur (Figure 2).

The pressure profiles in long pipes are theoretically fairly well understood in the region of the **stable detonation** (scenario 3) and for **the reflection of a stable detonation** (scenario 4) at a blinded pipe end. In both cases the pressure profiles are also amenable to experimental determination.

A reliable theoretical prediction of the pressure profiles **at the DDT in long pipes** (scenario 1) and **at the DDT in short pipes** (scenario 5) is currently problematic. Additionally, the experimental validation of theoretical predictions is extremely difficult due to (a) the locations of the finite number of pressure sensors which can be mounted in a pipe only rarely coinciding with the location of the DDT and that (b) even with piezoelectric pressure sensors reliable quantitative measurements of very short duration detonative pressure peaks (full width at half maximum less than 30 µs for peaks at the DDT) are hard to achieve.

Please cite this article as: Schildberg H.P., Sudano G. and Streuber C., 2013, Quantification of the static equivalent pressure of gas phase detonations in pipes at the ddt, in the region of stable detonation (if any) and at the reflection point, Chemical Engineering Transactions, 31, 613-618 DOI: 10.3303/CET1331103

In the case where the **DDT occurs directly in front of the blinded pipe** end, i.e. DDT and reflection coincide (scenario 8), any attempt to predict pressure/time/space profiles seems to fail completely.

Whereas there are already substantial difficulties in quantitatively predicting the pressure/time/space profiles associated with the various detonation scenarios for gas mixtures in pipes, the quantitative investigation of the interaction of these pressure profiles with the walls of a pipe is also a complicated task due to the following effects, even if the pressure profiles were known:

- the step-function like leading edge of the detonative pressure peaks excites the natural oscillation modes of the enclosure. Subsequent interference and mode coupling may cause extremely high stresses.
- flexural waves propagating in the axial direction will be excited. When being reflected at welded flanges, which represent a pipe wall of almost infinite stiffness, the incoming wave interferes with the reflected one and may cause additional hoop stresses.
- catastrophic resonance may occur when the detonation velocity gets close to the flexural wave velocity.
- under detonative impact the strain rate of the pipe wall is about 6 orders of magnitude larger than the strain rate applied in standardized stress/strain measurements (applied strain rate $d\varepsilon/dt = \Delta L/L/\Delta t \cong 10^{-4}$ s^{-1}) to determine the yield strength $R_{p0.2}$ of the wall material. For low-strength steels a strain rate of 100 s^{-1} brings about an increase of $R_{p0.2}$ by almost a factor 2, for high strength steels the increase is marginal.
- loads of short duration will be dampened by the inertia of the wall material when the peak width at half height is shorter than half of the cycle time of the considered oscillation mode.

Due to problems in quantifying the pressure profiles generated by detonative mixtures and in quantifying the mechanical interaction of these pressures with an enclosure, no design guidelines for detonation pressure resistant pipes are currently available.

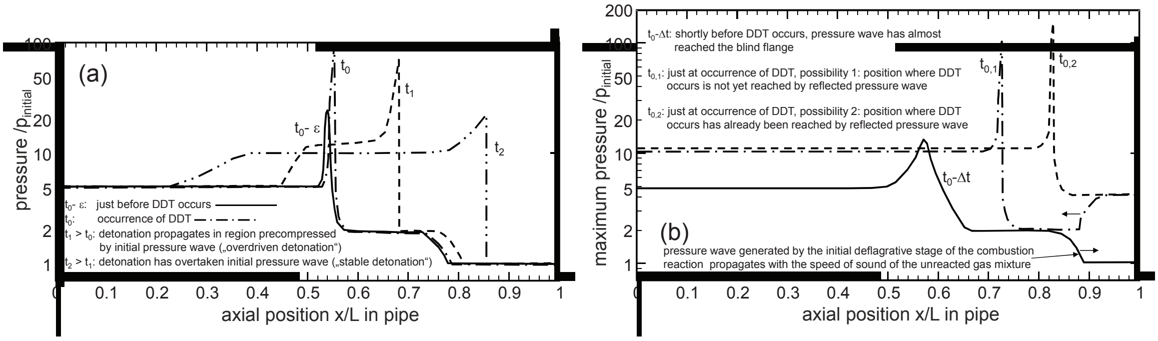


Figure 1: (a) Pressure/distance profiles in pipes referred to as "long" in the context of gas phase detonations. Here the detonation front arrives at the blind flange of the pipe before the pressure wave generated by the initial deflagrative stage does.

