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Gas Explosions Mitigation by Ducted Venting

Almerinda DI BENEDETTO
Istituto di Ricerche sulla Combustione, Consiglio Nazionale delle Ricerche,
Piazzale Tecchio 80, 80125 Napoliu-ITALY
Paola RUSSO
Dipartimento di Ingegneria Chimica e Alimentare, Università di Salerno,
Via Ponte don Melillo, 84084 Fisciano (SA)-ITALY
Ernesto SALZANO
Istituto di Ricerche sulla Combustione, Consiglio Nazionale delle Ricerche,
Piazzale Tecchio 80, 80125 Napoli-ITALY
e-mail: salzano@irc.cnr.it

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Abstract

The mitigation of effects of gas and dust explosions within industrial equipment is effective if venting the combustion products to safe location. The presence of relief duct is however likely to increase the severity of the explosion with respect to equipment vented to open atmosphere, due to secondary explosions occurring in the initial sections of duct, frictional drag and inertia of the gas column, acoustic and Helmholtz oscillations. The weights of these phenomena on explosion enhancement in terms of peak pressure and rate of pressure rise are still uncertain. As a consequence, appropriate design of duct-venting configuration is still a matter of debate.

We recently found that the main phenomenon among those cited is the burn-up occurring in the initial section of duct, which leads to the backflow from the duct towards the protected vented equipment, thus restricting the effective vent section and turbulizing the flame within the combustion chamber. Starting from this result, we have identified dimensionless numbers which quantifies the burn-up effects and then we identified engineering correlations for the appropriate design of relief section in the presence of duct.

Key words: Ducted venting correlation, Venting design, Gas Explosion, Mitigation systems.

Introduction

Venting devices are common solutions for the mitigation of accidental explosions in industrial equipment. However, relief ducts are often necessary for the discharge of combustion products to safe location, as also recommended by the international standards NFPA 68 (2002) and VDI 3673 (2002). The presence of duct has the clear positive effects of limiting the dispersion of hot gases in the close surrounding of equipment but, on the other hand, in most cases may increase the severity of the explosion with respect to explosion vented to free atmosphere, either in terms of maximum overpressure or in terms of rate of pressure rise reached in the protected equipment (Cooper et al., 1986; Lunn et al., 1988; Molkov, 1994; Ponizy and Leyer, 1999a, 1999b). As a consequence, designed section of venting systems may be under-estimated. To this regard, it has been recently shown that the available guidelines for the design of ducted vents for gas explosions, as those proposed by Bartknecht (1981), also reported in NFPA 68 (2002), can lead to significant overestimations (Russo and Di Benedetto, 2007).

In order to predict the effects of the presence of relief duct on the effectiveness of venting systems, many experimental and numerical studies have been performed in the last decades aiming at recognizing the phenomena which drive the increase of explosion severity, either for gas (Wiekema et al., 1977; McCann et al., 1985; Kordylewski and Wach, 1986, 1988) or dusts (Cooper et al., 1986, Ferrara et al., 2006; Pineau et al, 1980 ; Ural, 1993; 2005). Several mechanisms have been then proposed: frictional drag and inertia of the gas column in the duct (Cooper et al., 1986; Ural, 1993; 2005); acoustic and Helmholtz oscillations; secondary explosion in the duct (burn-up) (Molkov, 1994; Ponizy and Leyer, 1999a; Kordylewski and Wach, 1986, 1988; Ferrara et al., 2006; Tamanini, 1995). However, the relative weight of each phenomenon and the effects of geometry and fuel mixture reactivity on each of the cited mechanism are not yet quantified. To these aims, we have recently showed, by means of CFD (Computation Fluid Dynamics) simulations of duct-vented explosion in lab-scale rigs, that the main mechanism affecting the pressure rise during gas explosion in ducted-vented vessel is the violent combustion which occurs in the initial sections of the relief tube (Ferrara et al., 2003, 2006). This phenomenon is currently referred as “burn-up”. Also, we have found that pressure drop and gas column inertia, and the acoustic and Helmholtz oscillations are less relevant. Due to the burn-up phenomenon, the pressure impulse in the duct induces temporarily a flow reversal across the vent thus enhancing the burning rate by means of turbulization of the flame in the main protected vessel (Molkov, 1994; Ponizy and Leyer, 1999a, 1999b; Kordylewski and Wach, 1986, 1988). Besides, an added negative effect on the protection system is given by the reduction of effectiveness of the venting flow rate from the vessel toward the duct (Ferrara et al., 2006). This result has been clear also from a recent sensitivity analysis (Ferrara et al., 2005) that we have performed for any of relevant geometrical, chemical and fluid-dynamic parameter which may affect the peak overpressure obtained in ducted-vented vessel, showing that combustion-related parameters (flame speed, maximum adiabatic pressure, i.e. expansion ratio, and the geometry of duct, i.e. the burn-up) are the only relevant variables to take into account. Furthermore, CFD results have showed unambiguously that the increase of the burning rate due to turbulization is not a necessary condition for the increase of pressure observed experimentally when ducting the vent (Ferrara et al., 2006).

