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Venting of gas explosion through relief ducts: Interaction between internal and external explosions

G. Ferrara [a], S.K. Willacy [b], H.N. Phylaktou [b], G.E. Andrews [b], A. Di Benedetto [c,*], E. Salzano [c], G. Russo [a]

[a] Dipartimento di Ingegneria Chimica, Università di Napoli "Federico II", P.le Tecchio 80, 80125 Napoli, Italy
[b] Energy and Resources Research Institute, University of Leeds, United Kingdom
[c] Istituto di Ricerche sulla Combustione, Consiglio Nazionale delle Ricerche, P.le Tecchio 80, 80125 Napoli, Italy

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Abstract

Relief ducts fitted to venting openings is a widespread configuration in the industrial practice. The presence of a duct has been reported to severely increase the violence of the vented explosion posing a problem for the proper design of the venting device. Several studies have reported the leading importance – in the whole complex explosion phenomenology – of a secondary explosion in the duct. Modern approaches in the study of simply vented explosions (without ducts) have focused on the study of the interaction between internal and external explosion as a key issue in the mechanisms of pressure generation. The issue is even more relevant when a duct is fitted to the vent due the confined nature of the external explosion. In this work the interaction between internal and external events is experimentally investigated for gas explosions vented through a relief duct. The work has aimed at studying mechanisms underlying the pressure rise of this venting configuration. The study has put the emphasis on the *mutual* nature of the interaction. A larger scale than laboratory has been investigated allowing drawing results with a greater degree of generality with respect to data so far presented in literature.

Keywords: Venting; Relief ducts; Internal and external explosion; Mutual interaction

1. Introduction

Vent devices for gas and dust explosions are often directed to safe locations by means of relief pipes for the discharge of hot combustion products or blast waves. Both the international standards NFPA 68 [1] and VDI 3673 [2] prohibit the discharge of deflagration vents inside buildings, and recommend the use of relief ducts to direct the discharge to a safe external location.

The presence of a duct has been reported to increase the severity of the explosion with respect to simply vented vessels [3–6] posing an engineering problem when the proper design of this venting configuration is sought for.

In the last decades a significant number of works have addressed the issue of explosion vented through relief ducts for both gas [5–13] and dusts [4,14].

The presence of the duct to protect the vessel from explosion has been traditionally addressed in terms of increased pressure drop due to the gas flow through the vessel–duct assembly [4,15,16]. A more in depth approach, has evidenced that the phenomenology is strongly affected by a violent external explosion in the initial sections of the duct rather than by additional pressure losses [5,6,9,10,12,13]. The flow restriction in correspondence of the duct entrance is responsible for a strong flow acceleration that produces high levels of turbulence [6,17]. When the flame enters the duct, due to the high turbulence levels, hot and fresh gases undergo an effective mixing that promotes a violent burning (an explosion-like combustion: *burn-up*) in the initial sections of the duct. The related pressure impulse in the duct has been suggested to temporarily induce a flow reversal across the vent (usually referred to as *back-flow*) [6].

* Corresponding author at: Istituto di Ricerche sulla Combustione, Consiglio Nazionale delle Ricerche, Via Diocleziano 328, 80124 Napoli, Italy.
Tel.: +39 0817682947.
E-mail address: dibenede@irc.cnr.it (A. Di Benedetto).

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While some level of agreement has been reached on the leading importance of the secondary explosion in the duct, several proposals on the mechanisms triggered by the external event still stand without sufficient investigation. To this regard some authors have explained the increased violence of the ducted explosion – with respect to simply vented vessels – indicating an enhanced burning rate in the vessel [5,6,9,11]. Others have proposed that the pressure rise in the vessel is related to the reduced effectiveness of the venting process caused by the pressure rise in the duct [13].

Two different mechanisms for an enhanced burning rate have been proposed. One of these would be the interaction of the flame with the turbulence generated by the violent flow reversal produced by the secondary explosion [5,6]. The other mechanism proposed for the enhanced burning would be due to the growth of a flame instability (Taylor–Rayleigh instability) triggered by the interaction of residual combustion in the vessel with the strong pressure wave produced in the duct [9,10]. From literature it is known that rich hydrocarbon–air mixtures are very sensitive to such instabilities, which can lead to significant pressure rises during the vented explosion [3,18–20].

Conversely, on the basis of a CFD model, Ferrara et al. [13] recently indicated that the pressure rise in the protected vessel could possibly not have originated from enhanced burning, but rather by the reduced venting effectiveness due to the secondary combustion in the duct. The authors argued that the combustion in the duct caused reduced pressure differences across the vent, thus effectively inhibiting the vented flow rate. Numerical CFD results have unambiguously indicated that no substantial increase of the burning rate is necessary to produce the experimentally observed pressure levels.

The experimental data analysed by Ferrara et al. [13] refer to data presented in the works of Ponizy and Leyer [6,11]. The data from Ponizy and Leyer and all the other detailed available studies on the ducted venting configuration, refer to laboratory scales (primary vessel volume $\sim 10^{-3}$ m^3) and conclusions cannot be safely generalized to larger scales. However, it must be acknowledged that both turbulence and pressure wave effects are much more effective in accelerating combustion on larger than laboratory scales [19,21,22]. Thus, mechanisms of enhanced burning rate cannot be ruled out in principle for scales larger than the available studies as mentioned above.

Also, there is evidence that no simple scaling-up is feasible from laboratory scale data to larger scales. The scale of the explosion is likely to change the extent to which different mechanisms play. As an example, data for gas explosions vented through ducts on laboratory scale [11] have indicated that central ignition produces the highest maximum pressures inside the vessel. However, data gained from larger scale explosions for the same configuration [28] have indicated that the maximum pressure of the explosion increases as the ignition point is positioned further from the vent.

This issue makes it necessary to extend the detailed study of such venting configuration – both theoretically and experimentally – to larger scales than so far proposed in literature, aiming at investigating mechanisms affecting the violent pressure rise in this venting configuration.

The approach used in many of the quoted experimental works also appears to be susceptible to some improvement. The reported contributions have mainly focused attention on the influence of the external event on the internal while there is substantial evidence that combustion in the duct is strictly controlled by the flame dynamics in the vessel [17]. Very few works have focused attention on this issue and the “mutual” nature of the interaction has received very scarce attention. The only experimental work that has considered this latter issue to some extent is the already mentioned contribution from Ponizy and Leyer [11]. These authors have acknowledged the qualitative importance of the flame dynamics in the vessel as this determines the gas velocity in the duct and consequently the violence of the secondary explosion. On the other hand, they have searched for a quantitative relationship between the violence of the external and internal explosion eventually failing to find any. They have suggested that the external event only triggers the pressure rise in the vessel whose final level depends on other factors such as the residual amount of unburned mixture and the effective burning rate. In summary, the literature survey on explosions vented through ducts displays the lack of understanding of the actual nature of the interaction between external and internal explosion and, as a consequence, of the quantitative relationship between them. Moreover the laboratory scale nature of almost all available data in literature makes their interpretation/extrapolation questionable. It then results that improvement to comprehension will stem from a systematic investigation of the interaction between external and internal explosions on scales larger than laboratory scales.