The final stage of detonation propagation is always propagation in the unreacted gas mixture which is still present in the pipe at the initial temperature and pressure, i.e. at the values valid at the moment of ignition. When this stage is reached, the detonation is termed „stable detonation".

In the region between the location of the DDT and the position of the pressure front propagating with the speed of sound, the detonation propagates in a mixture having a higher pressure than the initial pressure at the moment of ignition. This is the region where the detonation is usually termed „unstable" or „overdriven" detonation.

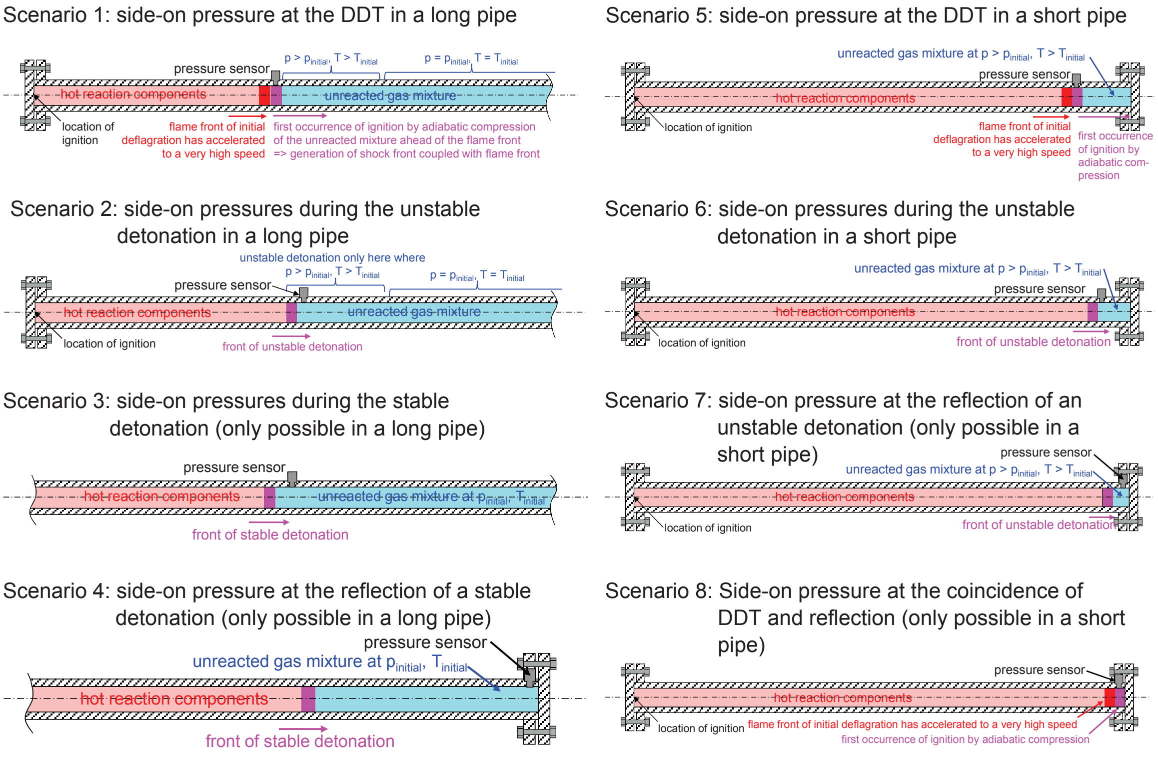
(b) Pressure/distance profiles in pipes referred to as "short" in the context of gas phase detonations. Here the detonation front arrives at the blind flange of the pipe after the pressure wave generated by the initial deflagrative stage does.

There has not yet emerged a consistent terminology when referring to this case, however, it is sometimes known as „detonation in a precompressed gas mixture" or „detonation with precompression".

There is never a region where the detonation propagates as stable detonation. Between the location where the DDT occurs and the blinded pipe end the detonation propagates as an „overdriven" or , alternatively, an „unstable" detonation.

The location where the DDT occurs is always very close to the blind flange. Otherwise the fast (1600 – 2500 m/s) detonation peak would have overtaken the slow (ca. 350 m/s) pressure wave and would be termed detonation in a „long" pipe.

When trying to realize a detonation in a short pipe in an experiment, in the majority of all cases the DDT will occur in the region already influenced by the back-travelling pressure wave. This corresponds to what is expressed by possibility 2 in Figure 1b.


