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Experimental Determination of the Static Equivalent Pressures of Detonative Explosions of Cyclohexane/O_2/N_2-Mixtures in Long and Short Pipes (part 1of 3)

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In the past 5 years the Safety Engineering Group of BASF had determined the static equivalent pressures (“p_{stat}”) of the eight detonative pressure scenarios which explosive gas mixtures can exhibit in long and in short pipes. More precisely, for different combustibles the p_{stat}-values of the corresponding ternary mixtures combustible/O_2/N_2 were determined on the stoichiometric line and on the O_2-line of the explosion triangle. By doing so, the p_{stat}-values of all other compositions inside the explosion triangle could be predicted by extrapolation with an accuracy sufficient for practical applications. Furthermore, a proposal of how to transfer these results to the huge number of other combustibles not investigated so far was provided. A key-parameter in this context was the ratio R between the static equivalent pressure at the point where the deflagration-to-detonation transition occurs in the long pipe and the static equivalent pressure in the region of the stable detonation.

In the present work the p_{stat}-values of the new ternary mixture cyclohexane/O_2/N_2 are reported. Cyclohexane is of special interest because its autoignition temperature (AIT) in air is substantially lower than the AIT-values of all combustibles that had been tested before. According to our hitherto existing understanding the low AIT should noticeably reduce the ratio R. The experiments, however, did not confirm this hypothesis. After presenting the experimental results, which actually confirm the findings for the combustibles investigated so far, an explanation for the unexpected behaviour regarding R will be presented in terms of the differences between the low-temperature and the high temperature oxidation mechanism. As kind of spin-off, this explanation also allows to better understand quantitatively the degree of precompression in the yet unreacted mixture required for the occurrence of the deflagration-to-detonation Transition (DDT).

1. Introduction

In chemical process plants explosive gas mixtures with compositions in the potentially detonative regime can occur. Since effective ignition sources can in general not be excluded with certainty and since explosion pressure venting cannot be applied for detonative explosions, the only method to ensure safe operation is detonation pressure resistant design of the affected plant components. Because no guidelines giving recommendations for detonation pressure resistant design had been available, BASF launched a research project 5 years ago to determine the static equivalent pressures (“p_{stat}”) of the 8 detonative pressure scenarios occurring inside long and short pipes. (For quantifying the p_{stat}-values of detonations in vessel-geometry BASF started research in 2019). The results for pipes can be found in Schildberg (2013, 2014, 2015, 2016a and 2018) and in TRGS407 (2016). In Schildberg (2016b) a general overview of the entire detonation issue in pipes is provided (explanation of the 8 different pressure scenarios, experimental technique, definition of p_{stat}, explanation of the key-parameter R, application of p_{stat} for designing pipes detonation pressure resistant, generalization of the results to combustibles other than those tested).

The key-parameter R is the ratio between the static equivalent pressure at the point where the DDT occurs in a long pipe and the static equivalent pressure in the region of the stable detonation. This ratio – in combination with the Chapman-Jouguet pressure ratio, which can be calculated in straightforward manner from the thermodynamic properties of the mixtures in question for any value of the initial temperature and pressure –

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is the key to quantitatively predict the static equivalent pressures of all design relevant detonative pressure scenarios occurring when explosive gaseous mixtures undergo a DDT inside pipes. A recommendation for the values to be expected for R over the entire detonative regime of the explosion triangle of a common combustible/O_2/N_2-mixture at ambient temperature is given in chapter 7 of Schildberg (2018). By applying this diagram a pretty good estimate for the static equivalent pressures of any combustible/O_2/N_2 mixture is possible.