The aim of the current work is to investigate the mechanisms of pressure generation in gas explosions vented through ducts on a larger than laboratory scale. In the next sections, experimental data will be presented and discussed in the framework of the afore-mentioned *mutual*-nature interaction between external and internal events.

2. Experimental apparatus

Experimental data gained for a pilot scale (0.2 m^3) cylindrical vessel will be presented (see Fig. 1). Explosion data have been obtained both in a “simply vented” and “duct vented” configuration (where a relatively short discharge duct is fitted). Comparison between the two configurations is valuable as it provides clear indication on the selective effect of the presence of the ducting.

Accurate data on pressure evolution in several selected positions of the rig during the vented explosions have been collected and analysed. The flame propagation has been tracked by means of thermocouples.

The interaction between the external and internal events has been studied, keeping constant the geometry and varying the fuel, the concentration of mixtures and the ignition position (see Table 1).

The experimental configuration used consists of a cylindrical 0.2 m^3 vessel ($L = 1.0$ m, $D = 0.5$ m) connected to a large dump volume (~ 50 m^3), through a gate valve ($D = 0.162$ m) and a vent duct ($L_t = 1.0$ m, $D_t = 0.162$). For the purpose of this research, the

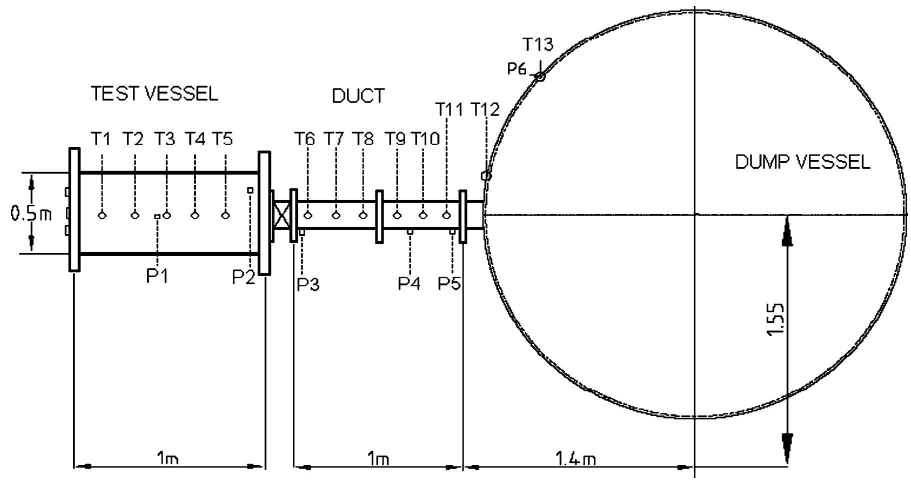

Fig. 1. Schematic of the experimental rig: side view; "Tn" are the thermocouple positions; "Pn" are pressure transducers.

dump volume was sufficient to allow these results to hold a good approximation to an explosion vented out into the atmosphere (see Fig. 1).

The gate valve was opened just before the electrical spark thus allowing to simulate an uncovered vented explosion (i.e. the venting relief pressure has been held to 0 bar g: $P_{stat} = 0$ bar g). Uncovered vents, or low-pressure relief venting devices, are encountered in common practice in industry when considering storage tanks or buildings [1].

Measurements of flame speed were recorded from the primary vessel and duct using an array of exposed junction, mineral insulated, type-k thermocouples, positioned along the centre line of the vessel and duct (where attached) (see Fig. 1). Flame speed data were generated from flame arrival times (marked as an abrupt change in the thermocouple output). Pressure within the vessel was monitored using an array of piezoresistive pressure transducers. The data generated was collected using a transient data recorder.

Table 1
Summary of the experimental test

Ignition position	Fuel	Fuel concentration (%, v/v)	Φ
Rear	Propane	3.2	0.79
Rear	Propane	4.0	1.0
Rear	Propane	4.5	1.13
Rear	Propane	5.5	1.39
Rear	Propane	6.0	1.53
Central	Propane	3.2	0.79
Central	Propane	4.0	1.0
Central	Propane	4.5	1.13
Central	Propane	5.5	1.39
Central	Propane	6.0	1.53
Rear	Methane	8.0	0.82
Rear	Methane	9.5	1.0
Rear	Methane	10.0	1.06
Rear	Methane	12.5	1.36
Central	Methane	8.0	0.82
Central	Methane	9.5	1.0
Central	Methane	10.0	1.06
Central	Methane	12.5	1.36

The same test have been carried out both for simply vented and duct vented configurations. Φ is the equivalent ratio of the exploded mixtures.

Table 2
Position of the thermocouples and pressure transducers along the vessel–duct assembly

Thermocouple tag	Position* (m)	Pressure transducer tag	Position* (m)
T1	0.19	P1	0.51
T2	0.36	P2	0.85
T3	0.53	P3	1.3
T4	0.7	P4	1.89
T5	0.85	P5	2.14
T6	1.34	P6	2.65
T7	1.46		
T8	1.59		
T9	1.84		
T10	1.96		
T11	2.09		
T12	2.3		
T13	2.65		

*Positions are evaluated from the rear end of the vessel.

Table 2 displays the positions of the thermocouples and of the pressure transducers along the duct.

Ignition was actuated in the primary vessel using a standard 16J combustion engine spark plug of modified length, positioned either at the rear wall or central to the vessel, each along the centre line opposite the entrance to the duct.

Mixture preparation in this vessel was achieved by partial pressure method in the primary vessel only, this was isolated from the duct using a gate valve which was opened immediately prior to ignition. Homogeneity of the mixture was confirmed using gas chromatography.

Each test was performed three or more times to check for consistency and repeatability of the data.

3. Results and discussion

Some general behaviour of the exploded mixtures will be presented on a "base-case" configuration. This configuration

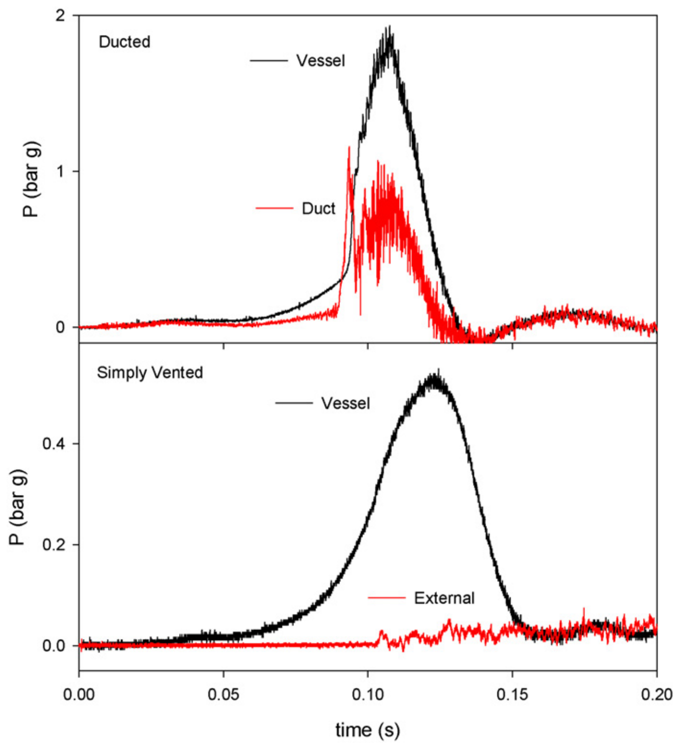

Fig. 2. Effect of the presence of the duct: pressure traces as a function of time for propane–air stoichiometric mixtures, rear ignition. Black curves are the pressure traces in the vessel; red curves are in the duct or dump vessel. Upper part of the figure: explosions with the duct fitted; lower part of the figure: simply vented test.

consists of a stoichiometric propane–air mixture ignited at the rear position.