Scenario 1: side-on pressure at the DDT in a long pipe

Scenario 2: side-on pressures during the unstable detonation in a long pipe

Scenario 3: side-on pressures during the stable detonation (only possible in a long pipe)

Scenario 4: side-on pressure at the reflection of a stable detonation (only possible in a long pipe)

Scenario 5: side-on pressure at the DDT in a short pipe

Scenario 6: side-on pressures during the unstable detonation in a short pipe

Scenario 7: side-on pressure at the reflection of an unstable detonation (only possible in a short pipe)

Scenario 8: Side-on pressure at the coincidence of DDT and reflection (only possible in a short pipe)

Figure 2: Pressure load scenarios that can be distinguished for gas phase detonations occurring in pipes. Scenarios 1 to 4 occur in long pipes, in short pipes scenarios 5 to 8 are found. $P_{initial}$ and $T_{initial}$ denote the pressure and temperature in the gas mixture at the moment of ignition. Note that when a pipe which must be regarded as „short“ under the given conditions (composition of gas mixture, pipe diameter, pipe length, initial temperature, initial pressure) shall be designed detonation pressure proof, the end of the pipe must always be designed for the worst case (scenario 8), which is represented by the occurrence of the DDT at a location very close to the blind flange. „Very close“ encompasses a section of between 0 and 2 pipe diameters ahead of the flange. The reason for having to assume this worst case in pipe design is that the DDT will occur in any case close to the blind flange (otherwise the pipe would have been classified as long) and that the location of the DDT is to some extent stochastic.
Note that the static equivalent pressures occuring in scenarios 2 and 6 are less than in scenarios 1 and 5, respectively. Therefore, they are of minor importance with regard to detonation pressure proof pipe design.

For the process industry a generally accepted design guideline is urgently needed, as this would allow construction of detonation pressure resistant equipment on a routine basis and, henceforth, detonable mixtures could be admitted in reactions involving gas phase. By doing so, the admissible range of process parameters (temperatures, pressures, concentrations, dimensions of packings etc.) will be increased. This usually translates into an increase of the efficiency of the plant.

2. The static equivalent pressure as basis for detonation pressure resistant pipe design

The so-called “static equivalent pressure” (in the following referred to by p_{stat}) of a detonative pressure scenario is defined as the static pressure applied in a hydraulic test which causes the same degree of residual plastic strain in the pipe wall as caused by the detonative pressure scenario. Once p_{stat} is known, one can apply the common pressure vessel design rules dealing with static or quasi-static loads only and design the pipe to be explosion pressure resistant or explosion pressure shock resistant for the value of p_{stat}. By doing so, the pipe is then detonation pressure resistant or detonation pressure shock resistant for the considered highly dynamic detonative load scenario.
If p_{stat} is to be determined for a particular detonative load scenario, the initial pressure in the test must be high enough to generate measurable residual plastic strain in the pipe wall, i.e. 1% or more.
Care should be taken not to generate too large residual plastic strain because as soon as the pipe wall starts to bulge outwards the increase in cross section has an immediate feedback on the value of the

detonative pressure in the sense that it will be reduced. Thus, if p_{stat} were to be determined for the same detonative load scenario in a pipe with a thinner wall, the resulting larger deformation will result in a smaller value for p_{stat}. A method for eliminating the influence of the degree of bulging on the measured value for p_{stat} is explained in chapter 4.

3. Investigated detonative load scenarios and experimental equipment

Table 1 summarizes the investigated load scenarios and the pipes used. For the pipe materials we chose RA2 (steel number: 1.4541) as the most common representative of stainless steel and P235GH (1.0345) as the most common representative of carbon steel employed in the pipework of process plants. Pipe dimensions were 48.3 x 2.6 and 114.3 x 3.6 (outer diameter [mm] x wall thickness [mm]). In standard applications the smaller pipe is usually utilized for design pressures of 10, 25, 40 and 63 bar g, the wider pipe for 10, 25 and 40 bar g. Alltogether 10 pipes of about 9.6 m length were fabricated for each combination of pipe material and pipe dimension. The pipes consisted mostly of 2 individual tubes with welding neck flanges, the lengths being 6.4 m and 3.2 m. The design pressure of the flanges was 250 bar. The flanges were slightly drilled out to make their inner diameters equal to the inner diameters of the tubes (43.1 mm and 107.1 mm).

