University of Miskolc

Faculty of Mechanical Engineering and Informatics

Theoretical, Simulation and Experimental Investigation of Systems with Explosion Protection

PhD Booklet of PhD dissertation

Prepared by
Viktória Mikáczó
Mechanical Engineer MSc

István Sályi School of Mechanical Engineering Sciences
Topic Field of Basic Engineering Sciences
Topic Group of Transport Processes and Machines

Head of Doctoral School
Prof. Dr. Gabriella Bognár Vadászné
DSc, Full Professor

Head of Topic Group
Prof. Dr. Tibor Czibere
HAS Regular Member

Scientific Supervisor
Prof. Dr. Zoltán Siménfalvi
Full Professor

Scientific Co-Supervisor
Dr. habil. Gábor L. Szepesi
Associate Professor

Miskolc, 2023

Viktória Mikáczó

Theoretical, Simulation and Experimental Investigation of Systems with Explosion Protection

Booklet of PhD dissertation

Miskolc, 2023

JUDGING COMITTEE

Chair: **Prof. Dr. Edgár Bertóti**
DSc, full professor (University of Miskolc)

Secretary and member: **Dr. Péter László Kiss**
PhD, associate professor (University of Miskolc)

Members: **Dr. Imre Barna**
PhD, senior research fellow (Wigner Research Centre of Physics)

Dr. Gyula Joó
CSc, retired associate professor (University of Miskolc)

Dr. Péter László Kiss
PhD, associate professor (University of Miskolc)

OFFICIAL REVIEWERS:

Dr. Csaba Póliska
PhD, associate professor (University of Miskolc)

Dr. Gábor Kun
PhD, head of certification (ExNB Tanúsító Intézet Kft.)

1 Research assignment

1.1 Introduction

Explosive dusts are originate from every segments of industrial production [1], and facilities in which explosive gases, mists, or hybrid mixtures occur are particularly high source of danger. Since the 20th century, numerous case studies have been prepared related to this type of accidents. Drawing the appropriate conclusions from the occurred events, explosion protection plays an increasingly important role in today's industrial practice. When an explosion occurs, damage can be caused simultaneously by the escaping material, sharpnel from the device, the pressure wave and heat of the explosion. Therefore, protecting the integrity of systems and devices is not only a financial interest.

1.2 Objectives

The physico-chemical background of dust and gas explosions is extremely complex, and the phenomena occurring them depend on many parameters. For this reason, specifications of the standards for explosions in closed vessels and vented cases were tipically created as the result of experimental work, and they try to cover as wide spectrum as possible in explosive materials and geometric characteristics. However, at the borders of the apprication range of correlations – for example unvented and vented explosions in small vessels, or complex geometries of vent ducts – these correlations provide inaccurate results. The examined size range of small vessels can be found in pharmaceutical, chemical, or even semi-industrial experimental laboratory applications, which are particularly dangerous areas from the point of view of the risk of explosion.

The overall goal of my dissertation was to investigate the physico-chemical processes during dust and gas explosions, the phenomenon itself, its conditions and circumstances.

During my research, one of my goals was to develope laboratory measurement procedure which – in the case of an arbitrary gas mixture – is suitable for examining the processes during closed and vented gas explosions, determining the characteristics of the explosion, and recording the pressure values occurring in the vent ducts. Using this measurement procedure and the theoretical knowledge I acquired on the subject, I defined the tasks performed below.

- Using my measurement results, I examine the applicability of the ideal gas model to calculate the explosion pressure against time. With the model, my aim is to describe the initial section of the explosion pressure curve, as this section plays a significant role in the set pressure of venting devices. During my research, I do not intend to simulate the entire explosion process, I only want to use it as a tool which is absolutely necessary for carrying out tests related to venting protection.

- Using the measurement results, I will examine the accuracy of equations of MSZ EN 14491:2013 and NFPA 68:2018 standards regarding increased reduced explosion pressure besides the use of vent ducts. If necessary, based on the correlations of the standards above, I will develop a procedure suitable for determining a new correlation for the calculation of the increased reduced pressure that occurs with the use of the vent duct.

- Using my measurement results for vented explosions, I determine the amount of resistance casued by the vent duct, and the proportion of the friction loss in it. As a part of this, I examine the applicability of the relationships of pressure losses resulting from pipe friction to vented explosions, as well as quantify the losses resulting from other effects.

- I examine the location and maximum value of the secondary explosion, as well as the magnitude of the pressure peaks that develop in the channel during the venting process.

The global scope of the research is to develop such procedures, which can be applied to other explosive gases that typically occur in industrial practice.

2 Scientific preliminaries

2.1 Explosions in closed vessels

2.1.1 Characteristic values

Explosions occurring in closed vessels and their intensity can ben described with numerous characteristic values. In industrial practice, such characteristic values are the maximum explosion overpressure (P_{max}), and deflagration index (K_G in case of gases) calculated from maximum rate of pressure rise.