These results have been used for the development of new engineering correlation for the prediction of peak pressure reached within any empty equipment endowed with duct venting - or equivalently for the correct design of vent in terms of vent section - starting from classical semi-empirical methodologies reported in the literature and guidelines (Bartknecht, 1981; NFPA 68, 2002; VDI 3673, 2002; Di Benedetto et al., 2007). To this regard, we have recently tested all correlation available in the literature to evaluate the experimental peak pressure measured during gas explosion in ducted vented vessel [9]. As expected, NFPA 68 (2002) correlation for gas explosion is not adequate as it underestimates the peak pressure and takes into account only the effects related to the duct length. Furthermore, both experimental and theoretical studies reported in the literature clearly show that the duct length can not be assumed as the unique parameter affecting the overpressure with respect to the ductless system [Molkov, 1994; Ponizy and Leyer, 1999a; Kordylewski and Wach, 1986, 1988; Ferrara et al., 2006; Ural, 1993; Di Benedetto et al., 2007). This last result is not surprising if considering the strong influence of burn-up as described above. Also overpressure is influenced by the ignition position, which is not accounted in any of the proposed correlations.

Methodology

We started from the assumption that in ducted-vented explosion the peak pressure reached in the equipment P_{red} is proportional to the ratio of the two characteristic times reproducing respectively the turbulent combustion (τ_c) and the flow of combustion products through the vent section and the following duct (τ_v):

$$\frac{P_{red}}{P_o} = f\left(\frac{\tau_v}{\tau_c}\right) \tag{1}$$

where P_o is the absolute initial pressure.

We have performed the evaluation of the time ratio - in the presence of duct - starting from the corresponding ratio for the un-ducted vented explosions, which was originally defined as “vent ratio coefficient” by Bradley & Mitchelson (1978a, 1978b) in their pioneering works or, more recently, Bradley number, *Br* (Molkov, 1994):

$$Br = \frac{A'}{S'} \tag{2}$$

where A' is a geometrical function which depends on the discharge coefficient C_D, on the vent section A_v

and on the total internal surface of protected equipment A_s:

$$A' = C_D \frac{A_v}{A_s} \tag{3}$$

and the term S' is the flame Mach number, taking into account the sound speed c_0 and expansion ratio E at unburnt T,P conditions:

$$S' = \frac{S_u}{c_o}(E-1) \tag{4}$$

where S_u is the laminar burning velocity and E is the expansion ratio, i.e. the ratio of unburned to burned density.