Up to 15 piezoelectric pressure sensors could be mounted in a pipe. Figure 4 displays examples of the pipe geometry and the sensor positions. The sensors were of type PCB 113B03, pressure range 0 – 1034 bar, sensitivity ca. 5.6 pC/bar. Because of the high initial pressures in many explosion tests the pressure sensitive thin membrane of the sensors had to be protected against melting as described elsewhere (Schildberg, 2009). The charge amplifiers were from Kistler, type: 5015A1000. For data sampling two A/D-boards of Spectrum Systementwicklung Microelektronik GmbH were used (type M2i-3122, each one with 8 channels, 12 bit resolution, up to 10 MHz sampling rate). For the tests a sampling rate of 200 kHz and a recording time of 10 s was sufficient.

In order to determine the static equivalent pressure upon reflection at the blinded pipe end without adulteration of the value by the massive welding neck flange, a displacement body was inserted at the end of the pipes as depicted in Figure 3.

From each tube material charge used in the detonation tests two samples where subjected to a hydraulic test in which the degree of bulging was recorded as function of the internal static pressure up to tube rupture. These data allow lateron to assign to a detonative load scenario, which has caused a certain degree of bulging in the pipe, the corresponding static equivalent pressure.

The air used was technical air with 20 vol.-% O_2 and 80 vol.-% N_2.

Table 1: Summary of the investigated load scenarios and the pipes used. All pipes had a length of about 9.6 m with one exception (114.3 x 3.6 pipe with 7.6 m length). In case of the long pipes the DDT occurred after a predetonation distance between 3 m and 4 m ($69 \le L/D \le 92$). For the short pipes, slight variations in the O_2-content were used to shift the DDT as close as possible to the blinded pipe end. If one assumes a yield strength of 250 N/mm^2 for all pipes, the internal pressure in the pipes giving rise to a hoop stress equal to the yield strength is 301.6 bar g for the 48.3 x 2.6 pipe and 168.0 bar g for the 114.3 x 3.6 pipe.

Pipe type according to Figure 1	Pipe dimensions: outer diameter [mm] x wall thickness [mm]	Pipe material	L/D-ratio	Investigated scenarios according to Figure 2	Employed stoichiometric $C_2H_4/O_2/N_2$-mixtures	Range of $p_{initial}$ [bar abs]
long	48.3 x 2.6	1.4541	225	1, 3, 4	C_2H_4/air	8.14 – 42.6
long	48.3 x 2.6	P235GH	225	1, 3, 4	C_2H_4/air	8.03 – 16.11
long	114.3 x 3.6	1.4541	90	1, 3, 4	$C_2H_4/O_2/N_2$ with 30 up to 35 vol.-% O_2	2.66 – 3.5
short	114.3 x 3.6	1.4541	90	5, 7, 8	$C_2H_4/O_2/N_2$ with 18.75 to 21.5 vol.-% O_2	2.06 - 3.22
short	114.3 x 3.6	P235GH	90	5, 7, 8	$C_2H_4/O_2/N_2$ with 18.75 to 21.5 vol.-% O_2	2.12 – 2.2

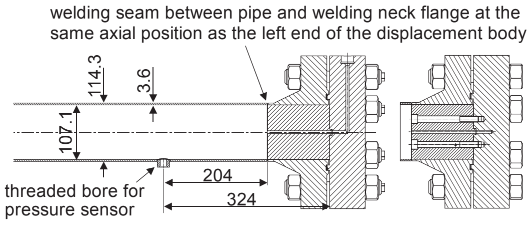


Figure 3: A Displacement body was inserted into the end of the 114.3x3.6 pipe (analogously for the 48.3x2.6 pipe) for to make the reflected pressure act on the original pipe wall and not on the section enforced by the welding neck flange.