The processes during explosion are also characterized by laminar burning velocity of the propagating flame (S_l, or $S_{l,ad}$). In the initial stage of combustion, when the flame advances under isobaric conditions, the following relationship exists between the burning speed (S_f) and the laminar flame propagation speed (S_l) [2]:

$$S_l = \frac{\rho_b S_f}{\rho_u}. \tag{1}$$

It can also be seen from the eq. (1), that the medium undergoes a density change during the reaction, which can be expressed by the E expansion factor [3]:

$$E = \frac{\rho_u}{\rho_b} = \left(\frac{T_{f,p}}{T_0}\right)\left(\frac{n_e}{n_0}\right). \tag{2}$$

The expansion pushes the flame front towards and forces it to accelerate. The spreading flame is unstable, due to local micro-processes, protrusions are formed in the flame front. In the slightly wrinkled flame front, the diffusion processes also take place unbalanced [4]. The resulting turbulence favors phase contact between reactants and combustion products, thus accelerating flame propagation [5]. The resulting turbulence favors phase contact between reactants, thus accelerating flame propagation [5]. The turbulent flame speed (S_t) is the speed at which the average flame surface passes through the reactants. A widely used version of the relation is attributed to Gülder [6]:

$$S_t/S_{l,ad} = 0,65 \cdot \left(u'/S_{l,ad}\right)^{3/4} \cdot \left(L/\eta_0\right)^{1/4}. \tag{3}$$

2.1.2 Simulation methods

Different models and procedures can be used to determine the characteristic values of the explosion for closed and vented cases. Empirical, phenomenological, reaction kinetic and CFD-based models are also included, however, each type uses different degrees of simplification [7]. In my dissertation, I examined phenomenological and reaction kinetic models in more detail.

Phenomenological models are simplified semi-empirical models, which determine some parameters by empirical relationships, while others are estimated based on physical laws. This group includes, for example, the widely used SCOPE model [7].

Reaction kinetics methods approximate the rate of chemical reactions by describing the partial reactions in full or in a simplified manner. One of its many types is the group of one-equation models, which take the equilibrium reaction equation of combustion as a basis, and then determine the differential equation of fuel loss with the an empirical relation. Equations for propane combustion, for example, Frolov et al. [8] and Wen and Wang's model [9].

2.2 Vented explosions

2.2.1 Physico-chemical phenomena during venting process

In case of vented gas explosions , the pressure increase measured in the vessel can be divided into three different stages, which are shown in Fig. 1.

In the first stage, the explosive mixture ignites, the flame spreads and expands. When the internal pressure reaches the opening pressure of the venting device, it opens and the medium starts to flow out of the space.

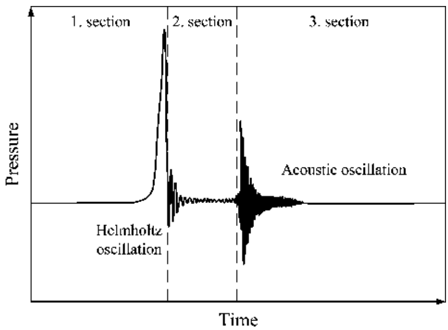

Figure 1: Characteristic sections of the pressure curve formed during venting [10]

In the second stage, Helmholtz oscillation may occur as a result of changes in material characteristics and status figures during venting. The sub-processes – which cause the oscillation – are repeated, gradually dying out in the meantime.

In the third stage, high-frequency vibrations occur which are known as acoustic oscillations, but this is not always observed during venting. The outgoing pressure wave can cause the device to vibrate acoustically close to its eigenfrequency [10].

Several models have been created to determine the maximum reduced explosion overpressure ($P_{red,max}$) inside the device, the most important onaes are the models of Molkov [11] Sustek [12] and Lautkaski [13].

2.3 Vented explosions with vent ducts

2.3.1 Processes in the vent duct

In order to the vented materials avoid the work area or neighboring pipelines and vessels, the venting device can be supplemented with a vent duct. However, this solution represents a resistance to the flow consisting several factors, which appears as backpressure and has a negative influence on the reduced pressure that can be measured in the protected vessel [14].

The processes taking place in the vent duct are very complex, which significantly influence the venting istelf and the explosion characteristic values that can be measured in the protected vessel. The observable stages and occurring phenomena are described by Ponizy and Leyer [15] and Pang et al. [16].

Based on these, the resistances occurring during the flow of the medium in the vent duct, can be the following [17]:

- friction losses of the venting system,
- inertia of the static air in the channel,
- secondary explosion in the channel,
- oscillations.

In the vent ducts, not only one pressure peak can be identified [16]. The first peak value is the effect of the turbulent disturbance following the opening of the venting protective device and the resulting shock wave. Its name is membrane break shock [18]. The second peak is the secondary explosion itself [19]. The most easily observed known pressure peak occurs when the effect of the secondary explosion weakens and the device starts venting again [20]. In addition, a secondary explosion may occur even outside the duct, which was described by Cao et al. [21].

2.3.2 Possible channel designs, standard specifications, reduced pressures

The prevention of explosions and mitigation of damage is an extremely important area of industrial practice. If, as explained above, the explosion is properly vented [22], its effect can be minimized. The inner explosion process itself does not ends by venting, however, its harmful consequences can be significantly reduced. Furthermore, the effects caused by the vented flames and pressure waves must also be taken into consideration.

In Hungary, the proper sizing of the opening surfaces is necessary for effective venting, as well as the basic requirements for their additional elements – vent ducts, deflector plates – in the case of gas-air mixtures are defined by the MSZ EN 14994:2007 standard [23], while in case of dust-air mixtures it is defined by the MSZ EN 14491:2013 standard [24]. In international practice, the application of NFPA 68:2018 [25] also represents a significant area.

The criteria for vent ducts – to minimize the reduced pressure-increasing effect of the duct – are mostly similar in the case of MSZ EN 14491:2013, MSZ EN 14994:2007, NFPA 68:2018 standards (non-exhaustive):

- the duct should be as short and straight as possible;
- the cross-section of the duct should be as large (MSZ EN 14491:2013) or at least as large as the vent area (MSZ EN 14994:2007, NFPA 68:2018);
- in the initial cross-section of the straight duct, close an angle of maximum 20° with the normal of the vent area.