Based on the conception of the transition to detonation described in Schildberg (2016b) the hypothesis emerged that combustibles with low autoignition temperatures (AIT) in air (e.g. in the range from 200 °C to 250 °C at 1 bar abs as shown by all alkanes and alkenes with more than 5 C-atoms) might exhibit substantially smaller values for R than found for the combustibles investigated so far, which all had AIT-values between 440 °C and 590 °C (always at 1 bar abs and in air). This hypothesis was based on the assumption that if a mixture M_1 autoignites at a lower temperature than a mixture M_2, the temperature at which the induction time for autoignition becomes small enough (less than about 10 µs) to allow for autoignition in the precompressed unreacted gas directly ahead of the reaction gases (this is the moment of DDT-occurrence) generated during the initial deflagrative stage of the explosion should also be lower for mixture M_1 than for mixture M_2. To explain why this hypothesis follows from the abovementioned assumption let us briefly recall the DDT-mechanism:

The expanding reaction gases act like an ever faster accelerating piston (final acceleration of the order of 1000000 m/s^2 and final speed relative to the pipe wall of the order of 1000 m/s to 1300 m/s) on the yet unreacted mixture ahead of the flame front and, consequently, generate a narrow zone (narrow in axial direction) of ever more compressed unreacted mixture directly ahead of the flame front, because the speed of the piston relative to this mixture is larger than the speed of sound in this mixture, i.e. the mixture gets shocked. Because the temperature in the precompressed mixture rises with the precompression ratio (ratio between initial pressure in the mixture at the moment of ignition and the instantaneous pressure in the precompressed mixture ahead of the flame front), the precompression ratio in mixture M_1 at the moment of DDT-occurrence should be lower than in mixture M_2, if the assumption from above were valid. Consequently, the ratio between p_{stat} at the location of the DDT and p_{stat} in the region of the stable detonation should be lower for mixture M_1 than for mixture M_2.

To check the validity of this hypothesis the p_{stat}-values of cyclohexane/O_2/N_2 mixtures were determined in long and short pipes. The AIT of cyclohexane (C_6H_{12}) in air at 1 bar abs is 260 °C (CHEMSAFE database).

2. Experimental procedure for determination of p_{stat}-values of cyclohexane/O_2/N_2 mixtures

Figure 1 exemplarily shows the flammable range of the ternary mixture C_6H_{12}/O_2/N_2 at 1 bar abs and 170 °C in the form of an explosion triangle. The yellow dashed-dotted stoichiometric line is based on the reaction equation $C_6H_{12} + 9\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O$. The solid yellow line denotes the air line. At the intersection of both lines the concentrations are: C_6H_{12} = 2.28 vol.-%, O_2 = 20.52 vol.-%, N_2 = 77.2 vol.-% (i.e, air (O_2+N_2) = 97.72 vol.-%). The explosion diagrams were measured by BASF in a spherical 20 l vessel.

The black crosses and open circles in Figure 1 mark the mixtures which were investigated in long pipes. Several of these mixtures were measured both at 80 °C and 130 °C. All 6 mixtures tested in short pipes were stoichiometric and had O_2 concentrations between 20.5 vol.-% and 29 vol.-% (these mixtures are not marked by symbols in Figure 1). The red dashed arrow marks the region where the DDT was immediately followed by the stage of stable detonation under omission of the stage of unstable detonation.

The detonation tests were carried out in straight pipes made of stainless steel (DIN-code: 1.4541) with lengths between 9.2 m and 9.6 m. The formats were 48.3x2.6 (outer diameter [mm] x wall thickness [mm]) and 114.3x3.6. Piezoelectric pressure sensors (Manufacturer: PCB, Types: M112A05, 0-345 bar and 113B03, 0-1035 bar) were mounted in the walls at distances of about 320 mm and 640 mm. The details of the experimental procedure, i.e. the mechanical characterization of the employed pipes and the carrying out of the actual detonation tests, was analogous to the tests presented and explained in detail in Schildberg (2013, 2014, 2015, 2016a). The bulging characteristics (i.e. the increase of the pipe diameter in dependence of the inner hydraulic pressure, which was continuously increased until rupture occurred) of the three different pipe melts used in the present tests can be found in Schildberg (2013, 2015). In all tests a displacement body was present inside the welding neck flange at the end of the pipe, i.e. opposite to the side where the ignition source was mounted. By doing so, the reflection of the shock front at the blinded pipe end occurred at a location where the wall still had the normal thickness and not the much larger thickness of the welding neck flange.

