Multidiszciplináris tudományok, 12. kötet. (2022) 3 sz. pp. 207-216 **https://doi.org/10.35925/j.multi.2022.3.19**

GAS EXPLOSION VENTING OF 20-LITRE VESSEL WITH AND WITHOUT VARIOUS LENGTH OF VENT DUCTS

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Abstract

When gas explosion occurs in closed vessel, venting devices can reduce the pressure inside the protected equipment, and vent ducts can be used to direct burnt and unburnt mixtures. In this paper, some ductless and duct vented explosion measurements were performed in a standard 20-liter explosion chamber with 2.8 to 6.3 vol.% propane-air mixture at atmospheric pressure (1 bar_g) and ambient temperature (298 K). Experimental investigations were performed with different lengths of vent duct (0 meter, 0.15 meter, 1 meter). During the measurements, effects of vent ducts to the venting process had been studied. Aluminium foils were used as rupture disks with 30 mm diameter circular venting area. During each measurement, static activation overpressure of aluminium foil, maximum explosion overpressure of propane-air mixture, the gas deflagration index in case of the vented vessel, and the pressure drop along the 1 meter length duct were determined.

Keywords: *propane explosion, measurement, vent, pressure drop*

1. Introduction

Hazardous gas or fluid leakages and dusts occur in many fields of industry. They can be caused by false valve openings, improper seals, incorrectly fitted flanges, mechanical injuries of closed systems, storage and handling devices etc. Evaporation of liquid, spread of the gas or developing of dust clouds can be prone to ignition in open field and also in closed areas (Tugyi et al., 2021). Dust safety science report made by Cloney (Cloney, 2021) summarized incidents worldwide between January and June of 2021. related to dusts: 8 fatalities, 28 dust explosions and 51 fire incidents. It is evident, that explosion protection provisions are essential in industry.

Explosion protection has three levels: primary, secondary, and tertiary protection. The aim of primary protection is to replace or reduce to safe amount the explosive materials or oxygen in the technology. Secondary explosion protection covers solutions to prevent formation of ignition sources or their effects in hazardous areas (Király et al., 2021). Tertiary protection includes avoidance of flame spread, suppression, and venting when explosion has already been occurred. Since probability of the occurrence cannot be eliminated perfectly, tertiary protection is essential in technologies which handles combustible or explosive materials. During explosion in a closed volume (e.g., vessel, technology apparatus, building etc.), the pressure rises quickly to maximum explosion overpressure (P_{max}), which can exceed maximum allowable pressure of the enclosure or the building. The rate of pressure rise (dP/dt) is a significant value too, which is the slope of the inflection point of the pressure curve in time. These characteristics depend on the concentration of the fuel in the mixture between lower and upper explosibility limits. From the rate of pressure rise, a well-comparable K_{max} deflagration index can be produced with the Eq. (1) cubic root law, and which is marked with K_G in case of gas mixtures.

$$K_{max} = \left(\frac{dP}{dt}\right)_{max} \cdot V^{1/3} \tag{1}$$

The maximum pressure values and deflagration indexes can be used to design proper venting protection for enclosures. Explosion venting devices, when pressure inside the vessel reaches their P_{stat} static activation pressure, become open in their full area and reduce the pressure inside the vessel (to $P_{red,max}$ reduced explosion overpressure), below the resistance of protected equipment. In this case, flames and burnt with unburnt components release into the environment, which can cause serious damage in the other enclosures and pipelines around, and in the health of employees. To reduce the effect of the released flames, e.g., quenching tubes are applicable. To direct the flames without their extinction, deflector plates and/or vent ducts can be used, which – with their hydrodynamical resistance and subprocesses in the duct – can prevent proper venting and makes reduced explosion overpressure higher again. Physical phenomena which occur in the duct during venting, in early researches can be found (Ponizy and Leyer, 1999):

- friction losses, and outflow through hole with sharp edges to the vent duct,
- inertia of the gas column in the duct,
- burn-up in the duct,
- acoustic oscillations.