Based on the comprehensive study by Lautkaski [13], the correlations for the calculation of the reduced pressures increased by the vent duct proposed by the mentioned standards can estimate the real measurement results with a relative error of 44%.

The most important calculation models for increased reduced pressure with the use of a vent duct are the following: Bartknecht (1993) (cited: [13]); Tamanini and Fischer (2003) (cited in [13]); Ural (2005) [26]; Di Benedetto et al. [27]: Yao's extended theory (2007); Lautkaski (2012) [13].

3 Investigation methods

3.1 Investigation of explosions in closed vessels

Fig. 2 provides a scemaic of the measurement setup were carried out. The central element of the setup is an explosion test chamber (*2*) made by Kühner with a capacity of 20 liters that meets the requirements of the EN 14034-1:2004+A1:2011 standard [28]. The pressure values in the chamber were recorded with two Kistler pressure transmitters (*K1* and *K2*) and a Hottinger type pressure transmitter sensor (*P2*), with 9600 Hz.

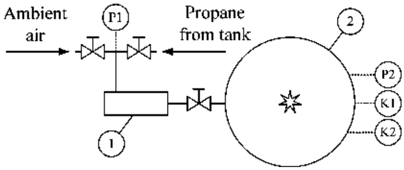

Figure 2: Schematic of a propane-air filling system;
1 – gas filling chamber, 2 – explosion test chamber

The measurements were performed at atmospheric initial pressure and ambient temperature (298 K) with a propane-air mixture containing 2.8, 3.8, 4.8, 5.8 and 6.3 V/V% propane. To fill the required amount of gas, a filling chamber (*1*) were designed with a capacity of 0.6 liters, including the fittings. The loaded amount of gas were measured by a pressure transmitter marked *P1* and located on the filling chamber.

The Fig. 3 shows the characteristic values resulting from the tests: the P_{max} maximum explosion overpressure (left) and the K_G deflagration index (right).

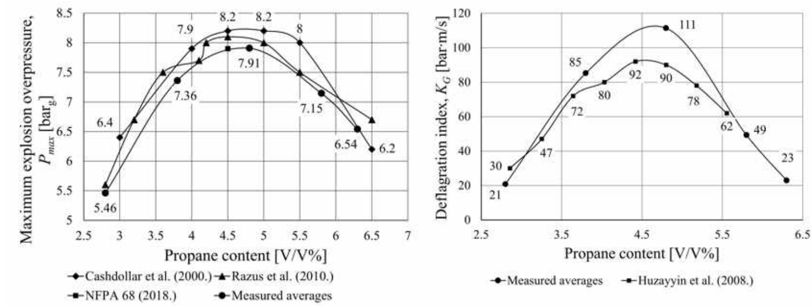

Figure 3: Measured maximum explosion overpressures (left) and
deflagration indexes (right) [25, 29, 30, 31]

Using the results of the measurements in the closed chamber, the applicability of the ideal gas model were studied to describe the pressure-time function of the explosion.

The original application range of the model were to P_0+10% [2]. Using the measurement results, an ϵ modification factor was added to the original formula, which allowed to extend the applicability of the model to the P_0+150% range:

$$P = P_0 \cdot e^{\epsilon \cdot E^2 \cdot (E-1)\left(\frac{S_l \cdot t}{R}\right)^3}, \tag{4}$$

where ϵ is the introduced factor, which numerically expresses the effect of the additional processes taking place during turbulent flame propagation. The E expansion factor, $T_{f,p}$ adiabatic isobaric flame temperature and S_l laminar flame speed were determined by literature data [2, 3, 31, 32]. The values of the ϵ correction factor are illustrated in Fig. 4, and its dependence on propane content is described by the relation (5), in which V_p^* represents the volume concentration of propane in the initial mixture.

$$\epsilon = -0,0132 \cdot V_p^{*2} + 0,0832 \cdot V_p^* + 0,1853 \tag{5}$$

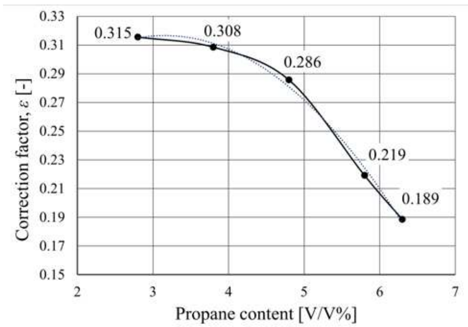

Figure 4: Values of the ϵ factor

3.2 Investigation of vented explosions

3.2.1 Results achieved by modifying the measurement procedure

Vented explosions were examined with modifying the measurement setup (Fig. 5) which was used for the closed chamber tests, with the previous mixture compositions, and in the case of mixtures containing 7.8 and 9.8 V/V% propane.

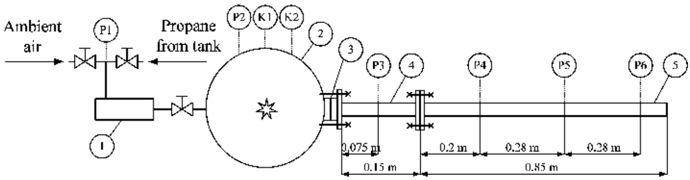

Figure 5: Schematic of the measurement arrangement of vented explosions

The measurements were performed without vent duct (0 m long duct) and with 0.15 m (*4*) and 1 m (*4* and *5*) ducts. Both the vent area and the inner diameter of the ducts were 30 mm, so the l/d ratio of the investigated ducts were 0, 5 and 33.3, respectively. The pressure transmitters (*P3-P6*) were placed along the duct. The average opening pressure of the aluminum foils (*3*) – which were used as venting devices – was $P_{set} = 0.49\ \text{bar}_\text{g}$.