3.1. Effect of the presence of the duct

In Fig. 2, the temporal trends of the vessel pressure are shown as obtained in the presence (top) and in the absence of the duct (bottom) for the rear ignition case. The presence of the duct brings both qualitative and quantitative differences in the pressure histories of the explosions.

Quantitatively, it is observed that the presence of the duct is responsible for maximum pressures several times higher in the vessel than for the corresponding simply vented configuration. A similar trend is recorded for the maximum rates of pressure rise (Table 3).

Considering the external pressure signals, it is worth noting the difference in the violence of the external event (occurring in the initial sections of the duct for the ducted test and in the dump vessel for the simply vented test). In particular it is shown that the presence of the duct produces a violent external explosion which is almost absent when it is removed.

Table 3
Comparison between maximum rates of pressure rise (dP/dt_{max}) for duct vented and simply vented explosions of stoichiometric propane–air mixtures

Test description	dP/dt_{max} (bar/s)
Ducted (C_3H_8–air mixture; $Y_{C_3H_8} = 4.0\%$, rear ignition)	211
Simply vented (C_3H_8–air mixture; $Y_{C_3H_8} = 4.0\%$, rear ignition)	20

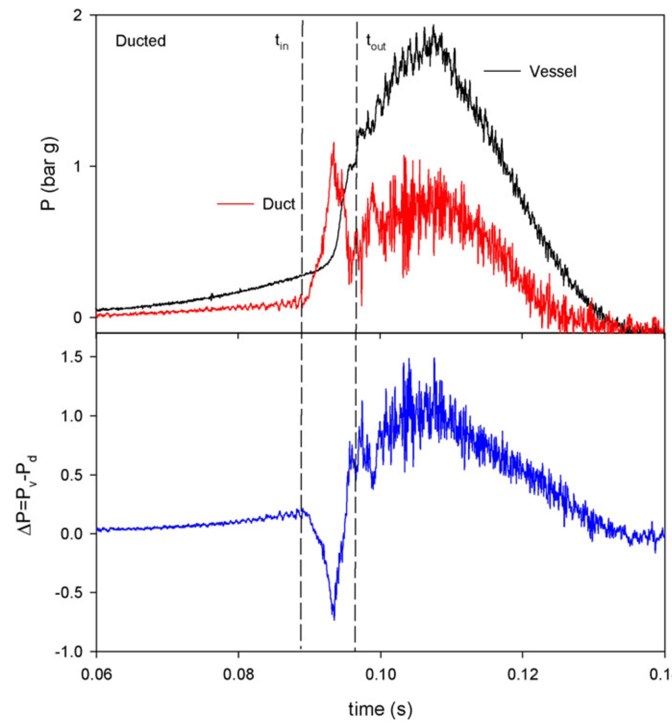

Fig. 3. Pressure traces in the vessel as a function of time: propane–air stoichiometric mixtures; rear ignition. Pv is the pressure in the vessel; Pd in the duct; tin and tout, are respectively the times of flame entrance and exit from the duct.

On the qualitative side, it should be noted that the opposite time relationship between the internal and the external events depend on the presence of the duct. When the explosion is vented directly to the dump vessel, the external event (that manifests itself merely as a disturbance in the atmospheric pressure level) occurs after, or nearly in correspondence, with the maximum rate of combustion inside the vessel (i.e. the maximum rate of pressure rise inside the vessel). On the other hand, when the duct is fitted to the vessel, the external combustion clearly anticipates and (possibly) drives the main internal pressure rise (Fig. 2).

The proposed comparison is effective as it allows to characterize the secondary explosion in the duct as the phenomenon that triggers the pressure rise in a venting configuration when a relief duct is fitted to the protected vessel.

3.2. Pressure histories

In Fig. 3 the pressure trends as a function of time for explosions of stoichiometric propane–air mixtures as measured at position x_1 in the vessel (P_v) and x_3 in the duct (P_d) are shown for *rear* ignited mixtures. Vertical dashed lines represent the times that flame enters (t_{in}) and exits the duct (t_{out}), respectively. The pressure difference between the vessel and the duct ($\Delta P = P_v - P_d$) is also shown.

The time at which the flame enters the duct ($t = t_{in}$) separates two qualitatively different behaviours of the vented explosions. During the initial stages (before the flame enters the duct), a relatively slow pressure rise is observed and the pressure differ-

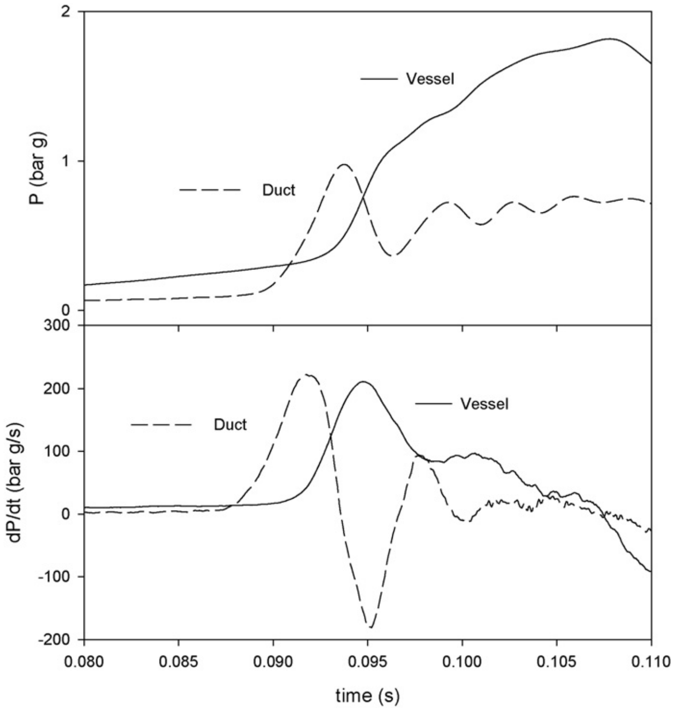

Fig. 4. Smoothed pressure traces. Upper part of the figure: pressure vs. time profiles; lower part: rates of pressure rise vs. time. Propane–air stoichiometric mixtures; rear ignition. Averaging period is ms; curves are averaged in the sense that points are reiteratively averaged over 5 ms periods.