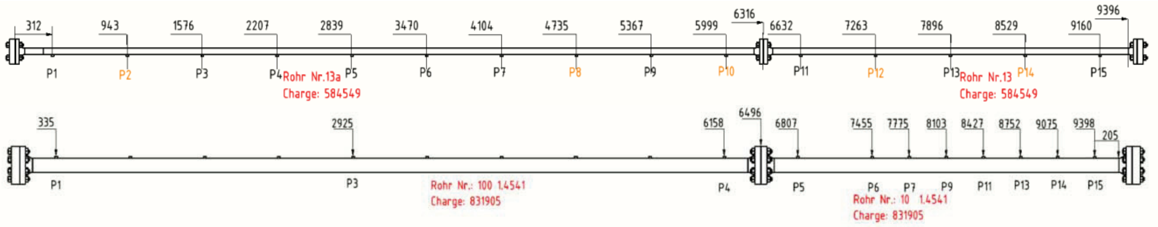


Figure 4: Examples of a 48.3x2.6 pipe and a 114.3x3.6 pipe used in the tests. All numbers are distances in units of mm, counted from the inner surface of the left blind flange. The ignition source was in a bore of the left blind flange, flush with the inner surface (i.e. at x = 0 mm). Threaded boreholes for mounting piezoelectric pressure sensors were provided along the pipe at almost equal distances of approximately 633 mm, for some of the 114.3x3.6 pipes the distance was only about 316 mm. Unused boreholes where closed by a plug which was flush with the inner surface of the pipe wall.

4. Results obtained in long and short pipes with stoichiometric C_2H_4/air

Due to the adamant restriction to 6 pages imposed for this paper by AIDIC, a more detailed presentation of the experimental results of 33 tests could only be included in the electronic version available on the CD that will be distributed at the Loss Prevention 2013 conference.

As an example for the tests conducted to investigate pressure scenarios 5, 7 and 8, Figure 5 displays photos of the bulged pipe ends from three tests in which the DDT had occurred at a very short distance to the flange.

All static equivalent pressures derived from the individual tests for the scenarios 1 to 8 are expressed as multiples of the Chapman-Jouguet pressure ratio p_{CJ_r}, which is characteristic for the employed gas mixture. This value was calculated on the basis of the measured or interpolated propagation speed of the stable detonation according to the formula provided by Courant et al. (1976) and by Nettleton (1987):

$$p_{CJ\_r} = p_{CJ} / p_{initial} = \left(\gamma_0 \cdot M^2 + 1\right) / \left(\gamma_1 + 1\right) \tag{1}$$

Here M denotes the Mach number given by D/c, where D is the propagation speed of the stable detonation and c is the speed of sound in the unreacted gas mixture. γ_0 denotes the ratio c_p/c_v of the unreacted gas mixture, γ_1 denotes the c_p/c_v of the hot reaction products. The value of c was calculated from $c = \sqrt{\gamma_0 \cdot R \cdot T_{initial} / M}$, where R = 8.314 J/(mol*K), M is the mean molar mass of the unreacted gas mixture in units of kg/mol and $T_{initial}$ is the temperature of the unreacted mixture.

As already mentioned in chapter 2, it must be assumed that as soon as the pipe wall starts to bulge outwards there is an immediate feedback on the value of the detonative pressure in the sense that this pressure will be reduced due to the increase in the cross section of the pipe. Hence, the resulting static equivalent pressure will also be less than it would have been if a pipe with a thicker wall had been used which would have exhibited a smaller diameter increase. Correction factors were derived from 3 tests in long pipes where, by variation of the initial pressure, scenario 4 resulted in diameter increases ranging

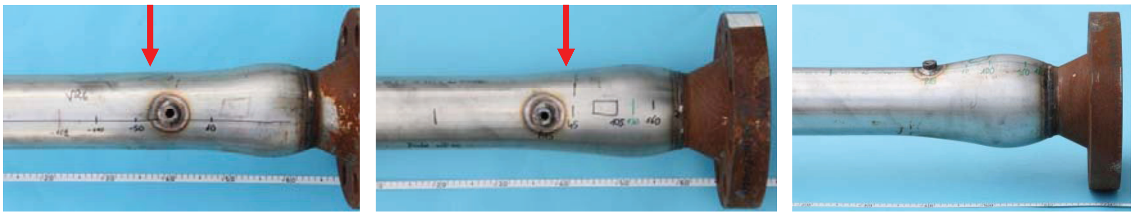


Figure 5: Left photo: test no. 26, DDT about 50 mm upstream of P15 (red arrow), distance to effective blind flange is about 250 mm.The smaller DDT-bump and the reflection bump are well separated. Middle photo: test no. 16, DDT about 45 mm downstream of P15 (red arrow), i. e. about 155 mm ahead of effective blind flange. When sliding with one's hand over the pipe surface two separate bumps are discernible. Right photo: test no. 27, DDT between P15 (9406 mm) and effective blind flange (9609 mm). In the bulged region one can not distinguish between a DDT-bulging and a reflection-bulging, i.e. the DDT occurred presumably at a distance of less than 120 mm to the effective blind flange. All tests were conducted at $p_{initial}$ = 2.17 bar a.

from 2.5 % over 19.5 % to 27 %, which gave rise to ratios of $p_{stat\_reflection}$ to p_{stat_stable} of 2.36, 1.41 and 1.15 although in all cases the same ratio of about 2.4 should have resulted.