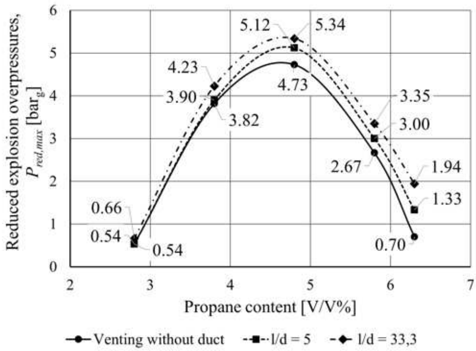

Figure 6: Average measured reduced explosion overpressure maximum values in the test chamber

Fig. 6 graphically illustrates the average values of the reduced pressures as a function of the initial propane content. As can be seen in the figure, the use of the duct and its length have a significant effect on the pressure values that can be measured in the chamber. Furthermore, it can also be observed that the leaner the mixture the smaller the effect on the maximum reduced overpressure in the chamber.

3.2.2 Development of a new equation suitable for calculating the increased reduced explosion overpressure

Both MSZ EN 14994:2007 [23] and NFPA 68:2018 [25] stanards provide calculation methods for estimating the maximum value of the reduced explosion pressure in the chamber. According to the former standard, the increased reduced explosion pressure caused by the duct, when the length of the vent duct is shorter than 3 meters, can be estimated as the following:

$$P'_{red,max} = 1,24 \cdot P_{red,max}^{0,8614}.$$

According to the NFPA 68:2018 standard, if the length of the vent duct is between 3 and 6 meters, or shorter, but the length is greater than four times the hydraulic diameter, the increased reduced pressure due to the channel can be calculated using the following:

$$P'_{red,max} = 0,172 \cdot P_{red,max}^{1,936}.$$

The reduced pressure values calculated according to the standard specifications are illustrated on Fig. 7 in comparison with the measurement results of the vent duct with a length of $l/d = 33.3$.

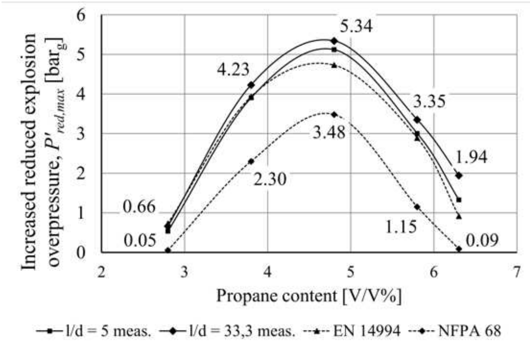

Figure 7: Measured and estimated reduced explosion overpressure maxima

As the figure shows, the calculations according to the named standards approximate the measurement results from below at the most critical concentrations. Thus, an equation that more accurately approximates the value of the increased reduced pressure in the chamber were defined in the following form:

$$P'_{red,max} = a \cdot P^{b}_{red}. \tag{6}$$

Based on the performed measurement results, the constants of the correlation were determined: $a = 1.6953$ and $b = 0.7384$, and the new approximation equation:

$$P'_{red,max} = 1,6953 \cdot P^{0,7384}_{red}. \tag{7}$$

The reduced explosion pressures obtained using the eq. (7) are shown in Fig. 8. The new correlation covers the curve of the measurement results from above, even at the maximum value and its adjacent values.

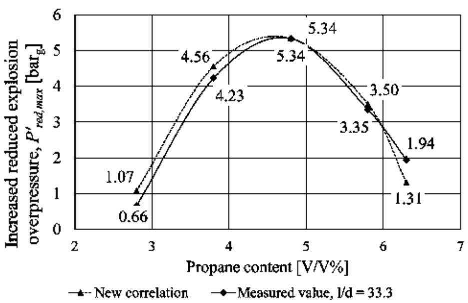

Figure 8: Comparison of the measured reduced pressure maxima with the results according to the equation (7)

3.2.3 Pressure losses along the $l/d = 33,3$ length vent duct

Fig. 9 summarizes the measured maximum values by each pressure transmitter, in the case of a vent duct with a length of $l/d = 33.3$.

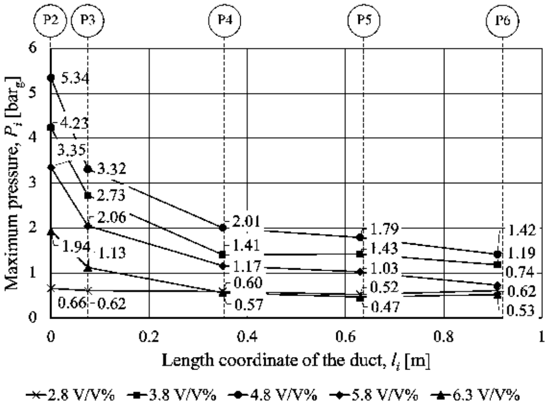

Figure 9: The average maximum pressure values measured by *P2* – *P6* transmitters in case of $l/d = 33,3$ length vent duct

A considerable pressure loss can be observed in the initial section of the duct. The absolute pressure difference between the results of *P2* and *P3* transmitters, as well as the difference per unit length, is significantly different for the 2.8 V/V% mixture compared to the other compositions. With detailed analysis of the pressure values has been found, that in case of mixtures containing 2.8 V/V% propane, the secondary explosion does not occur or is negligible during venting.