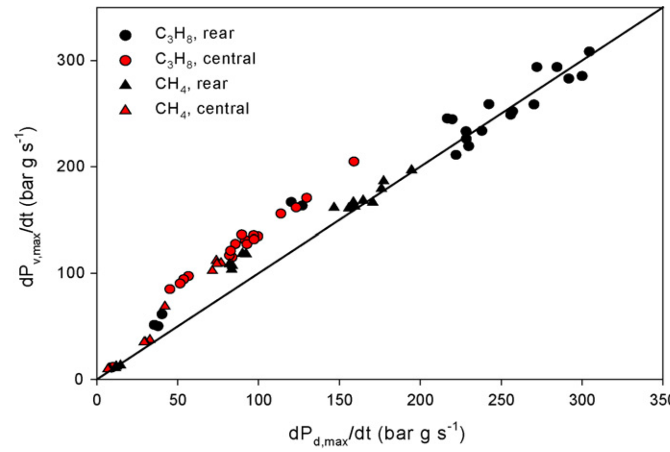

Fig. 5. Maximum rates of pressure rise in the vessel as a function of maximum rates of pressure rise in the duct.

ence across the vent is positive ($\Delta P > 0$), allowing quite effective venting pressure relief. Shortly after the flame reaches the vent opening, a steep pressure rise is observed in the initial sections of the duct followed by an analogous steep rise in the vessel pressure.

The steep pressure rise is recorded earlier in the duct than in the vessel and this produces a short duration negative spike in the pressure difference between the vessel and the duct ($\Delta P < 0$). Shortly after this negative spike, positive pressure drops are readily restored across the vessel–duct assembly and the maximum value of pressure inside the vessel is reached.

The steep pressure rise occurring in the duct has been ascribed to the combustion (*burn-up*) following the ignition/explosion of the unburned gases accumulated in the duct under intense levels of turbulence [5,6,9,10,23].

3.2.1. Evaluation of mechanisms of pressure generation

In Fig. 4 the smoothed time profiles of pressures and rates of pressure rise (dP/dt) are reported to display a clearer picture of the time relationships between the pressure curves. The tests shown represent the same general qualitative behaviour observed for all conducted tests.

From the pressure plots presented in Fig. 4 it can be seen that at least the first part of the main pressure rise in the vessel (solid line) is driven by the pressure rise in the duct (dashed line). In analogy with that observed for large scale simply vented explosions [34] we will indicate this “parallel” pressure rise as a “coherent deflagration”.

Fig. 4 also shows that the maximum rates of pressure rise in the vessel and duct are very similar in magnitude, even if shifted in time. This equality is not to be considered accidental as it has been observed for all performed tests. In Fig. 5 the maximum rates of pressure rise in the vessel $(dP_v/dt)_{max}$ as a function of the maximum rate of pressure rise in the duct $(dP_d/dt)_{max}$ are reported. It can be seen that data collect with a good approximation on the relationship:

$$\left(\frac{dP_v}{dt}\right)_{max} = \left(\frac{dP_d}{dt}\right)_{max} \quad (1)$$

This equality allows the evaluation of the mechanisms of pressure generation inside the vented vessel. The rate of pressure rise in the vessel has been traditionally employed to characterize the reactivity of the mixture. As already reported, in previous work it has been proposed that the steep slope of the pressure rise in the vessel (for duct vented explosions) is promoted by enhanced burning rate due to turbulence [5,11]. However, from our data this does not seem to be necessarily the case. If the value of the maximum rate of pressure rise in the vessel had to be related to enhanced burning rates, it would not be equal to the rate of pressure rise in the duct. Burning rates are complex functions of the local flow; as fluid-dynamic conditions in the vessel and in the duct are different indeed it would not be possible for the burning rates to be equal.

It is proposed that the pressure rise in the duct is leading the pressure rise in the vessel by means of a back-transmitted pressure wave that confers its slope to the pressure trace in the vessel. The only way for the two times of pressure rise in the vessel and in duct to be equal, is to assume that the pressure rise in the vessel (at least the first part) originated from a mechanism of pressure wave transmission and not by combustion with enhanced burning rate. In other words, the two pressure profiles are simply shifted by the characteristic time of travelling sound waves and slopes have to be the same. The final peak pressure is then the result of the combustion inside the vessel starting from a pre-compressed mixture caused by the initial stages of combustion—before the flame reaches the vent.

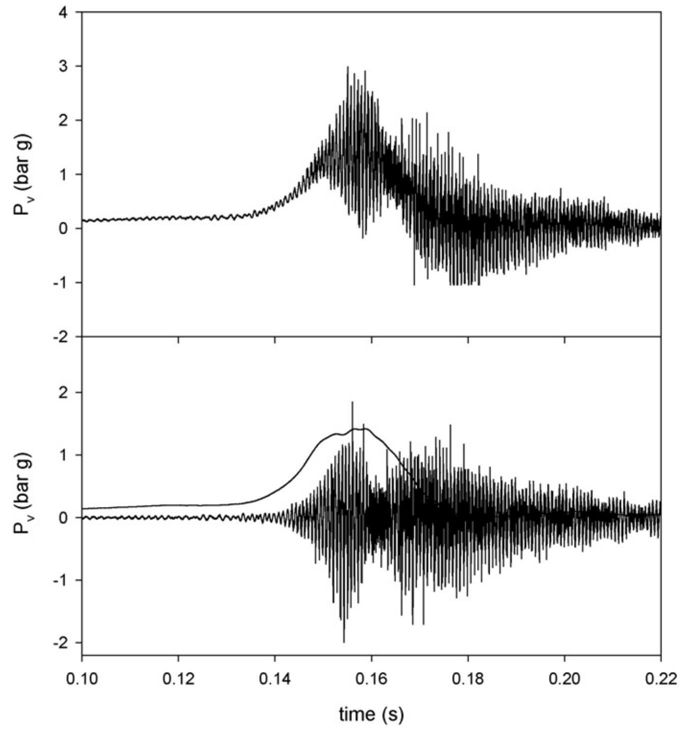

Fig. 6. Pressure vs. time in the vessel for rich propane–air mixtures ($\Phi = 1.39$; 5.5% vol) in the absence of the relief duct (simple vented vessel). The lower part of the figure shows the high and low frequency pressure components. The characteristic time evolution of the acoustic enhancement is visible in the high frequency component.