The evaluation of turbulent time ratio (Eq. 1) accounts for the turbulization of combustion reaction and for the frictional effects of the vent section through two parameters named respectively "turbulization factor" χ, and "discharge factor" μ, which takes into account for frictional effect and is essentially correspondent to C_D. The factor χ describes the interaction between the flame and the turbulent flow field created by the vent flow and combustion instabilities. An increase of this parameter means a decrease of the characteristic chemical time, hence the increase of the maximum pressure experience in the protected vessel. The ratio of χ over μ has been also named "Deflagration to Outlet Interaction" (DOI) and extensively discussed, for un-ducted vented explosion, by several authors (see for instance Bradley and Mitchelson (1978a) and Molkov (2001)). Typical values for χ and μ are 4 and 0.65 in vented gas explosion even if more complex correlation can be found in the literature (Molkov, 2001).

These two values have been considered in the following analysis.

When the duct is fitted on the vent section it can be assumed that the intense burn-up occurring in the initial section of the duct affects both flame turbulization and frictional effects. More in particular, the effect of duct produces on one hand an additional reduction of the vent section, thus affecting the discharge flow (e.g. the parameter μ). On the other hand, the inversion of flow from the duct to the vessel due to burn-up produces further turbulization of the mixture in the vessel, then increasing the parameter χ.

For the sake of describing duct-vented explosion phenomenon, we have then re-defined a ducted-turbulent Br number ($Br_{t,ducted}$) which takes into account the effect of the duct with respect to the conventional turbulent Bradley number defined for un-ducted vented vessels, in the following referred as $Br_{t,un-ducted}$. Hence, it can be written:

$$\frac{Br_{t,\text{ducted}}}{Br_{t,\text{un-ducted}}} = \frac{(\mu/\chi)_{ducted}}{(\mu/\chi)_{\text{un-ducted}}} = \varphi\,(\text{reactivity, geometrical properties}) \tag{5}$$

The ratio of the turbulent Bradley number is expected to be a function of reactivity and geometrical properties of the ducted vessel.

In order to evaluate the ϕ function reported in Eq. 5) we have then analyzed all the experimental data of duct-vented explosion available in the literature by varying the ignition position, the duct diameter and length, the vessel volume and the mixture reactivity (fuel type and composition) (Tables 1a-1c). Hence, we have calculated the turbulent Bradley number either for the ducted or for the un-ducted vented explosions, i.e. the experimental ϕ.

We have used the experimental peak overpressure P_{red} reported in the Table 1 to calculate the turbulent ducted Bradley number ($Br_{t,ducted}$) by means of the equation of Yao (1974), which is valid for un-ducted vented vessels and has been extended to the ducted cases (Yao, 1974):

$$\frac{P_{\text{red}}}{Po} = Br_{t,\text{ducted}}^{-2} \tag{6}$$

where the turbulent Bradley number for un-ducted vessels ($Br_{t,un-ducted}$) has been evaluated starting again from the correlation by Yao (1974):

$$Br_{0t\ \text{un-ducted}} = 1.38\left(\frac{E-1}{E^{7/6}}\right)Br \tag{7}$$

According to the experimental results and analysis reported above, it turns out that the following relation for ϕ may reproduce the duct-vented explosion phenomena in equipment:

$$\frac{Br_{t\cdot\text{ducted}}}{Br_{t\cdot\text{un-ducted}}} = \varphi\,(D_t, L_t, S_u, V, \rho) \tag{8}$$

That is, we have six variables and three dimensions (length, time, mass). So, according to Buckingham π-theorem we may derive four dimensionless groups, thus obtaining:

$$\frac{Br_{t\cdot\text{ducted}}}{Br_{t\cdot\text{un-ducted}}} = \varphi\left(Re_f, Br, \frac{L_t}{D_t}\right) \tag{9}$$

Table 1a. Experimental peak overpressures (P_{red}) for acetone/air explosions at stoichiometric concentration in duct vented equipment, by varying geometry and vent set pressure P_v, as reported by Molkov et al. [26]. Initial conditions: ambient P,T. Central ignition. V= volume, D_t = duct diameter, L_t = duct length.