The presence of the duct not only causes increase of pressure in the device, but for longer lengths (l > 10-20 m) the velocity of the flow in the duct can exceed the speed of sound and turn into detonation (Schildberg, 2018). For this reason, it is recommended to design the vent ducts shorter than 10 meters and with higher resistance than 10 bar_g (NFPA 68, 2002).

For the calculation of the ducted reduced overpressure, some of the ruling standards, such as EN 14491 (EN 14491, 2012), EN 14994 (EN 14994, 2007), NFPA 68 (NFPA 68, 2018) and VDI 3673 (VDI 3673, 2002) contain applicable correlations. However, their using obligated to strict conditions, which are not always can be used in practice.

This paper describes the venting experimental results in a standard 20-liter explosion chamber with 2.8 to 6.3 vol.% propane-air mixture at atmospheric pressure and ambient temperature. Experimental investigations were performed with different lengths of vent duct (0 meter, 0.15 meter, 1 meter). In this article, author investigated effects of vent ducts to the venting process, more specifically, to the maximum explosion overpressure and the deflagration index.

2. Measurements

2.1. Experimental set-up

Author performed the tests in a test chamber, made by Kühner. Main parts of the chamber were designed according to the principles of standard EN 14034-2:2006+A1:2011 (EN 14034-2, 2006). The test chamber is a 20-liter sphere with double stainless steel wall, which is used as water-cooled jacket to control the test temperatures. The explosion pressure inside the vessel is recorded with three independent pressure transducers of 9,600 Hz. The process control and data acquisition unit operated on the computer with data collection function.

Propane-air mixtures with 2.8, 3.8, 4.8, 5.8 and 6.3 vol.% were used in experiments. Air was applied from the environment for more realistic circumstances. For testing, the gas in proper concentration is dispersed into the vacuumed chamber via gas filling nozzle. The ignition source was in the centre of the sphere. For gases, it is an electric spark, with computer-regulated 10 J energy.

To increase the reliability of the measurements, a filling chamber was applied with 0.6 litre volume. Its function was to fill the required amount of propane to the 20-liter chamber. The desired propane amount was checked by a pressure transducer placed in the filling chamber, also at 9,600 Hz.

Scheme of complete measurement setup with the gas filling chamber is shown in Figure 1. At the figure, '*1*' means gas filling chamber, '*2*' means Kühner explosion chamber. '*P1*' shows pressure transducer connected to the filling chamber and '*P2*' shows pressure transducer connected to explosion chamber. Both were P6A type, made by Hottinger Brüel & Kjaer GmbH. The chamber originally is equipped with, and ignition process was controlled automatically by '*K1*' and '*K2*' Kistler piezoelectric pressure transducers.

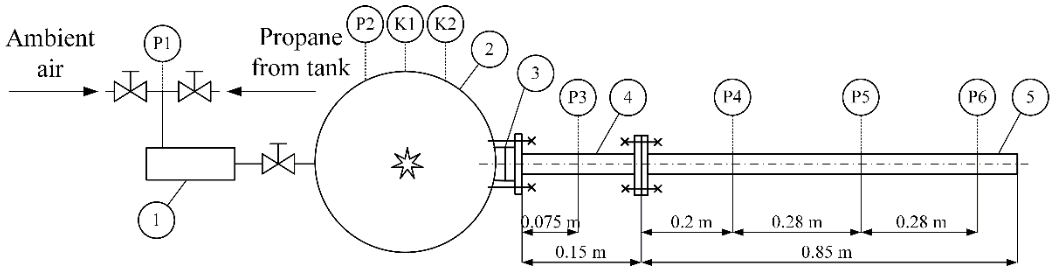

***Figure 1.** Scheme of the experimental setup*

For installing additional elements to the chamber, a nozzle can be used to set up. In current experiments, rupture disks and vent ducts were installed to the nozzle. Aluminium foils were used as rupture disks with 30 mm diameter circular venting area, between special clamping tools, marked with '*3*' in the figure. '*P3*' to '*P6*' show pressure transducers along the duct(s). They were P6A type, made by Hottinger Brüel & Kjaer GmbH, too. Measurement limit of every Hottinger pressure transducers were 10 bar_g. Pressures in the vent ducts during explosion were recorded with 9600 Hz.