3.2.4 Identification of phenomena and pressure peak values in the vent duct

In order to investigate the phenomena taking place in the vent ducts, the characteristic local pressure maxima meantioned in the literature (Helmholtz and acoustic oscillations, the local maximum resulting from the membrane rupture, the possible secondary explosion and the prolonged pressure increase phase) were identified on the measured pressure curves in case of $l/d = 33.3$ length duct.

During the research, outstanding pressure peak(s) following the secondary explosion – which are not mentioned in the literature – were identified too. These are supposedly secondary explosions, of which the observed quantities are according to the Table 1 (below).

Examining the individual measurements, it was also established that in some cases one of the maximum pressure values of the secondary explosions exceeded the extended pressure maximum.

Propane amount [V/V%]	Secondary explosions [nr.]	Average maxima of secondary explosions [bar_g]		
2,8	0 – 1	0,26	–	–
3,8	1	0,875	–	–
4,8	1	1,343	–	–
5,8	2	0,809	1,563	–
6,3	3	0,538	0,843	0,979
7,8	1	0,242	–	–
9,8	0	–	–	–

Table 1: Average maximum pressures of secondary explosions measured by *P3* pressure transducer

3.2.5 Determining the proportion of pipe friction loss

In order to identify the extent of the secondary explosion occurring in the vent duct, it is necessary to quantify the frictional loss of the duct istelf. This is the loss that occurs with each venting. The additional effects are superimposed on this component and together give the total resistance resulting an increase of the reduced pressure in the vessel. So, in order to be able to quantify the other effects – secondary explosions, oscillations – the amount of firction loss occurring in the duct need to be known.

To determine the latter, the measurement results without the vent duct and with the 1-meter ($l/d = 33.3$) long duct were used. Since that no secondary explosion occurred in the channel when the mixture contains 2.8 V/V% propane, or its effect was negligible, the pipe friction loss were determined based on the data of this mixture.

3.2.6 Pressure losses in case of the mixtures with 2.8 V/V% propane

Measured and calculated pressure values along the channel are illustrated in Fig. 10.

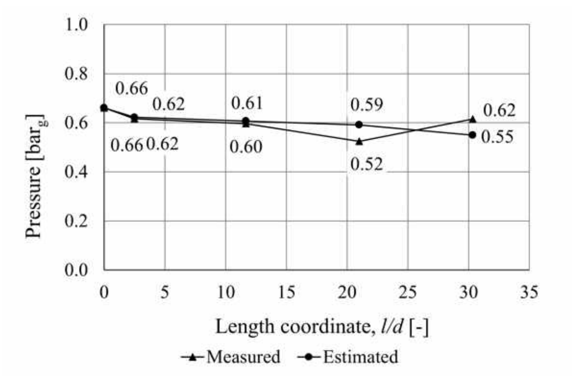

Figure 10: Comparison of measured and estimated pressure values along the vent duct ($l/d = 33,3$; 2,8 V/V% propane)

In the figure, clearly visible differences between the measured and calculated pressure peaks can be observed in positions $P5$ and $P6$. The explanation for this phenomenon is the combined effect of the Helmholtz oscillation and the significant turbulence that occurs during venting.

With the measurement results and the performed calculations, it was established that the relationships applicable to the calculation of the pipe friction loss are also suitable for the calculation of the friction loss of the vent duct in case of vented explosions, and the value of the reduced pressure that increases as a result of the vent duct can be determined with high accuracy. In case of mixtures where a secondary explosion is also experienced, the friction loss of the total loss of the channel can also be determined.

3.2.7 Pressure drops in case of the mixtures with 3.8 – 6.3 V/V% propane

In the case of mixtures with 3.8 – 6.3 V/V% propane, friction losses of the vent duct were determined. By subtracting the calculated friction losses from the measured pressures at the specified coordinates of the duct, the other occurring resistances which superimposed on the pipe friction loss during venting were determined (Fig. 11).

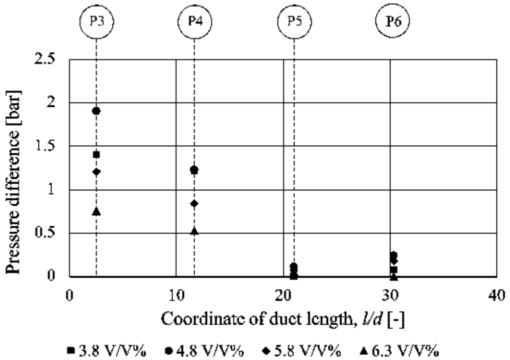

Figure 11: The differences between the measured pressure maxima and the calculated pipe friction losses of 3.8 to 6.3 V/V% propane-air mixtures

It can be concluded that the most intense secondary explosion occurred near to the $P3$ transmitter. The measured highest pressure maximum at this location occurred in case of the 4.8 V/V% mixture. This proves that the mixture which was pushed in front of the flame front and suddenly expanded after the aluminium foil was ruptured in this place. Subsequent secondary explosions are re-explosions of the residual propane content of the vented mixture.

Furthermore, it can be established that the effect of the secondary explosions exists up to the channel's coordinate $l/d = 21$, and at the end of the duct, a magnitude change occurs in the values.

In the initial stage, the effect of the secondary explosions prevails the most, while the subsequent increase in pressure difference is due to the oscillation in the channel, which is negligible compared to the effect of the secondary explosion.

4 New scientific results

Based on the results of theoretical and simulation investigations and measurements on the explosion of propane-air mixtures with a propane content of 2.8 – 6.3 V/V%, performed in a 20-liter volume, spherical explosion chamber, using a modified gas filling process, was carried out in a closed vessel and vented cases (with a set pressure of 0.49 bar_g rupture disk and vent ducts with $l/d = 0$, 5 and 33.3 length-to-diameter ratio), I formulate the following new scientific results.