Because the tests had to be conducted at elevated initial pressures in order to produce residual plastic deformations in the walls of the pipes employed, the tests had to be conducted at elevated initial temperatures.

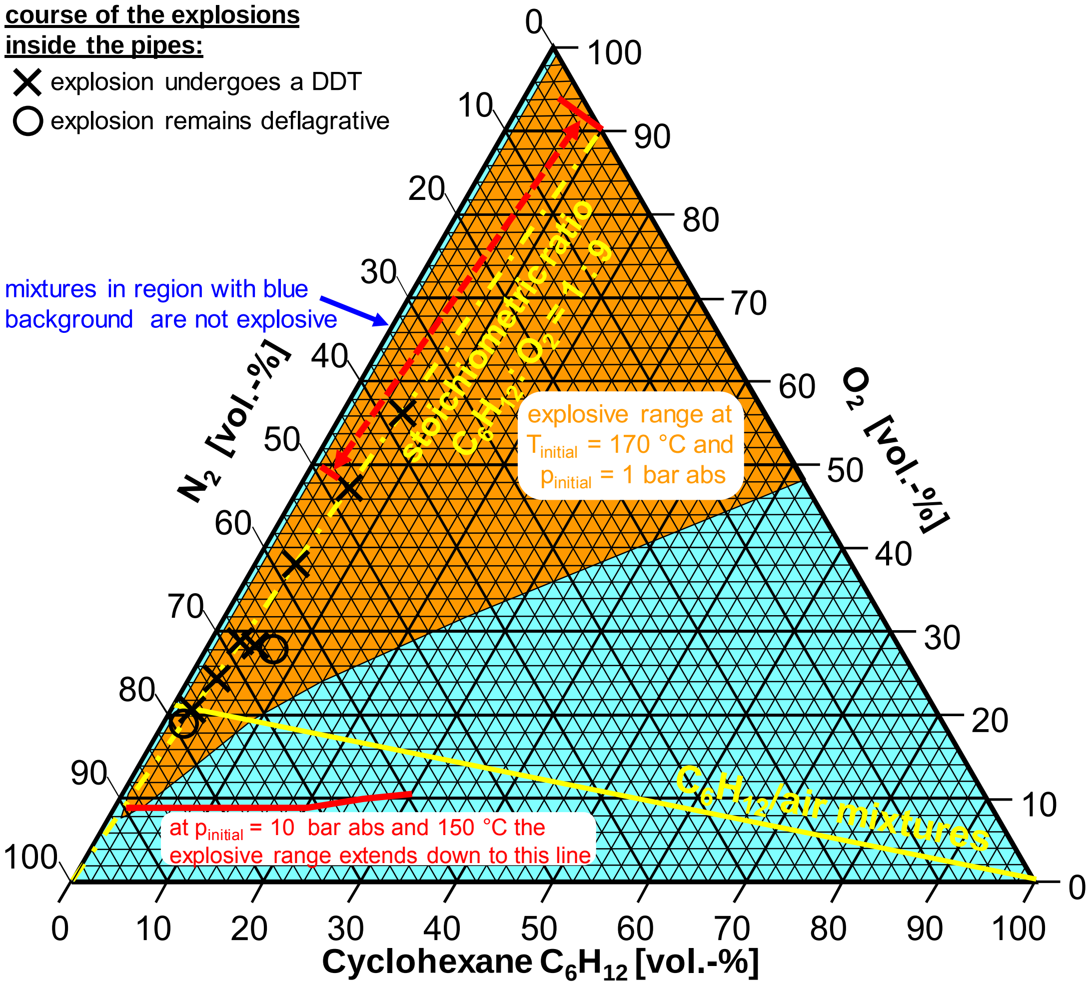

Figure 1: Explosion triangle of C6H12/O2/N2 at 1 bar abs and 170 °C. The lower and upper flammability limits (LFL and UFL) are: LFL in O2: 0.5 vol.-%, UFL in O2: 52.0 vol.-%, LFL in air: 0.5 vol.-%, UFL in air: 9.0 vol.-%, Limiting oxygen concentration: 8.0 vol.-%. In addition, the lower boarder of the explosive range at pinitial = 10 bar abs and 150 °C is shown. C6H12 concentrations larger than 30 vol.- % could not be investigated at 10 bar abs because autoignition occurred while injecting O2 into the test vessel.