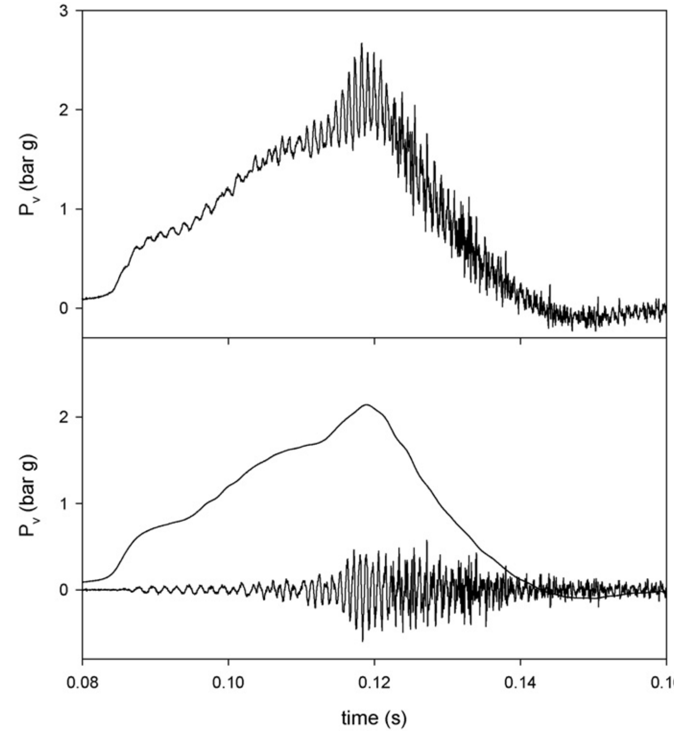

Fig. 7. Pressure vs. time in the vessel for propane–air rich mixtures ($\Phi = 1.39$; 5.5% vol) in the presence of the relief duct. The lower part of the figure shows the high and low frequency pressure components. No acoustic enhancement is visible in the high frequency component.

The time shift between the pressure curves in the duct and in the vessel (see Fig. 4) was measured to be about 2 ms corresponding to a wave travelling at about 460 m/s.

A frequency analysis of the pressure trace signals was performed to evaluate the interaction between the pressure wave produced in the duct and the combustion in the vessel. The pressure traces were digitally filtered and split into high and low frequency components (a 350 Hz cut-off frequency was chosen on the basis of the fundamental modes of the vessel).

In Figs. 6 and 7 the high and low frequency components of the pressure traces of centrally ignited rich propane–air mixtures ($Y_{C_3H_8} = 5.5\%$; $\Phi = 1.4$) are reported for simply vented and duct vented tests, respectively.

In the absence of a duct, the high frequency component of the pressure signal displays the typical pattern exhibited when acoustic enhancement (triggered by the afore-mentioned Taylor–Rayleigh instability) is leading the pressure trace toward a later peak [24]. Pressure oscillations start with the frequency of the fundamental mode of the vessel and experience a progressive exponential increase in both amplitude and frequency. After a stage of exponential growth of pressure amplitude, the frequency reaches its maximum values in correspondence of the maximum pressure recorded in the vessel. From this analysis it then appears that the peak pressure in the vessel may be, in principle, triggered by the acoustic enhancement.

When the duct is fitted to the vessel (Fig. 7), even if there is still visible a growth of pressure amplitude and frequencies, the acoustic enhancement is quite modest and is definitely not as prominent as in the absence of the duct. This suggests that the presence of the duct disrupts the interaction between combustion and pressure waves dumping the acoustic waves [3,24].

3.3. *Effect of reactivity*

3.3.1. *Maximum pressure in the vessel and duct as a function of mixture reactivity*

In Fig. 8 the maximum pressures recorded in the vessel ($P_{v,max}$) and the average values of the flame speeds in the last section of the vessel (u_F) – just before the flame enters the duct – are plotted versus the equivalence ratio for both methane– and propane–air mixtures.

Comparison of data for $P_{v,max}$ and u_F in the vessel, suggest that for rear ignition, the final maximum pressure in the vessel closely resembles the effective reactivity of the mixtures in terms of flame speeds values in the vessel. The flame propagation in the vessel is affecting the final maximum pressure recorded in the vessel (occurring well after the flame has left the vessel, see Fig. 3).

Starting from this observation, an intermediate link was searched between the flame propagation in the vessel and the later following final maximum pressure therein.

Fig. 9 shows all the obtained values of the maximum pressure of the secondary explosion in the duct ($P_{d,max}$) as a function of the gas velocity in the initial sections of the duct. Data suggest a definite relationship between such variables. On increasing the gas velocity in the initial sections of the duct,

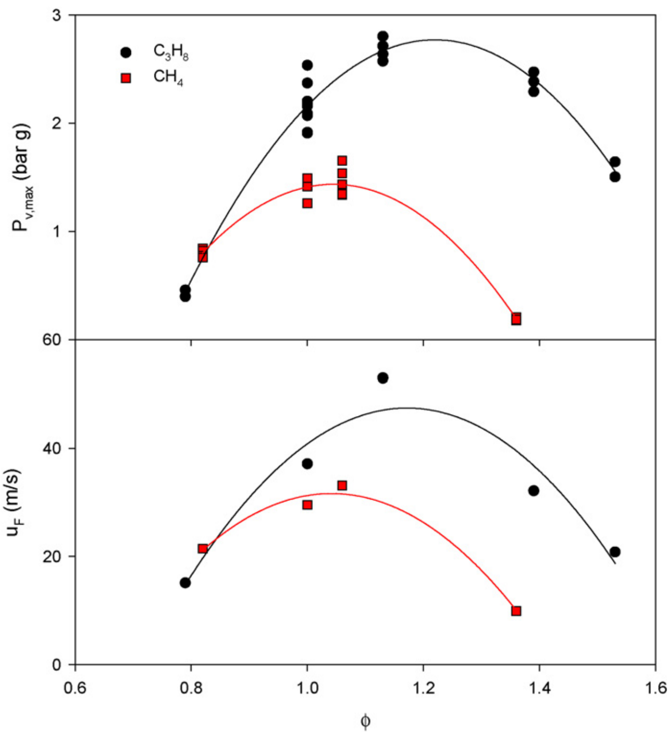

Fig. 8. Effect of mixture reactivity. Upper part of the plot: maximum pressures recorded in the vessel as a function of the equivalence ratio. Lower part: flame speeds in the last sections of the vessel as a function of the equivalent ratio. Rear Ignition.

the maximum pressure reached in the duct increases for both methane– and propane–air mixtures regardless of the ignition position.

The velocities in the initial sections of the duct (u_{duct}) have been estimated from the pressure differences across the duct entrance by means of classical formulas (see for instance Bird et al. [25]). Velocities in the duct (u_{duct}) and flame speeds in the terminal section of the vessel ($u_{\text{F,vessel}}$) are related by a constant

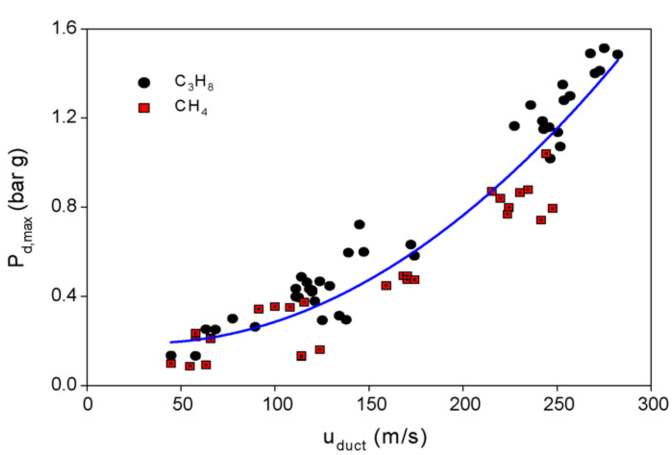

Fig. 9. Maximum pressure of the secondary explosion in the duct as a function of gas velocity in the initial sections of the duct. Velocities in the initial sections of the duct (unduct) have been estimated from the pressure differences across the duct entrance by means of classical formulas (see for instance Bird et al. [25]).

factor, as a result it is possible to state:

$$P_{\text{d,max}} = \text{const} \times (u_{\text{F,vessel}})^n \quad (2)$$

The physical meaning of Eq. (2) is that the faster the flame enters the duct, the more violent will be the subsequent explosion in the duct.