T1. In the case of a laboratory-sized device (with a capacity of 20 liters), to clarify the equations found in the MSZ EN 14994:2007 and NFPA 68:2018 standards, I defined a new correlation for the increase in reduced explosion overpressure caused by the vent duct in the following form:

$$P'_{red,max} = a \cdot P^b_{red,max}.$$

The correlation provides a more accurate result than the original ones in the allowed lower device size range of the mentioned standards.

In the case of propane-air mixtures, I determined the constants a and b of the correlation ($a = 1.6953$ and $b = 0.7384$) in the range of the most dangerous concentrations from the point of view of explosion.

Related publication: (16)

T2. I developed a procedure for modeling the pressure change during the initial stage of an explosion in a closed vessel, which can be used in engineering practice. By applying the ϵ modifying factor inserted into the pressure function of the ideal gas model, I extended the scope of the function. The modified function can be written in the following form:

$$P = P_0 \cdot e^{\epsilon \cdot E^2 \cdot (E-1) \left(\frac{S_l \cdot t}{R} \right)^3}.$$

I verified the applicability of the correlation in case of a propane-air mixtures by measuring and validating with literature data, and I determined the dependence of the ϵ correction factor on the propane content in the following form:

$$\epsilon = -0,0132 \cdot {V_p^*}^2 + 0,0832 \cdot V_p^* + 0,1853.$$

Using the presented procedure, the ϵ factor can be determined for the mixture of any explosive gas with air.

Related publications: (1)(2)(9)(10)(14)

T3. I have verified with experimental tests that in case of venting from a 20-liter spherical esxplosion chamber, with the use of a vent duct, in addition to the single secondary explosion that generally appears in the literature, additional secondary explosions can occur, which in some cases may even exceed the maximum value of the extended pressure peak that can be measured in the channel.

By applying the measurement procedure to different concentrations of the propane-air mixture, I verified that in the case of a 20-liter spherical explosion chamber and a vent duct with an $l/d = 33.3$ length-to-diameter ratio, additional secondary explosions occur. The number of secondary explosions is a function of the propane concentration, which reaches its maximum near the stoichiometric mixture.

Related publication: (15)

T4. Using the performed theoretical, simulation and experimental investigations, I made the following findings in the case of explosion of vented gas-air mixtures equipped with a vent duct.

a) I proved that in the case without secondary explosion, the increase in the reduced explosion overpressure measured in the chamber is caused by the pipe friction loss of the vent duct.

b) With experimental invesigation and calculations, I proved that the relationships used for calculating the the friction losses in pipelines can also be used to calculate the friction loss occurring in the vent duct.

c) In case of propane-air mixtures, I showed that if secondary explosion can be observed in the channel, the most intense secondary explosion occurs in the vicinity of the vent opening. The pressure maxima that can be measured at this location are also a function of the initial concentration, which reaches its peak near the stoichiometric mixture.

d) I found that the firstly occurring secondary explosion is caused by the explosion of the mixture with the initial composition appearing in the channel. The subsequent secondary explosions are caused by the re-explosion of the residual fuel content of the vented media (which already contains combustion products).

e) The effect of secondary explosions appears in a given section of the duct. The reason for the increase in pressure difference in the vicinity of the exit of the duct is the oscillation in the channel, which, however, is negligible compared to the effect of secondary explosions.

Related publication: (15)

5 Opportunities of development

As can be seen from the thesis, the topic of explosion protection has a lot of scientific potential in each of the examined areas. Based on this, I would like to continue my research on the topic.

All of the procedures described in the thesis were designed in such a way that the explosion characteristics (maximum explosion pressure, deflagration index) can be determined not only propane-air mixtures, but also any explosive gas mixture can be examined both in the explosion chamber and – if vent ducts are used – in the duct .

Since the tests mentioned in the thesis were carried out for mixtures with a given composition, I determined the correction factor ϵ fitted to the ideal gas model, as well as the constants a and b for calculating the increased reduced explosion pressure. In order for these to be useful research results for engineering practice, the first and most important aspect is to extend them to other gas mixtures occurring in industry as well. Thus, this line is my primary research direction.

The topic of vented explosions is also extremely complex. This is especially valid for the use of vent ducts, whose many parameters (changes in the length-to-diameter ratio, cross-section geometry, non-straight channel shapes) were not examined in the current thesis. Thus, in order for the results cover the real conditions in wide range, their examination also indicates a further direction of research. The location of the secondary explosions and their portion in the pressure loss of the vent duct are basic information that can serve future scientific progress and, with further work, can also affect the development directions of explosion protection equipment.

The performed tests on the vent duct only covered flows below the speed of sound, however, a flow above the speed of sound can also develop in the duct, which causes completely different flow and pressure conditions in both the duct and the device. A further research opportunity is the examination of these processes.

Among the reviewed standards in the dissertation, only the NFPA 68:2018 concerning dust explosions provides a calculation method for the pressure loss of channels with a different design than a straight line, but they are also empirical correlations based on a limited amount of measurement results. Such standard recommendations for gas explosions do not exist in the area I examined. Clarifying these or expanding the range of usable relationships can also be a further research direction.

6 List of publications related to the topic of the dissertation

1. V. Mikáczó, G. L. Szepesi *„Theoretical Investigation of Pressure-Characteristic in case of Gas Explosion"*, Proceedings of the International Scientific Conference on Advances in Mechanical Engineering (ISCAME 2014) Debrecen, Magyarország : University of Debrecen Faculty of Engineering (2014) pp. 82-90. , 8 p.