Otherwise the vapour pressure of cyclohexane would not have been sufficient to produce explosive $C_6H_{12}/O_2/N_2$-mixtures (vapor pressures of C_6H_{12} at 20, 70, 80, 130 and 170 °C: 103, 724, 989, 3600, 8027 mbar, respectively). Figure 2 displays how the pipe was heated and insulated. Temperature was controlled by several thermocouples clamped onto the surface of the pipe.

Mixtures of $C_6H_{12}/O_2/N_2$ were produced in a 100 l vessel, which was heated up to 130 °C, according to the partial pressure method. The vessel was first evacuated and then filled with nitrogen up to 1 bar abs. Then liquid cyclohexane was pumped into the vessel by means of a HPLC-pump while controlling the weight loss in the cyclohexane reservoir. The pressure rise inside the vessel due to immediate evaporation of the cyclohexane was in good agreement with the mass injected under the assumption of ideal gas behavior. Thereafter nitrogen was injected up to the required partial pressure. Then an assembly of 4 fans inside the vessel was started, thereby producing a closed loop flow around a baffle plate mounted in axial direction. With the fans running, oxygen was injected as last component up to the required partial pressure. Before the mixture was allowed to flow into the heated and evacuated test pipe, the test pipe was flooded with nitrogen up to a pressure about 2 bar less than the pressure inside the vessel. When mixing was completed, the high pressure valve between the vessel and the test pipe was opened (ϕ_i = 6 mm). Thereafter an opening (ϕ_i = 4 mm) in the blind flange at the end of the test pipe was opened to the off gas such that the combustible mixture from the vessel pushed out the nitrogen in test pipe by plug flow. When reaching the desired initial pressure for the test (at this moment the nitrogen inside the test pipe had been replaced at least two times by the combustible mixture), all valves were closed and the mixture was ignited. By this filling procedure the fast expansion of the combustible mixture with concomitant cooling and potential condensation of cyclohexane as well as adiabatic compression effects at elbows or tees in the pipework (risk of autoignition) are avoided.

Figure 2: Details of the heating and the insulation. Two electrical heating cables with same power per length were attached on both sides of the pipe over the entire length (white strips in the picture). Then the pipes were enclosed by a 4 cm thick thermal insulation. The green cable in the left photo is from a piezoelectric pressure transducer mounted in the wall. On the right photo the feed gas pipe and the air-operated high-pressure valve can be seen (both components were heated by electrical heating cables and were wrapped in aluminum foil). This valve separates the feed gas section from the test pipe.

3. Experimental results for p_{stat}-values of cyclohexane/O_2/N_2-mixtures

Table 1 summarizes the results of all tests. The following comments a) to h) provide some explanations to this table:

a) No transitions to detonation did occur for stoichiometric C_6H_{12}/O_2/N_2 mixtures with O_2-concentrations of 19 vol.-% (in the total mixture) and less.

b) Correcting the static equivalent pressures for the influence of bulging was done as explained in Schildberg (2013), i.e. it was assumed that when the wall of a pipe 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 derived from such a test will also be less than it would have been if the test had been conducted using a pipe with a thicker wall which would have exhibited a smaller diameter increase. The corrected values were obtained from the measured values by multiplication with the relative increase of the cross section of the pipe.