'*4*' marks the vent duct with 0.15 meter length, and '*5*' relates to the 1 meter duct. Duct lengths of 0 m (without vent duct), 0.15 m and 1 m with inner diameter of 30 mm were selected for the measurements.

2.2. Experimental process

Experimental studies were performed at atmospheric pressure (1 bar_g) and ambient temperature (298 K), according to the same filling process as described in (Mikáczó et al., 2022). Since authors of (Mikáczó et al., 2022) proven that measurement method correlates with wide range of literature data (in case of propane explosion in closed vessel), current investigations can be performed according to the same filling and data collecting method. Author performed three types of measurements to investigate the effect of the vent duct to maximum explosion overpressure and deflagration index:

- vented explosion without vent duct (with '*1*', '*2*', '*3*' devices),
- vented explosion with 0.15 meter length vent duct (with '*1*', '*2*', '*3*', '*4*' devices),
- vented explosion with 1 meter length vent duct (with '*1*', '*2*', '*3*', '*4*', '*5*' devices).

During each measurement, four main parameters of explosion were determined:

1. the set pressure of aluminium foil (P_{stat}),
2. the reduced maximum explosion overpressure of propane-air mixture ($P_{red,max}$),
3. the gas deflagration index (K_G) in case of the vented vessel, and
4. pressure drop along the 1 meter length duct.

Besides the pressure in the chamber, measured values of '*P3*' to '*P6*' were recorded. As mentioned earlier, the tests were performed with propane-air mixture. The compositions of the mixtures were 2.8, 3.8, 4.8, 5.8 and 6.3 vol.% propane in air. For each concentration, at least five different measurements were developed, discarding the smallest and largest of these, and averaging the others, to reduce the deviation of the results. Furthermore, as it can be seen from the description of the measurement, the pressure values in the explosion chamber were recorded by three independent pressure transducers, so that the characteristic values for a single concentration is the average of at least nine different measurements.

2.2.1. Acceptable tolerances

Tolerances of $P_{red,max}$ reduced maximum explosion overpressures should be equal or below 10%. According to EN 14031-1 standard, these tolerances are acceptable in case of standard determination of maximum explosion overpressure values (EN 14031-1, 2004).

Deflagration indexes usually show significant deviation from the averages. Reason of the phenomenon can be found at the physical-chemical background of the deflagration and venting processes. Di Benedetto et al. (Di Benedetto et al., 2012) proved in case of methane explosion and the same type of closed 20-litre vessel, that change of ignition energy an initial turbulence has significant effect on K_{max} deflagration index (from the order of hundreds, it tends to zero, directly proportional with the initial turbulence level) and moderate effect to P_{max} maximum explosion overpressure. The initial turbulence has an extreme influence on the instantaneous flame velocity and on the rate of explosion pressure rise, this may explain significant deviation in measured values.

Any information for deflagration indexes in case of vented cases in the literature cannot be found, however it can be established, that opening of the rupture disk and processes in the vent duct (e.g. burn-up, backflow, friction of the gas column) improves uncertainties the determination of this parameter.

3. Measurement results

3.1. Set pressures of the rupture disks

Identical aluminium foils were used as rupture disks in the investigations with 0.02 m thickness. To ensure approximately constant set pressure of the foils, author had been exposed them to homogenization heating at 300°C for 30 minutes. During this time, structure of the foil material became more homogenous.