From this result it may be concluded that the flame propagation in the vessel (and then the reactivity) directly affects the size of the external explosion whose effect is then felt on the internal explosion in the way discussed in the previous section.

3.3.2. *Flame self-acceleration in the vessel*

The mixture reactivity in the vessel determines the violence of the external explosion, it is then relevant to discuss the possible mechanisms affecting the flame speeds.

The laminar burning velocities for propane/air and methane/air mixtures are not substantially different for the two hydrocarbon–air mixtures while the measured values of the flame speeds for propane are higher than those of methane (Fig. 8). Therefore, some additional mechanisms should be considered other than the purely reactive-diffusive mechanisms behind the nominal laminar burning velocities.

A laminar propagating flame is affected by hydrodynamic and thermo-diffusive instabilities which tend to wrinkle its surface, enhancing the combustion and the energy release. There is some evidence in literature [26] that propane–air mixtures are more susceptible to hydrodynamic instabilities than methane–air mixtures. Additionally, rich propane–air mixtures display thermo-diffusive instabilities, while the same is not true for rich methane–air mixtures. These issues could explain why the stoichiometric-rich branch of the flame speeds stay higher for propane than for methane.

On the contrary, lean methane–air mixtures display thermo-diffusive instability that is not shown by lean propane–air mixtures allowing the lean branch to stay higher for methane than for propane.

To quantitatively evaluate the acceleration of the flame due to both instabilities and the flow field, a non-dimensional enhancement factor has been introduced:

$$\eta = \frac{u_{\text{F}}}{\text{ES}_1} \quad (3)$$

It is then assumed that the η factor accounts for mechanisms of flame acceleration and can give a quantitative measure of them.

In Fig. 10 the enhancement factor η is reported as a function of the equivalence ratio. The very high values of η for rich propane mixtures in rear ignition cases, reflect the higher tendency of such flames to self-accelerate with respect to methane mixtures. It is also worth noting the differences between the η values obtained for rear ignition and central ignition. In the case of rear ignition, the flame propagates on a length that is twice than central ignition. As a result, the wrinkling of the flame is greater for rear ignition condition.

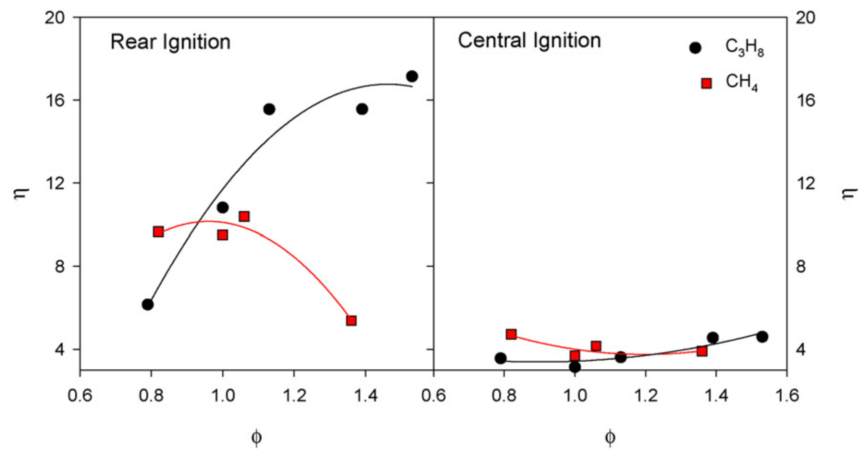

Fig. 10. Enhancement factor of combustion in the vessel as a function of the equivalent ratio. Black points are propane data; red points are methane data. Left: rear ignition; right: central ignition.

3.4. Effect of the ignition position

3.4.1. Maximum pressures as a function of ignition position

The effect of the ignition position has been studied by varying the position of the spark inside the vessel as shown in Fig. 1. In Figs. 11 and 12 the maximum pressures and rates of pressure rise in the vessel for both methane– and propane–air mixtures are reported. For maximum pressures, it can be seen that while for methane the curve relative to the rear ignition stays above the corresponding one for central ignition, for propane–air mixtures is not possible to neatly separate the curves.

On the other hand, univocal behaviour is recovered when considering the comparison between rates of pressure rise for the two hydrocarbon–air mixtures: higher rates of pressure rise are recorded for rear ignited mixtures. However, the final maximum pressure in the vessel is not necessarily linked to this rate of rise. More specifically, for rich propane–air mixtures, it results that the maximum pressure is higher for centrally ignited mixtures even if the rate of pressure rise is lower with respect to rear ignited mixtures (see Fig. 11).

The mutual interaction between internal and external events depends on the ignition position. Fig. 13 shows the maximum pressure in the vessel as a function of maximum pressure in

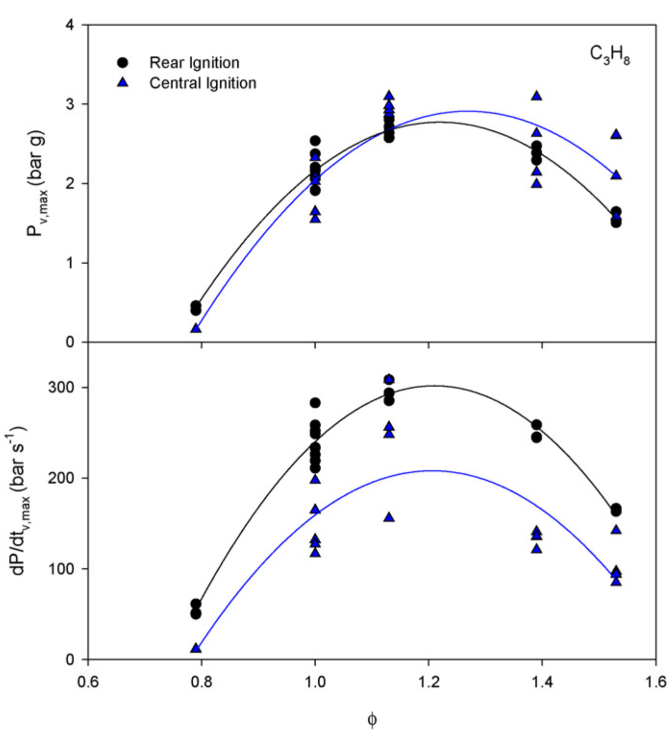

Fig. 11. Effect of ignition position. Maximum pressure and rate of pressure rise in the vessel as a function of the equivalent ratio parametrically with respect tot the ignition position. Propane–air mixtures.