c) In the present tests bulging of the stainless steel pipes (all with DIN code 1.4541) occurred at temperatures between 70 °C and 130 °C. To account for the slight softening of the stainless steel at the elevated temperatures, the static equivalent pressures determined on the basis of the bulging characteristics at 20 °C (Schildberg 2013, 2015) were corrected by multiplying with the ratio between the yield strength ($R_{p0.2}$) at the elevated temperature and the yield strength at 20 °C. According to the material data sheets availabe for 1.4541 the minimum $R_{p0.2}$-values the manufactures have to guarantee change as follows for the temperatures of 20, 70, 80, 115 and 130 °C: 210, 190.6. 190.6, 180.6, 178 N/mm^2.

d) To reduce the experimental effort, the same pipes were sometimes used for several tests conducted successively with increasing O_2-concentration (see column AM). By doing so, the DDT always occurred in a pipe section having not been exposed to a detonative load before, because when increasing the O_2-concentration the predetonation distance drops. Because the focus of the experimental work was on the determination of the static equivalent pressure at the location of DDT occurrence, this goal could still be reached under clean experimental conditions. However, by this reduction of experimental effort the reflection at the blind flange of the pipe sometimes occurred in a section that had already been bulged slightly by the preceding test.

Table 1: Compilation of the experimental conditions and results of all conducted detonation tests with $C_6H_{12}/O_2/N_2$ at different initial conditions. The lower table is the continuation of the upper table to the right side. To ease reference, the columns B and C are repeated in the lower table. Note that the tables use the German convention for decimal points. Abbreviation "bf." in column AM stands for "blind flange".