Set pressures of the foils were determined from measured pressures in the vessel (from the sign of '*P2*' transducer). Their opening was identified, where the first derivative of the pressure curve had discontinuity at the initial stage of the explosion (earlier than 1 bar_g pressure rise).

With this method, set pressure of the foils was 0,49 bar_g with +8.71% and -8.25% tolerance. Although tolerance seems to be unacceptably high in measuring practice, aluminium foil acts as flat bursting disc in this case. According to EN ISO 4126-6 standard, specified set pressure of flat bursting disc is ± 50% (EN ISO 4126-6, 2003). Considering the standard tolerance of the disks, measured values can be approved.

3.2. Measured characteristic explosion values

Characteristic explosion values (maximum explosion overpressure in the vessel and deflagration index) from the tests with their tolerances are summarized in Table 1. They were recorded by '*P1*', '*K1*' and '*K2*' transducers. For proper understanding and giving a context for vented results, closed vessel values are shown in the table, too.

Tolerances of P_{max} maximum explosion overpressures were equal or below 10% in every case, hence they are acceptable according to EN 14031-1 standard (EN 14034-1, 2004). Deflagration indexes show significant deviation from the averages (+37%, -34%). Reason of the phenomenon can be found at the causes mentioned above.

Table 1. *Measured maximum explosion overpressures and deflagration indexes*

Vent duct length, m	Propane amount, vol.%	Maximum explosion overpressure, P_{max} [bar_g]	Deflagration index, K_G [bar·m/s]
Closed vessel (Mikáczó et al., 2022)	2.8	5.46 +1%, -2%	21 +3 %, -6%
	3.8	7.36 +2%, -0%	85 +9%, -6%
	4.8	7.91 +1%, -3%	111 +1%, -2%
	5.8	7.15 +1%, -1%	49 +8%, -9%
	6.3	6.54 +3%, -2%	23 +23%, -19%
Vented, without duct (0 m)	2.8	0.54 +5%, -5%	3 +7%, -11%
	3.8	3.82 +6%, -5%	33 +8%, -8%
	4.8	4.73 +2%, -3%	53 +5%, -1%
	5.8	2.67 +10%, -7%	34 +13%, -10%
	6.3	0.7 +8%, -6%	5 +5%, -9%
Vented, with duct (0.15 m)	2.8	0.54 +4%, -6%	3 +3%, -2%
	3.8	3.9 +1%, -1%	27 +1%, -2%
	4.8	5.12 +0%, -2%	58 +10%, -7%
	5.8	2.99 +3%, -2%	19 +2%, -1%
	6.3	1.33 +2%, -5%	5 +4%, -4%
Vented, with duct (1 m)	2.8	0.66 +5%, -5%	2 +37%, -2%
	3.8	4.23 +5%, -5%	31 +11%, -18%
	4.8	5.34% +2%, -1%	43 +34%, -27%
	5.8	3.35 +2%, -3%	26 +19%, -34%
	6.3	1.94 +10%, -10%	7 +22%, -19%

3.2.1. Maximum explosion overpressures in the test chamber

Figure 2. shows graphically the measured averages of maximum explosion overpressure. As it seems, existence of the vent duct and its length has a significant effect on both characteristic values. On the figure can be observed, that the leaner the mixture, the vent duct effects less to the P_{max} values (at 2.8 vol% propane, $P_{red,max}$ values almost identical). For richer mixtures, the difference of these values became more significant. Its cause can be the fact, that richer mixtures contain higher amount of unburnt propane when they release into the vent duct. Here they can stir with fresh air and secondary explosion occurs. The more violent is the secondary explosion, the higher the pressure peak in the test chamber.