2. Mikáczó V., Szepesi L. G. *„Nyomás-idő függvény elméleti vizsgálata gázrobbanás esetén"*, GÉP 65: 1 pp. 33-37 (2014)

3. Mikáczó V. *„Hydrodynamical Investigation of Vent Duct in case of Dust Explosion"*, Tavaszi Szél 2014 Konferencia: Konferenciakötet VII., Debrecen, Magyarország : Doktoranduszok Országos Szövetsége (DOSZ) (2014) 570 p. pp. 460-470. Paper: ISBN 978-615-80044-6-6 , 11 p.

4. Mikáczó V. *„Lefúvóvezeték hatásának vizsgálata töltetrobbanás hasadópaneles védelme esetén"*, Pokorádi, László; Vámossy, Zoltán (szerk.) XXXII. OTDK Műszaki Tudományok Szekció : Tartalmi kivonatok, Budapest, Magyarország : Óbudai Egyetem, (2015) p. 298 Paper: ISBN

5. V. Mikáczó, G. L. Szepesi *„Theoretical and Experimental Investigation of Pressure Rise Generated by Dust Explosion"*, Tavaszi Szél : Absztraktkötet 2015 Budapest, Magyarország, Győr, Magyarország : Doktoranduszok Országos Szövetsége (DOSZ), Publio Kiadó (2015) 485 p. pp. 332-332. Paper: ISBN , 1 p.

6. Mikáczó V. *„Gázkeverék robbanása során történő lefúvatás vizsgálata - I. rész"*, The Publications of the MultiScience - XXX. microCAD International Multidisciplinary Scientific Conference, Miskolc, Magyarország : University of Miskolc (2016) Paper: D4.8 , 5 p.

7. V. Mikáczó, Z. Siménfalvi, G. L. Szepesi *„Investigation of deflector plates in case of gas explosion"*, Proceedings of the 4th International Scientific Conference on Advances in Mechanical Engineering (ISCAME 2016) Debrecen, Magyarország : University of Debrecen Faculty of Engineering (2016) 654 p. pp. 330-335. , 6 p.

8. V. Mikáczó, Z. Siménfalvi, G. L. Szepesi *„Influence of the vent duct design in case of gas explosion in 20 litre sphere apparatus"*, 22nd International Congress of Chemical and Process Engineering, CHISA 2016 and 19th Conference on Process Integration, Modelling and Optimisation for Energy Saving and Pollution Reduction, PRES 2016, Prága, Csehország : Czech Society of Chemical Engineering (2016) p. 682 *Scopus*

9. V. Mikáczó, Z. Siménfalvi, G. L. Szepesi *„Simulation of propane explosion in closed vessel"*, Annals of Faculty of Engineering Hunedoara - International Journal of Engineering 15 : 3 pp. 49-54. , 6 p. (2017)

10. V. Mikáczó, G. L. Szepesi *„Phenomenological modeling of gas explosion in closed vessel"*, MultiScience - XXXIII. microCAD International Multidisciplinary Scientific Conference, Miskolc-Egyetemváros, Magyarország : Miskolci Egyetem (2019) pp. 1-9. Paper: D3-4 , 9 p.

11. Mikáczó V., Szepesi L. G., Siménfalvi Z. *„Lefúvóvezeték hatása a redukált robbanási nyomásra - elméleti modellek"*, GÉP LXXII. : 1-2 pp. 26-30. , 5 p. (2021)

12. Mikáczó V., Szepesi L. G. *„Por- és gázrobbanásokkal kapcsolatos vizsgálatok alapjai és tapasztalatai"*, Multidiszciplináris Tudományok: A Miskolci Egyetem közleménye 11 : 2 pp. 93-99. , 7 p. (2021)

13. V. Mikáczó, Z. Siménfalvi, G. L. Szepesi *„Practical Extension of Ideal Gas Model for Propane Explosions"*, Abstract book for the 17th Miklós Iványi International PhD & DLA Symposium: Architectural, Engineering and Information Sciences, Pécs, Magyarország : Pollack Press (2021) 227 p. p. 143

14. V. Mikáczó, Z. Siménfalvi, G. L. Szepesi *„Practical Extension of Ideal Gas Model for Propane Explosions"*, Pollack Periodica: An International Journal for Engineering an Information Sciences, Paper: 10.1556/606.2022.00603 (2022) *Scopus, Q3*

15. V. Mikáczó *„Gas explosion venting of 20-litre vessel with and without varoius length of vent ducts"*, Multidiszciplináris Tudományok: A Miskolci Egyetem közleménye, 12 : 3 pp. 207-216. , 7 p. (2021), DOI: https://doi.org/10.35925/j.multi.2022.3.19

16. Mikáczó V., Siménfalvi Z. *„Lefúvatott robbanások maximális redukált nyomásának vizsgálata az EN 14994 és NFPA 68 szabványok tükrében"*, GÉP LXXIII : 5 pp. 52-55., 4 p. (2022)

References

[1] Chris T. Cloney. 2021 Mid-year combustible dust incident report - Version 1. Technical report, DustEx Research Ltd. Retrieved, 2021.

[2] Qingming Liu, Yunming Zhang, Fang Niu, and Lei Li. Study on the flame propagation and gas explosion in propane/air mixtures. *Fuel*, 140:677–684, 2015.

[3] Venera Brinzea, Maria Mitu, Codina Movileanu, Adina Musuc, Domnina Razus, and Dumitru Oancea. Propagation velocities of propane-air deflagrations at normal and elevated pressures and temperatures. *Revista de Chimie*, 63(3):289–292, 2012.