	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	T	U	V	W	X
1		Data of pipe				Data of $C_6H_{12}/O_2/N_2$ gas mixture												Diameter increase at location of DDT				
2	number of test	pipe dimension: outer diameter [mm] x wall thickness [mm]	number of the melt of the material use for manufacturing the pipe	inner pipe diameter [mm]	length of pipe (effective for the enclosed gas mixture) [mm]	initial pressure of the gas mixture used in the test $p_{initial}$ [bar abs]	initial temperature of the gas mixture used in the test [°C]	chosen O_2-concentration in O_2/N_2 mixture [vol.-%]	stoichiometric C_6H_{12} concentration in total mixture [vol.-%]	chosen C_6H_{12}-concentration in total mixture [vol.-%]	resulting O_2-concentration in total mixture [vol.-%]	resulting N_2-concentration in total mixture [vol.-%]	calculated* speed of sound in $C_6H_{12}/O_2/N_2$-mixture at initial temperature [m/s]	measured speed of stable detonation [m/s]	calculated* speed of stable detonation [m/s]	calculated* Chapman-Jouguet pressure ratio p_{CJ_r} [-]	calculated* Chapman-Jouguet pressure $p_{CJ} = p_{initial} * p_{CJ\_r}$ [bar abs]	measured strain caused by DDT [%]	static equivalent pressure at DDT $p_{stat\_DDT\_m}$ (as derived from strain as measured) [bar abs]	static equivalent pressure at DDT $p_{stat\_DDT\_c}$ (corrected for influence of bulging) [bar abs]	static equivalent pressure at DDT $p_{stat\_DDT\_c}$ (corrected for elevated temperature**) [bar abs]	ratio $p_{stat\_DDT\_c}/p_{stat\_stable}$ [-]
3		**Experiments in long pipes (exception is test 19, here reflection at pipe end is scenario 7, but DDT is scenario 1), format 48.3 x 2.6, tests at 70 °C and 80 °C**																				
4	1	48.3 x 2.6	584549	43,1	9260	20,00	70,00	21,00	2,280	2,280	20,521	77,199	356,00	1955	1855	16,65	333,04	27,5	630,00	1024,14	929,92	3,99
5	19	48.3 x 2.6	836880	43,1	9390	14,10	80,00	25,00	2,703	2,703	24,324	72,973	358,00	2069	1920	17,45	246,00	26,5	500,00	800,11	726,50	4,22
6	20	48.3 x 2.6	836880	43,1	9390	14,00	80,00	30,00	3,226	3,226	29,032	67,742	354,00	2045	1991	19,14	268,00	16,7	506,00	689,12	625,72	3,34
7	21	48.3 x 2.6	836880	43,1	9390	14,00	80,00	40,00	4,255	4,255	38,298	57,447	346,00	2121	2101	22,00	308,00	25,6	504,00	795,08	721,93	3,35
8		**Experiments in long pipes (exceptions are tests 5 and 22: reflections at pipe ends are scenario 7; for test 22 the DDT is scenario 5, for test 5 the DDT is scenario 1), format 48.3 x 2.6, most tests at 130 °C**																				
9	5	48.3 x 2.6	584549	43,1	9260	20,00	130,00	21,00	2,280	2,280	20,521	77,199	385,00	1994	1853	14,20	284,00	18,12	600,00	837,14	711,57	3,58
10	22	48.3 x 2.6	836880	43,1	9390	14,00	130,00	25,00	2,703	2,703	24,324	72,973	381,00	2032	1917	15,36	215,00	22,5	505,00	757,82	644,14	4,28
11	25	48.3 x 2.6	836880	43,1	9390	12,00	130,00	30,00	3,226	3,226	29,032	67,742	376,00	2010	1984	16,74	200,90	10,14	488,00	591,98	503,19	3,58
12	28	48.3 x 2.6	836880	43,1	9390	12,00	130,00	30,00	3,226	4,600	28,620	66,780	368,00	2095	2032	17,90	214,80	17,81	510,00	707,84	601,66	4,00
13	27	48.3 x 2.6	836880	43,1	9390	12,00	130,00	30,00	3,226	6,700	27,990	65,310	357,00	(no det.)	1921	16,43	197,20	no transition to detonation, mixture too rich				
14	23	48.3 x 2.6	836880	43,1	9390	12,00	130,00	40,00	4,255	4,250	38,300	57,450	368,00	2123	2091	19,17	230,00	13,66	500,00	645,93	549,04	3,41
15	29	48.3 x 2.6	836880	43,1	9390	17,00	130,00	50,00	5,263	5,263	47,369	47,369	360,00	2189	2188	21,59	367,00	1,1	380,00	388,41	330,15	1,29
16	26	48.3 x 2.6	836880	43,1	9390	17,00	130,00	60,00	6,250	6,250	56,250	37,500	353,00	2272	2261	23,71	403,00	1,95	420,00	436,54	371,06	1,32
17	24	48.3 x 2.6	836880	43,1	9390	12,00	115,00	60,00	6,250	6,250	56,250	37,500	347,00	2280	2251	24,33	292,00	0				
18		**Experiments in short pipes, format 114.3 x 3.6, at 130 °C**																				
19	30	114.3x3.6	878536	107,1	9570	3,17	130,00	21,00	2,280	2,280	20,521	77,199	385,00	(no det.)	1824	13,02	41,27	no transition to detonation				
20	31	114.3x3.6	878536	107,1	9570	3,17	130,00	25,00	2,703	2,703	24,324	72,973	381,00	(no det.)	1888	14,11	44,73	no transition to detonation				
21	32	114.3x3.6	878536	107,1	9570	3,07	130,00	30,00	3,226	3,226	29,032	67,742	376,00	1940	1951	16,19	49,69	3,59	242,00	259,69	220,73	6,35
22	33	114.3x3.6	878536	107,1	9600	2,80	130,00	27,00	2,913	2,913	26,213	70,874	379,00	(no det.)	1912	15,39	43,10	no transition to detonation				
23	34	114.3x3.6	878536	107,1	9600	3,17	130,00	28,50	3,069	3,069	27,625	69,306	378,00	(no det.)	1934	15,83	50,18	no transition to detonation				
24	35	114.3x3.6	878536	107,1	9600	3,17	130,00	30,00	3,226	3,226	29,032	67,742	376,00	2303	1952	16,20	51,35	1,84	221,00	229,21	194,83	5,42