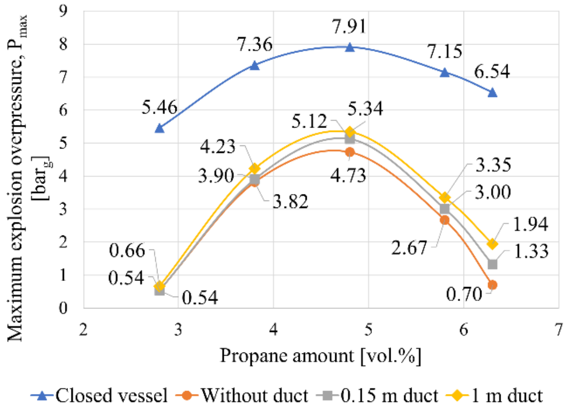

Figure 2. *Measured maximum explosion overpressure values in the vessel*

3.2.2. Deflagration index in the test chamber

The left side of Figure 3. shows graphically the averages of measured deflagration indexes. Deflagration index, similarly to explosion overpressure, also show a correlation with the length of the duct, except in case of the 0.15 m length one. To study the bell-shape curve of the 0.15 m duct, author investigated pressure maximums measured by '*P3*' transducer, and the same tendency can be observed in the initial section of the ducts (see Figure 3. right side).

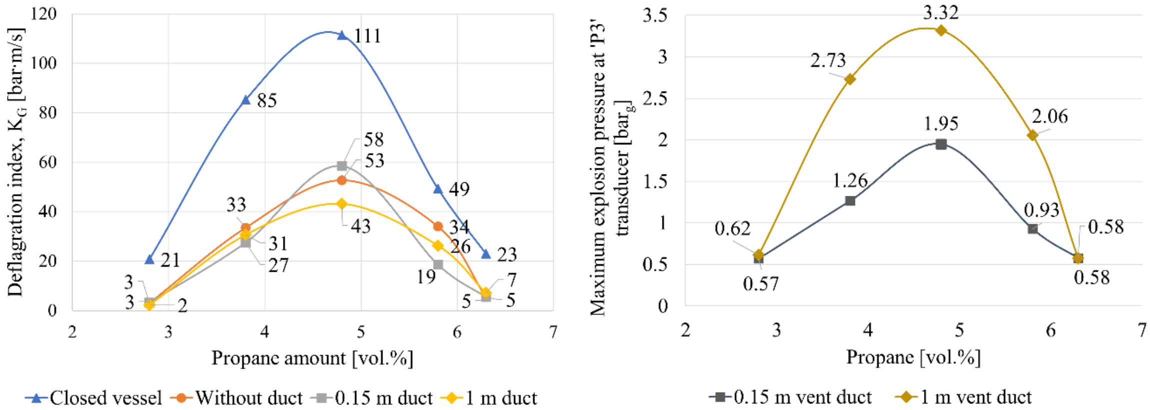

Figure 3. *Measured deflagration index values (left) and measured maximum overpressures by 'P3' transducer (right)*

Explanation of the phenomenon is the following. During ductless venting, beam expands behind the vent hole, substance releasing freely into the environment, and further effect of the burn-up is negligible. Then the only hydrodynamic preventing factor is the outflow through hole with sharp edges. Thus, K_G deflagration index in the test chamber and $P_{red,max}$ reduced maximum overpressure follows the same characteristic like unvented explosion.

In case of 1 meter length duct, outflowing stream remains continuous. During the venting process, all the above-mentioned hydrodynamic resistances can occur:

- friction losses and outflow through hole with sharp edges to the vent duct,
- inertia of the gas column,
- acoustic oscillations,
- burnup.

However, their effect can prevail in a nearly or fully developed flow pattern, because of the high L/D ratio of the duct. Effects of their individual impacts disturb the flow less. This is the cause, why $P_{red,max}$ overpressure follows the characteristic of unvented P_{max} curves.