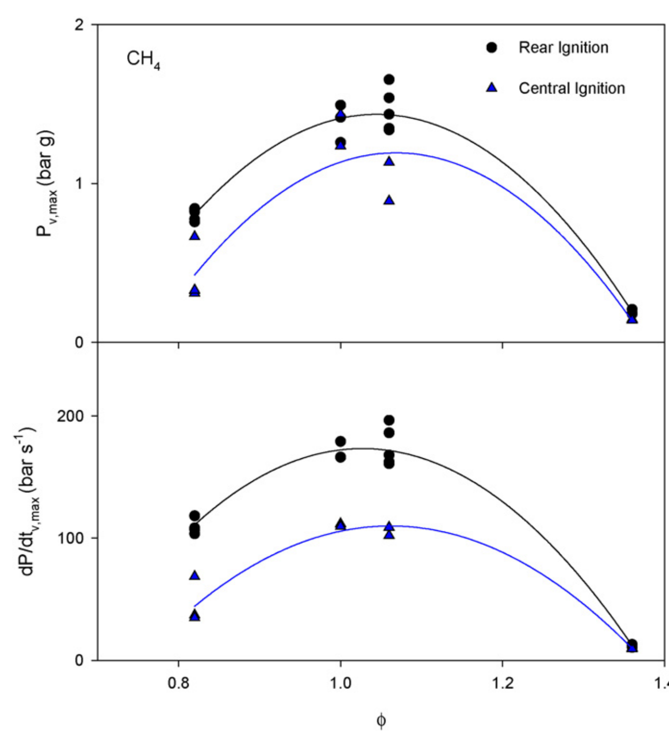

Fig. 12. Effect of ignition position. Maximum pressure and rate of pressure rise in the vessel as a function of the equivalent ratio parametrically with respect tot the ignition position. Methane-air mixtures.

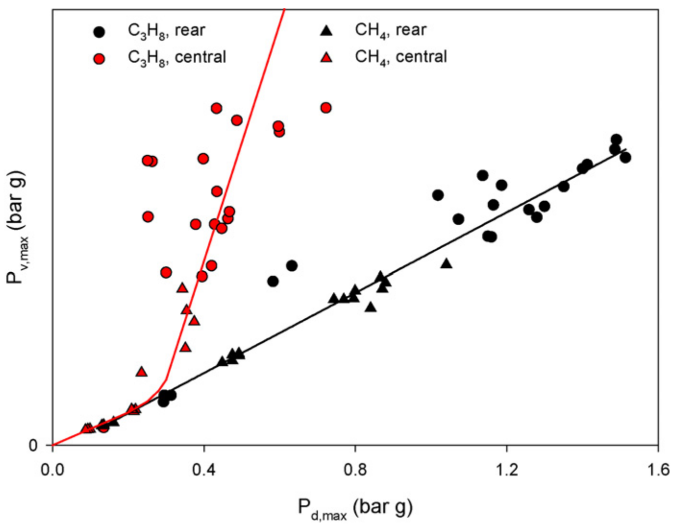

Fig. 13. Maximum pressure in the vessel vs maximum pressure in the duct.

the duct for all experimental tests performed. Data splits in two separated branches is dependent on rear or central ignition, but independent of the fuel used. In particular, when the mixtures are rear ignited, a proportionality relationship between pressure in the vessel and in the duct holds:

$$P_{\mathrm{v,max,REAR}} = \mathrm{const} \times P_{\mathrm{d,max}} \tag{4}$$

Centrally ignited mixtures behave as the rear ignition cases until a certain value of the maximum pressure in the duct is reached ($P_{\mathrm{d,max}} \approx 0.4$ bar g). Afterwards, they display an almost constant value for the maximum pressure of the explosion in the duct and the value of maximum pressure in the vessel is not controlled anymore by the value of $P_{\mathrm{d,max}}$ but rather, directly by reactivity:

$$P_{\mathrm{v,max,CENTRAL}} = \mathrm{const} \times \mathrm{reactivity} \tag{5}$$

Indeed, maximum pressures for centrally ignited mixtures move on an almost vertical line (in the plane $P_{\mathrm{v,max}} - P_{\mathrm{d,max}}$) in dependence of the mixtures reactivity as defined in the previous section.

For central ignition Eq. (5) confirms what has been observed by Ponizy and Leyer [6,11] on a laboratory scale. The external explosion only triggers the pressure rise in the vessel (by means of the pressure wave and a reduced venting effectiveness) and the final value of pressure depends only on the conditions of the burning inside the vessel (i.e. the reactivity). On the other hand – for rear ignition – Eq. (4) reveals that a direct quantitative relationship holds between the pressure amplitudes of the external and the internal events openly contradicting the conclusions from Ponizy and Leyer.

Eqs. (2), (4) and (5) represent the core of the experimental observations about the mutual interaction between internal (vessel) and external (duct) explosion:

$$P_{\mathrm{d,max}} = \mathrm{const} \times (u_{\mathrm{F,vessel}})^n \tag{6}$$

$$P_{\mathrm{v,max,REAR}} = \mathrm{const} \times P_{\mathrm{d,max}} \tag{7}$$

$$P_{\mathrm{v,max,CENTRAL}} = \mathrm{const} \times \mathrm{reactivity} \tag{8}$$

It can be proposed that reactivity – here intended not as the truly laminar burning velocity but also susceptibility to enhanced burning – controls the pressure rise in the vessel by means of two different mechanisms in dependence of the ignition position.

When mixtures are rear ignited, reactivity controls the maximum pressure in the vessel through the effect on the maximum pressure in the duct ($P_{\mathrm{d,max}}$) of the flame speed at the inlet section of the duct (Eqs. (2) and (4)). When mixtures are centrally ignited, reactivity directly controls the maximum pressure in the vessel (Eq. (5)).

In order to get insights about the reason of such behaviour, it should be noticed that the different flame propagation patterns characterizing rear and centrally ignited mixtures, are responsible for different residual amounts of unburned mixture in the vessel at the time the flame reaches the vent and ignites fresh mixture in the duct.

In particular, centrally ignited mixtures are characterized by higher amounts of unburned mixture left in the vessel with respect to rear-ignited mixtures [6,13]. It can then be proposed that while for rear ignition the combustion in the vessel is almost complete when the external explosion starts, for centrally ignited mixtures combustion is still far from completion. In the first case it is then straightforward to single out a fundamental role for the back-propagating pressure wave (i.e. the size of the secondary explosion in the duct) in the pressure rise in the vessel (see Eq. (4)). On the other hand, when mixtures are centrally ignited, the first pressure rise is still driven by the external explosion but it soon looses any link with the external event and the final pressure level is rather controlled by the combustion of the greater amount of unburned mixture left in the vessel (see Eq. (5)).