	B	C	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ	AK	AL	AM
1		Data of pipe	Diameter increase by stable detonation					Diameter increase upon reflection at blind flange					Characteristic distances and times				pipe history
2	number of test	pipe dimension: outer diameter [mm] x wall thickness [mm]	measured strain caused by stable detonation [%]	static equivalent pressure of stable detonation $p_{stat\_stable\_m}$ (as derived from strain as measured) [bar abs]	static equivalent pressure of stable detonation $p_{stat\_stable\_m}$ (corrected for elevated temperature**) [bar abs]	static equivalent pressure of stable detonation $p_{stat\_stable\_c}$ (corrected for influence of bulging) [bar abs]	ratio $\alpha = p_{stat\_stable\_c} / p_{CJ}$ [-]	measured strain caused by reflection at blind flange [%]	static equivalent pressure of reflected detonation $p_{stat\_reflection\_m}$ (as derived from strain) [bar abs]	static equivalent pressure of reflected detonation $p_{stat\_reflection\_m}$ (corrected for elevated temperature**) [bar abs]	static equivalent pressure of reflected detonation $p_{stat\_reflection\_c}$ (corrected for influence of bulging) [bar abs]	ratio $p_{stat\_reflection\_c} / p_{stat\_stable}$ [-]	location of DDT as inferred from pipe deformation [mm]	predetonation distance expressed as multiple of inner pipe diameter	end of region of unstable detonation [mm]	time interval until DDT occurred, counted from the instant of ignition [ms]	
3		**Experiments in long pipes (with few exceptions), format 48.3 x 2.6, tests at 70 °C and 80 °C**															
4	1	48.3 x 2.6	0					8,39	552,00	501,22	588,85	2,53	3740	86,8	8100	23,5	new pipe
5	19	48.3 x 2.6	no stable detonation					15,5	505,00	458,54	611,70	3,55	4530	105,1	9390	33,5	new pipe
6	20	48.3 x 2.6	0					6,4	450,00	408,60	462,57	2,47	3060	71,0	6700	16,3	first 6 m reused from test 19, last 3 m new
7	21	48.3 x 2.6	0					11,6	490,00	444,92	489,47	2,27	1710	39,7	2200	**26,0**	from test 20, at bf. already 6.4% bulging
8		**Experiments in long pipes (with few exceptions), format 48.3 x 2.6, most tests at 130 °C**															
9	5	48.3 x 2.6	no stable detonation					rupture due to scenario 7 (reflection of unstable detonation)					4750	110,2	9260	30,6	new pipe
10	22	48.3 x 2.6	no stable detonation					rupture due to scenario 7 (reflection of unstable detonation)					6140	142,5	9390	36,0	new pipe
11	25	48.3 x 2.6	0					4,35	440,00	374,00	407,25	2,90	3430	79,6	7100	16,2	new pipe
12	28	48.3 x 2.6	0					2,9	423,00	359,55	380,71	2,53	2980	69,1	4300	12,1	from test 27, i.e. still without bulging
13	27	48.3 x 2.6									0,00						new pipe
14	23	48.3 x 2.6	0					2,69	418,00	355,30	374,67	2,33	1690	39,2	1800	4,7	first 6 m reused from test 22, last 3 m new
15	29	48.3 x 2.6	1,1	380,00	323,00	330,15	0,90	20,3	510,00	433,50	592,50	2,31	<310	<7,2	(no unst)	< 1,2	from test 28, at bf. already 2.9% bulging
16	26	48.3 x 2.6	1,95	420,00	357,00	371,06	0,92	20,9	510,00	433,50	581,91	2,06	<310	<7,2	(no unst)	<0,7	from test 25, at bf. already 4.35% bulging
17	24	48.3 x 2.6	0					6,4	455,00	391,30	420,08	2,06	<950	<22	(no unst)	<1,2	from test 23, at bf. already 2.69% bulging
18		**Experiments in short pipes, format 114.3 x 3.6, at 130 °C**															
19	30	114.3x3.6															new pipe
20	31	114.3x3.6															from test 30
21	32	114.3x3.6	no stable detonation					17,76	320,00	272,00	377,19	10,84	7910	73,9	9570	41,0	from test 31, i.e. still without bulging
22	33	114.3x3.6															new pipe
23	34	114.3x3.6															from test 33
24	35	114.3x3.6	no stable detonation					11,9	285,00	242,25	303,34	8,44	7540	70,4	9600	38,5	from test 34, i.e. still without bulging