L_t[m]	D_t[m]	V [m^3]	P_v [bar g]	P_{red}[bar g]
25	0.50	10	0.11	4.10
25	0.50	10	0.06	2.80
4	0.20	2	0.16	4.30
10	0.20	2	0.16	5.20
10	0.38	2	0.16	2.15
1.83	0.05	0.027	0.21	5.00
2.35	0.05	0.027	0.26	4.40
2.35	0.05	0.027	0.26	3.50
2.35	0.05	0.027	1.66	1.90
1.83	0.05	0.027	1.43	4.40

Table 1b. Experimental peak overpressures (P_{red}) for propane explosions in duct vented equipment, by varying geometry, ignition position and vent set pressure P_v, as reported by Ponizy & Leyer [6,7] and De Good & Chatrathi [27]. Initial conditions: ambient P, T. V = volume, D_t = duct diameter, L_t = duct length.

Conc. v/v	Ignition	L_t[m]	D_t[m]	V [m^3]	P_v [bar g]	P_{red}[bar g]
stoich.	Rear	0.6	0.016	0.00366	0.01	1.45
stoich.	Rear	0.6	0.021	0.00366	0.01	1.17
stoich.	Rear	0.6	0.036	0.00366	0.01	1.27
stoich.	Rear	1.1	0.016	0.00366	0.01	1.80
stoich.	Rear	1.1	0.021	0.00366	0.01	1.45
stoich.	Rear	1.1	0.036	0.00366	0.01	1.92
stoich.	Rear	2.6	0.016	0.00366	0.01	1.92
stoich.	Rear	2.6	0.021	0.00366	0.01	1.55
stoich.	Rear	2.6	0.036	0.00366	0.01	1.92
stoich.	Rear	2.6	0.053	0.00366	0.01	2.11
stoich.	Central	1.7	0.036	0.00366	0.01	2.01
stoich.	Central	1.7	0.036	0.00366	0.31	2.16
stoich.	Central	1.7	0.036	0.00366	0.92	2.66
stoich.	Central	1.7	0.036	0.00366	2.31	3.37
stoich.	Rear	1.7	0.036	0.00366	0.01	1.76
stoich.	Rear	1.7	0.036	0.00366	0.33	1.88
stoich.	Rear	1.7	0.036	0.00366	0.84	1.81
stoich.	near the vent	1.7	0.036	0.00366	1.12	1.27
stoich.	near the vent	1.7	0.036	0.00366	2.25	2.24
5%	Centre	1	0.8446	2.6	0.11	0.19
5%	Centre	2	0.8446	2.6	0.11	0.30
5%	Centre	3	0.8446	2.6	0.11	0.39
5%	Bottom	3	0.8446	2.6	0.11	1.01

Table 1c. Experimental peak overpressures (P_{red}) for town gas explosions in duct vented equipment by varying geometry and vent set pressure P_v, as reported by Kordylewski & Wach [12,13]. Initial conditions: ambient P,T. Central ignition. V = volume, D_t = duct diameter, L_t = duct length.