By contrast, along 0.15 meter length of the duct the flow pattern cannot develop, and the effects of the resistances can strengthen or weaken each other. Near to the stoichiometric ratio of propane-air mixture (at 4.8 vol.%), deflagration index and explosibility is the highest. Harsh burnup occurs in the duct, and it causes backflow to the chamber with fresh oxygen. After that, explosion can continue in the chamber, and can be observed as the salient values of Figure 3. Concentrations but 4.8 vol.%, burnup and mixing back of the vented mixture is less violent, and vented substances can expand more efficiently in the environment.

3.3. Pressure drop along the 1 meter length vent duct

As it described before, flow in the 1 meter duct is more stable than the duct with 0.15 meter. Besides researching the safe use of non-standard solutions, this is the reason why the author investigated pressure loss of this construction. Figure 4. and Table 2. shows measured maximum overpressures by '*P2*', '*P3*', '*P4*', '*P5*' and '*P6*' pressure transducers in the vessel and along the 1 meter vent duct. Their tolerances are the smallest around the stoichiometric ratio of the mixture (see Table 2.).

Table 2. *Measured overpressure maximums along the 1 meter duct*

Propane amount, vol.%	Maximum overpressure [bar_g]				
	'*P2*' transducer – in the vessel	'*P3*' transducer	'*P4*' transducer	'*P5*' transducer	'*P6*' transducer
2.8	0.66 +5%, -5%	0.62 +18%, -27%	0.6 +11%, -13%	0.52 +11%, -15%	0.62 +12%, -20%
3.8	4.23 +5%, -5%	2.73 +5%, -6%	1.41 +6%, -6%	1.43 +6%, -6%	1.19 +9%, -10%
4.8	5.34% +2%, -1%	3.32 +2%, -3%	2.01 +15%, -26%	1.79 +2%, -3%	1.42 +2%, -3%
5.8	3.35 +2%, -3%	2.06 +2%, -2%	1.17 +4%, -4%	1.03 +6%, -9%	0.74 +6%, -3%
6.3	1.94 +10%, -10%	1.13 +13%, -13%	0.57 +21%, -12%	0.47 +24%, -18%	0.53 +22%, -13%

For 2.8, 3.8 and 6.3 vol.% propane, there is an additional increase in pressure along the length, but not for 4.8 and 5.8 vol.% (see Figure 4.). The latter can be caused by the higher deflagration index of the mixture which can burn faster, and significant burnup cannot obtain at the backward sections of the duct.

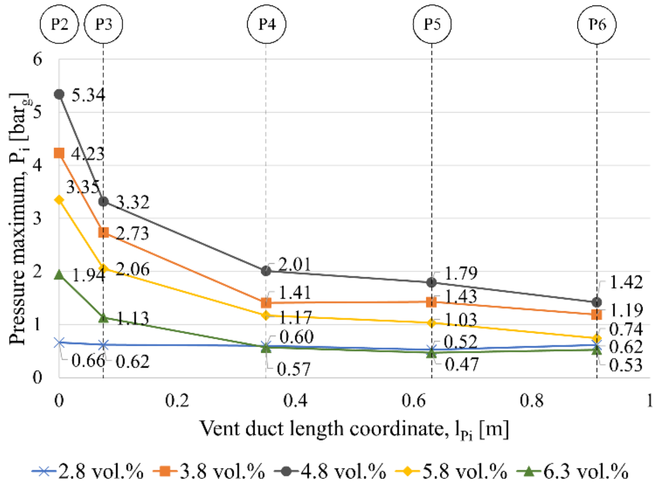

Figure 4. *Measured maximum explosion overpressures by 'P2', 'P3', 'P4', 'P5' and 'P6' pressure transducers along the 1 meter vent duct*

Table 3. shows pressure drops between the '*P2*' and '*P3*' transducers (at the initial section of the duct) referred to the distance of pressure transducers, compared the total pressure drop between '*P2*' and '*P6*' referred to the distance of pressure transducers. In the table, P_2, P_3 and P_6 shows measured pressure maximums in '*P2*', '*P3*' and '*P6*'transducers, and l_{P2}, l_{P3} and l_{P6} shows lengths coordinate of the transducer. The largest pressure drop at each concentration occurs in the first section of the duct, between '*P2*' and '*P3*'. In this section, sudden change in the cross section of the flow and the burnup can occur. According to current measurements, this effect is changing with the propane amount.