In summary, the following statements can be derived from the experiments:

a: From tests 3, 4 and 10 it follows that the static equivalent pressure of the stable detonation (p_{stat_stable}) is equal to 0.63 times the detonative pressure of the stable detonation, which is equal to the Chapman-Jouguet pressure: $p_{stat\_stable} = 0.63 \cdot p_{CJ} = 0.63 \cdot p_{CJ\_r} \cdot p_{initial}$

This statement should hold for any detonative gas mixture and all pipe materials exhibiting a comparable rise in yield strength at high strain rates as the materials used here.

b: From the tests where a stable detonation caused bulging upon reflection (tests 3, 4, 5, 31, 32 with material 1.4541) it follows that the static equivalent pressure at the reflection of a stable detonation ($p_{stat\_reflection}$) is 2.49 times larger than the static equivalent pressure p_{stat_stable} in the region of the stable detonation: $p_{stat\_reflection} = 2.49 \cdot p_{stat\_stable}$

This statement should be universal, i. e. hold for any detonative gas mixture and all pipe materials. Note that the factor 2.49 is about the same as the theoretically predicted ratio between the detonative pressure upon reflection and the detonative pressure of the incoming detonation.

c: The static equivalent pressure at the DDT in long pipes is a factor of 5.2 larger than p_{stat_stable}. This statement will only apply for the investigated mixture (stoichiometric C_2H_4/air at 20 °C). Since the DDT occurs after the adiabatic precompression of the unreacted mixture ahead of the flame front has brought this mixture to a temperature so far beyond the autoignition temperature that the induction time for ignition is in the range of microseconds, it must be assumed that the factor will depend on the difference between the autoignition temperature of the investigated mixture and its initial temperature. The author has preliminary experimental evidence that in Cyclohexane/air mixtures (autoignition temperature at 1 bar abs is 230 °C) at $p_{initial}$ = 15 bar and $T_{initial}$ = 150 °C the factor is not larger than 1.5.

d: With increasing oxygen content in stoichiometric Ethylene/O_2/N_2-mixtures the ratio between the static equivalent pressures at the DDT and the stable detonation drops. At 30 vol-% O_2 the ratio is about 3.6 (test 29, 32), at 35 vol.-% O_2 the ratio is 3.1. The author assumes that for stoichiometric Ethylene/O_2-mixtures the ratio is close to 1. Since the autoignition temperature of combustible/O_2/N_2 mixtures drops with increasing oxygen concentration, this experimental finding is in line with the above assumption.

e: From all tests conducted in short pipes it was test no. 27 where DDT and reflection really coincided. The static equivalent pressure at the reflection was a factor of 23 larger than the static equivalent pressure for stable detonation: $p_{stat\_reflection} = 23 \cdot p_{stat\_stable}$.

f: Both employed pipe materials P235GH and 1.4541 yield the same correlations between p_{stat} and p_{CJ_r} .

5. Conclusions

By the pipe deformation method, which automatically accounts for the hard-to-quantify structural effects of the highly dynamic detonative loads (yield strength increase due to high strain rates, short axial entension of zone under pressure at the DDT-location, ratio between peak duration and cycle time of breathing mode) it was possible for the first time to establish reliable static equivalent pressures for all different pressure scenarios that can be distinguished for a gas phase detonation in a pipe. For scenarios 3 and 4 (stable detonation and reflected stable detonation) p_{stat} is simply a multiple of the Chapman-Jouguet pressure ratio p_{CJ_r} of the involved mixture, and hence the determined correlations between p_{stat} and p_{CJ_r} will also be valid for other detonable gas mixtures. For the other scenarios, which are all more or less related to the DDT (1,2,5,6,7,8), p_{stat} will depend on additional parameters involving at least $T_{initial}$ and $T_{autoignition}$. Hence, the determined correlations are so far only valid for the mixture used in the tests.
A follow-up project intended to determine the functional dependencies for these other scenarios will be carried through in 2013.

6. References

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