[4] G. Ciccarelli and S. Dorofeev. Flame acceleration and transition to detonation in ducts. *Progress in Energy and Combustion Science*, 34(4):499–550, 2008.

[5] Christophe Proust. A few fundamental aspects about ignition and flame propagation in dust clouds. *Journal of Loss Prevention in the Process Industries*, 19(2-3):104–120, 2006.

[6] Ömer L. Gülder. Turbulent premixed flame propagation models for different combustion regimes. *Symposium (International) on Combustion*, 23(1):743–750, 1991.

[7] C J Lea and H S Ledin. A review of the State-of-the-art in gas explosion modelling. Technical report, 2002.

[8] S. M. Frolov, V. S. Aksenov, and I. O. Shamshin. Reactive shock and detonation propagation in U-bend tubes. *Journal of Loss Prevention in the Process Industries*, 20(4-6):501–508, 2007.

[9] Jennifer Wen and Changjian Wang. The new single-step reaction mechanism for propane explosions covering the entire spectrum of flame acceleration, transition to detonation and detonation. Technical report, The University of Warwick, 2013.

[10] Song Sun, Yanyu Qiu, Huadao Xing, and Mingyang Wang. Effects of concentration and initial turbulence on the vented explosion characteristics of methane-air mixtures. *Fuel*, 267(1):1–9, 2020.

[11] Vladimir V. Molkov. Unified correlations for vent sizing of enclosures at atmospheric and elevated pressures. *Journal of Loss Prevention in the Process Industries*, 14(6):567–574, 2001.

[12] J. Sustek and B. Janovsky. Comparison of empirical and semi-empirical equations for vented gas explosion with experimental data. *Journal of Loss Prevention in the Process Industries*, 26(6):1549–1557, 2013.

[13] Risto Lautkaski. Duct venting of gas explosions. Revision of two proposed engineering correlations. *Journal of Loss Prevention in the Process Industries*, 25(2):400–413, 2012.

[14] R. K. Eckhoff. Current status and expected future trends in dust explosion research. *Journal of Loss Prevention in the Process Industries*, 18(4-6):225–237, 2005.

[15] B. Ponizy and J. C. Leyer. Flame dynamics in a vented vessel connected to a duct: 1. Mechanism of vessel-duct interaction. *Combustion and Flame*, 116:259–271, 1999.

[16] Lei Pang, Zhiwen Zhang, Shiqi Cui, and Siheng Sun. Experimental study of the venting characteristics of dust explosion through a vent duct. *Journal of Loss Prevention in the Process Industries*, 65:104144, 2020.

[17] P. Russo and A. Di Benedetto. Effects of a duct on the venting of explosions - Critical review. *Process Safety and Environmental Protection*, 85(1 B):9–22, 2007.

[18] J. F. Ye, X. H. Jiang, Z. W. Jia, and B. C. Fan. Expermiental investigations of external second-explosion induced by vented explosion. *Explosion Shock Waves*, 04:356–362, 2004.

[19] M. Hey. Pressure relief of dust explosions through large diameter ducts and effects of changing the position of the ignition source. *Journal of Loss Prevention in the Process Industries*, 4(4):217–222, 1991.

[20] W. Kordylewski and J. Wach. Influence of ducting on the explosion pressure. *Combustion and Flame*, 66(1):77–79, 1986.

[21] Weiguo Cao, Wenjuan Li, Liang Zhang, Jianfa Chen, Shuo Yu, Zhuanghong Zhou, Yun Zhang, Xiaobo Shen, and Yingxin Tan. Flame characteristics of premixed H2-air mixtures explosion venting in a spherical container through a duct. *International Journal of Hydrogen Energy*, 46(52):26693–26707, 2021.

[22] MSZ EN 14797. Robbanásvédelmi szellőztetőeszközök, 2007.

[23] EN 14994. Gas Explosion Venting Protective Systems, 2007.

[24] MSZ EN 14491. Dust Explosion Venting Protective Systems, 2013.

[25] NFPA 68. Standard on Explosion Protection by Deflagration Venting, 2018.

[26] Erdem A. Ural. Dust explosion venting through ducts. In *AIChE 2005 Spring national meeting 39th annual loss prevention symposium, Atlanta, GA, April 11e13*, pages Paper TG004–5, 2005.

[27] Almerinda Di Benedetto, Paola Russo, and Ernesto Salzano. The Design of Duct Venting of Gas Explosions. *Wiley InterScience*, 2007.

[28] EN 14034-1+A1. Determination of explosion characteristics of dust clouds - Part 1: Determination of the maximum explosion pressure Pmax of dust clouds, 2004.

[29] Kenneth L. Cashdollar. Overwiev of dust explosibility characteristics. *Journal of Loss Prevention in the Process Industries*, (13):183–199, 2000.

[30] Domnina Razus, Dumitru Oancea, Venera Brinzea, Maria Mitu, and Codina Movileanu. Experimental and computed burning velocities of propane-air mixtures. *Energy Conversion and Management*, 51(12):2979–2984, 2010.

[31] A. S. Huzayyin, H. A. Moneib, M. S. Shehatta, and A. M A Attia. Laminar burning velocity and explosion index of LPG-air and propane-air mixtures. *Fuel*, 87(1):39–57, 2008.

[32] Venera Brinzea, Maria Mitu, Codina Movileanu, Adina Musuc, and Domnina Razus. Expansion coefficients and normal burning velocities of propane-air mixtures by the closed vessel technique. *Analele Universitatii Bucuresti: Chimie*, 19(2):31–37, 2010.