Explanations:

**: Calculated using GASEQ (2005) for the respective initial pressure, initial temperature and mixture composition (columns N, P, Q).*

***: the average decrease of the yield strength with increasing temperature was accounted for. At 70 °C and 80 °C the yield strength is about 90.8 % of the value at 20 °C, at 115 °C it is 86 % and at 130 °C it is 85 % (columns W, AA, AF).*

(no unst.): There was no region with unstable detonation, since the flame front overtook the initial pressure wave already before the DDT occurred.

magenta text in column O for tests 19, 5, 22, 32 and 35: This is the speed of the unstable detonation, because for these tests there was no stable detonation as consequence of the pre-detonation distance being very long and the pipe length being only about twice the pre-detonation distance.

blue text in columns T to X for tests 22, 32 and 35: The DDT is scenario 5 and not scenario 1 as for all other tests. The reason is the same as given above in context with the magenta-coloured text.

blue text in columns AD to AH for tests 19, 5, 22, 32 and 35: The reflection is scenario 7 and not scenario 4 as for all other tests. The reason is the same as given above in context with the magenta-coloured text.

In these cases, the correction for bulging at the blind flange was done in the same way as for new pipes, i.e. the static equivalent pressure, as taken from the strain/pressure diagrams determined in the hydraulic tests, was multiplied by the cross section of the pipe after the test divided by the cross section the already bulged pipe exhibited prior to the test. (Example: the value in field AG15 (592.50) is calculated by multiplying AF15 (433.50) by $(100+AD15)^2$ / $(100+AD12)^2$).

e) In column AL, the duration between the moment of ignition and the occurrence of the DDT is specified. The experimental error in these values is in the order of ±1.5 ms, because the duration of the arc discharge used for igniting the mixture was 3 ms. Although values of 0.5 ms could be defined mathematically as difference between t = 0 and the time coordinate of the leading edge of the first pressure peak associated with a detonation, all values less than about 3 ms should be interpreted as indication that the detonative reaction was either directly triggered by the ignition source or that the initial deflagrative stage extended over a few centimeters only.

f) In test no. 21 a very long value of 26 ms was found for the time interval until DDT occurrence. In this test a wire with a fivefold larger diameter was erroneously mounted between the two poles of the ignition source. This wire was only glowing but did not melt such that the arc discharge, which is a much more effective ignition source than a thin glowing wire, did not develop. A test with a correctly working ignition source and the same mixture composition and with almost the same initial pressure (test 23) yielded 4.7 ms as time interval, but the DDT occurred at about the same location. This means that the predetonation distance is obviously totally unaffected of these differences in the ignition process.

g) All values measured for the propagation speed of the stable detonation agreed extremely well with the values calculated by GASEQ (2005). The propagation speed of the unstable detonation was on the average 7 % faster (140 m/s faster) than the value calculated for the stable detonation. Tests 32 and 35 were disregarded in this context, because in these tests the distance, over which the unstable detonation propagated, was too short for to derive a reliable value.

h) Within the time slot available for carrying out the experiments in our concrete bunker we did not succeed in producing scenario 8, i.e. coalescence of DDT and reflection. All 4 tests we conducted with initial conditions chosen such that a slightly longer predetonation distance than found for tests 32 and 35 should result ended up in a purely deflagrative explosion.

Figure 3 displays examples for plastic deformations generated by the detonation tests. Figure 4 provides examples for the bulging as function of axial position.

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GASEQ, 2005, is a chemical equilibrium program for windows. The code is freeware and can be downloaded from http://www.c.morley.dsl.pipex.com/ or http://www.gaseq.co.uk.