Table 3. *Pressure drops along the 1 m vent duct*

Propane amount, vol.%	Absolute pressure drop between '*P2*' and '*P3*', bar	Pressure drop per unit length between '*P2*' and '*P3*', bar/m $(P_2 - P_3)/(l_{P2} - l_{P3})$	Pressure drop per unit length between '*P3*' and '*P6*', bar/m $(P_3 - P_6)/(l_{P3} - l_{P6})$
2.8	0.04	0.59	0.05
3.8	1.5	19.97	3.34
4.8	2.02	26.95	4.31
5.8	1.29	17.25	2.87
6.3	0.82	10.89	1.56

In case of 2.8 vol.% mixtures, significantly smaller pressure drop can be observed at the initial section of the duct, compared to the other concentrations. Its cause can be the lack of burnup, or if there is, its effect is negligible. Only the changing of the flow geometry at the entrance of the duct and the hydrodynamic pressure drop of the duct has the ruling effect to the pressure values in this case. Magnitude of acoustic oscillations were not comparable to maximum pressure at '*P3*'. From this observation, hydrodynamic pressure drop can be estimated in the further investigations.

4. Summary

In this paper, author performed some ductless and duct vented explosion measurements in a standard 20-liter explosion chamber with 2.8 to 6.3 vol.% propane-air mixture at atmospheric pressure and ambient temperature. Experimental investigations were performed with different lengths of vent duct (0 meter, 0.15 meter, 1 meter). During the measurements, effects of vent ducts to the venting process had been studied. Aluminium foils were used as rupture disks with 30 mm diameter circular venting area, between special clamping tools. Experimental studies were performed at atmospheric pressure (1 bar_g) and ambient temperature (298 K). During each measurement, static activation overpressure of aluminium foil (P_{stat}), maximum explosion overpressure of propane-air mixture ($P_{red,max}$), the gas deflagration index (K_G) in case of the vented vessel, and the pressure drop along the 1 meter length duct were determined.

Set pressures of the foils were determined from measured pressures in the vessel. They were 0,49 bar_g with +8.71% and -8.25% tolerance.

Typical explosion values (maximum explosion overpressure in the vessel and deflagration index) from the tests with their tolerances were summarized. Existence of the vent duct and its length has a significant effect on both characteristic values. The leaner the mixture, the length of the vent duct effects less to the P_{max} values. For richer mixtures, the difference of these values became more significant.

Deflagration index, similarly to explosion overpressure, also show a correlation with the length of the duct, except in case of the 0.15 meter length one. In this case, in 0.15 meter length duct cannot develop the flow pattern, and the effects of resistances can strengthen or weaken each other. Near to the stoichiometric ratio of propane-air mixture (at 4.8 vol.%), deflagration index and explosibility is the highest. Harsh burnup occurs in the duct, and it causes backflow to the chamber with fresh oxygen. After that, explosion can continue in the chamber, and can be observed as the salient values of the $P_{red,max}$ pressure curves. Concentrations but 4.8 vol.%, burnup and mixing back of the vented mixture is less violent, and vented substances can expand more efficiently in the environment.

Relative pressure drops at the initial section of the 1 meter length duct were also investigated. The largest pressure drop occurs in the first section of the duct. In this section, sudden change in the cross section of the flow and the burnup occurs. According to current measurements, this effect is changing with the propane amount. In case of 2.8 vol.% mixtures, significantly smaller pressure drop were observed at this section of the duct, compared to the other concentrations. Its cause can be the lack of burnup, or if there is, its effect is negligible. From this observation, hydrodynamic pressure drop can be estimated in the further investigations.

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