3.4.2. Scale-effects

In Table 4 the effect of ignition position as gained from available data in literature and from our data is summarized. It is interesting to note the effect of scale on the severity, shifting the worst case condition from the central to the rear ignition position as the size of the rig is increased.

To the authors' knowledge, no experimental work has been devoted to systematically investigate the effect of ignition position for gas explosions for venting configuration on scales of practical interest. Nevertheless, the suggested trend for the effect of the position of the ignition with scale can be reinforced when considering data for dust explosions in the same venting configuration. To this regard it must be recalled that some experimental evidence has reported a close similarity between the dynamics of gas and dust explosions [27].

Table 4
Summary of available data on the effect of ignition position for gas explosions vented through relief ducts and comparison with our data

Authors	V (m^3)	Fuel	Worst case
Ponizy and Leyer [6]	0.0036	C_3H_8	Central
Ferrara et al. [12]	0.2	C_3H_8 and CH_4	Central–rear
De Good and Chatrathi [28]	2.3	C_3H_8	Rear
Hey [29]	18.5	Dusts	Rear

Relying on this, the large scale data ($V = 18.5\,m^3$) for dust explosions gained at the HSE facilities seem to confirm the trend obtained for gas explosions, specifically *rear* ignition has been reported as the worst case [29]. The available experimental data then suggest that moving toward scales of industrial interest, ignition in a rear position produces more severe conditions in terms of maximum pressure of the explosion.

Eqs. (2), (4) and (5) previously obtained, can be used to interpret the trend of the effect of ignition position with scale.

In principle, scale should affect both the size of the internal and external explosions. It is known that turbulent burning rates are strongly affected by the length scale of the rig [21]. However, some evidence has been provided that the turbulent enhancing factor of the burning rate inside the vessel stays constant as the scale goes up when ducts are fitted to vented vessels [5]. Based on this finding, it could be proposed that the scale does not substantially affect the size of the internal explosion by means of turbulence related effects.

Conversely, increasing the scale of the primary vessel, more length is allowed for the flame to accelerate and, as previously seen, this results in higher terminal flame speeds. Then, since the size of the secondary explosion in the duct is controlled by the terminal flame speed (Eq. (2)), it is readily concluded that the maximum pressure of the external explosion increases as the scale increases as this is the expected trend for the flame speed.

Summarizing the effect of scale on the internal and external explosions it can be concluded that as the scale goes up:

(1) For rear ignited mixtures the maximum pressure of the explosion goes up through Eqs. (2) and (4).
(2) For centrally ignited mixtures the maximum pressure stays almost constant (Eq. (5)) as the reactivity does not benefit from any turbulence related effect.

The overall result is that as the scale goes up, the worst case conditions in terms of maximum pressures reached in the vessel move toward the rear ignition case.

It is interesting to notice that these findings, strictly valid for explosions vented through ducts, are probably more general than they appear. To this regard, it must be recalled that the same apparent contradiction about the effect of ignition position is also found for simply vented vessels.

Almost 30 years ago, Bradley and Mitcheson [30] published a very comprehensive collection of experimental data for vented explosions. One of the results of this survey was that central ignition had to be considered as the worst case in terms of the maximum pressures developed during the explosion. A more comprehensive analysis of data from more recent publications [31,32] reveals that the rear ignition poses a worst case scenario (especially when no acoustic enhancement is observed). Once again the apparent contradiction could lie in the different scales of works quoted. The data processed by Bradley and Mitcheson [30] referred to smaller scale explosions than the data of the more recent quoted works. This issue is important as there is some evidence that the importance of the external explosion is greater as the scale goes up [31,33]. It could be generally proposed that when the external explosion is the determining phenomenon (e.g. on large scales and when a duct is fitted to the vented vessel) the rear ignition has to be considered as the worst case. The explanation for this has to be found in the different sensitivity to scale effects of the internal and external explosions. As the scale goes up, the violence of the external explosion increases while the violence of the internal – as reported in Molkov [5] – is almost unaffected.

4. Conclusions

The interaction between internal and external explosion when a duct is fitted to a vented vessel has been studied on a pilot scale equipment:

(1) The study has highlighted the mutual nature of the internal–external explosion interaction: The flame propagation in the vessel drives the external explosion in the duct, which in turns affects the residual combustion in the vessel. In particular, on the side of the influence of the internal explosion on the external explosion, a relationship has been found between the gas velocity in the initial sections of the duct – in correspondence of the flame entrance – and the subsequent violence of the secondary explosion. On the side of the reverse interaction (i.e. the influence of the external explosion on the internal), it has been shown that at least the first stage of the pressure rise in the vessel is a *coherent deflagration*, i.e. the pressure rise inside the vessel closely resembles the pressure rise in the duct [34]. Analysis of data has allowed the evaluation of the mechanisms underlying the coherent deflagration. The previously claimed mechanisms of enhanced burning rate in the vessel – either turbulence generation or acoustic enhancement – do not play relevant roles. It has been rather observed that the impulsive pressure rise in the vessel is driven by the explosion in the duct by means of a back-propagating pressure wave that confers its slope to the pressure rise in the vessel. The pressure wave pre-compresses the burning mixture in the vessel whose final level of pressure is determined by the combustion of the remaining unburnt mixture in a regime of reduced venting effectiveness (reduced vent flow rate). The same coherent pressure rise was previously observed on smaller scales but the nature of the pressure rise was not acknowledged. On the other hand, the experimental data do not allow easy estimation of the amplitude of the back-propagating pressure wave nor of the venting rate reduction due to lowered pressure drop across the vent.
(2) The analysis of data has shown that reactivity affects the pressure recorded in the vessel in a twofold way dependent on the ignition position. When mixtures are rear ignited, the most part of combustion in the vessel occurs prior to the external explosion. Also, due to high terminal flame speeds, the external explosion is a violent event which directly affects the internal pressure rise (Eq. (4)). In this case reactivity affects the internal pressure rise by means of its influence on the external explosion (Eq. (2)). Conversely,

when mixtures are centrally ignited, the combustion inside the vessel is far from completion at the time the external event occurs. In this case, the slope of the pressure rise in the vessel is driven by the external event but the final level of pressure rather depends on the effective reactivity of the mixture (Eq. (5)) due to the relatively large amount of unburned mixture at the time the external explosions is felt inside the vessel.

(3) Presented data have suggested a simple formal frame (Eqs. (2), (4) and (5)) that has allowed the explanation for scale effects. Scale effects act differently on the size of internal and external explosions. This unbalance causes rear-ignited mixtures to represent the worst case – in terms of maximum pressure – as the scale of the rig departs from laboratory scales. More specifically, as the scale goes up, the maximum internal pressure for centrally ignited mixtures does not increase by turbulence related effects (Eq. (5)). However, as the scale is increased, more length is allowed for the flame to propagate in the vessel resulting in higher terminal flame speeds and greater maximum pressure in the vessel for rear ignited mixtures (Eqs. (2) and (4)). As a result, it must be concluded that the rear ignition is to be considered as the worst case on scales of industrial interest.

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