Conc.	L_t[m]	D_t[m]	V [m^3]	P_v [bar g]	P_{red}[bar g]
18% v/v	0.16	0.035	0.022	0.01	3.00
18% v/v	0.32	0.035	0.022	0.01	4.82
18% v/v	0.54	0.035	0.022	0.01	5.65
18% v/v	0.80	0.035	0.022	0.01	4.82
18% v/v	1.40	0.035	0.022	0.01	5.13
18% v/v	1.75	0.035	0.022	0.01	5.18
18% v/v	2.80	0.035	0.022	0.01	2.14
18% v/v	3.50	0.035	0.022	0.01	4.64
18% v/v	4.91	0.035	0.022	0.01	3.57
18% v/v	6.14	0.035	0.022	0.01	3.75
18% v/v	6.75	0.035	0.022	0.01	3.39
18% v/v	2.50	0.025	0.022	0.01	5.00
18% v/v	2.50	0.025	0.022	0.01	4.73
18% v/v	2.50	0.025	0.022	0.01	4.20
10% v/v	2.50	0.025	0.020	0.01	0.82
12% v/v	2.50	0.025	0.020	0.01	2.38
14% v/v	2.50	0.025	0.020	0.01	2.91
16% v/v	2.50	0.025	0.020	0.01	3.47
18% v/v	2.50	0.025	0.020	0.01	4.00
20% v/v	2.50	0.025	0.020	0.01	4.30
22% v/v	2.50	0.025	0.020	0.01	4.82
25% v/v	2.50	0.025	0.020	0.01	5.00
30% v/v	2.50	0.025	0.020	0.01	0.82
20% v/v	0.04	0.025	0.020	0.01	3.68
20% v/v	0.17	0.025	0.020	0.01	3.68
20% v/v	0.30	0.025	0.020	0.01	6.71
20% v/v	0.61	0.025	0.020	0.01	6.36
20% v/v	1.26	0.025	0.020	0.01	4.57
20% v/v	2.50	0.025	0.020	0.01	4.00

In Eq. 9), the ratio L_t/D_t accounts for the frictional losses and gas column inertia. The Bradley number (*Br)* and the flame Reynolds number (Re_f) account for flame acceleration in the duct. To this regard, Rota et al. (1990) used the flame Reynolds number to calculate the flame acceleration due to flame instabilities in their model of vented gas deflagration. In their correlation, the characteristic length is proportional to the vessel volume. In our model, the same length is considered as the diameter of vent, which accounts for the dimension of the vortexes generated by the back-flow at the moment of burn-up:

$$Re_f = \frac{\rho_u S_u D_t}{\mu}. \tag{10}$$

Results and Discussion

We have assumed the the function ϕ is a power law equation with respect to the dimensionless number defined above:

$$\varphi = a_1 \left(Re_f\right)^{a_2} (Br)^{a_3} \left(\frac{L_t}{D_t}\right)^{a_4} \tag{11}$$

The Marquardt-Levenberg algorithm (1986) has been then used to find the parameters of the independent variables (Re_f, Br, L_t/D_t) that give the best fit between the ϕ function of Eq. 11) and the ϕ function obtained by inverse analysis, starting from the experimental (ducted vents) P_{red}(Eq. 6) and $\mathrm{Br}_{tun-ducted}$

(Eq. 7). The found parameter values are given in Table 2. The results of model are shown in Figure 1 where the experimental values of ϕ ratio are compared with the modelled data for ϕ. It should be noted that a good agreement has been found with a regression factor equal to 0.91.

Table 2. Values of the empirical constants of Eq. 11)

Parameter	Reference variable	Value
a_1	-	4.29
a_2	Re_f	-0.25
a_3	Br	0.70
a_4	L_t/D_t	-0.006
R^2		0.91

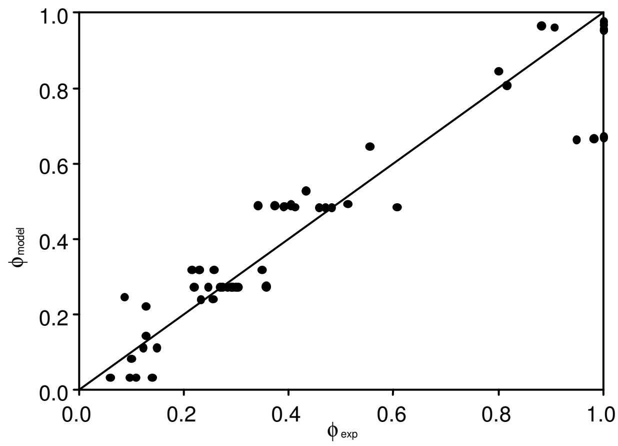

Figure 1. ϕ_{model} (Eq. 11) vs. ϕ_{exp}.

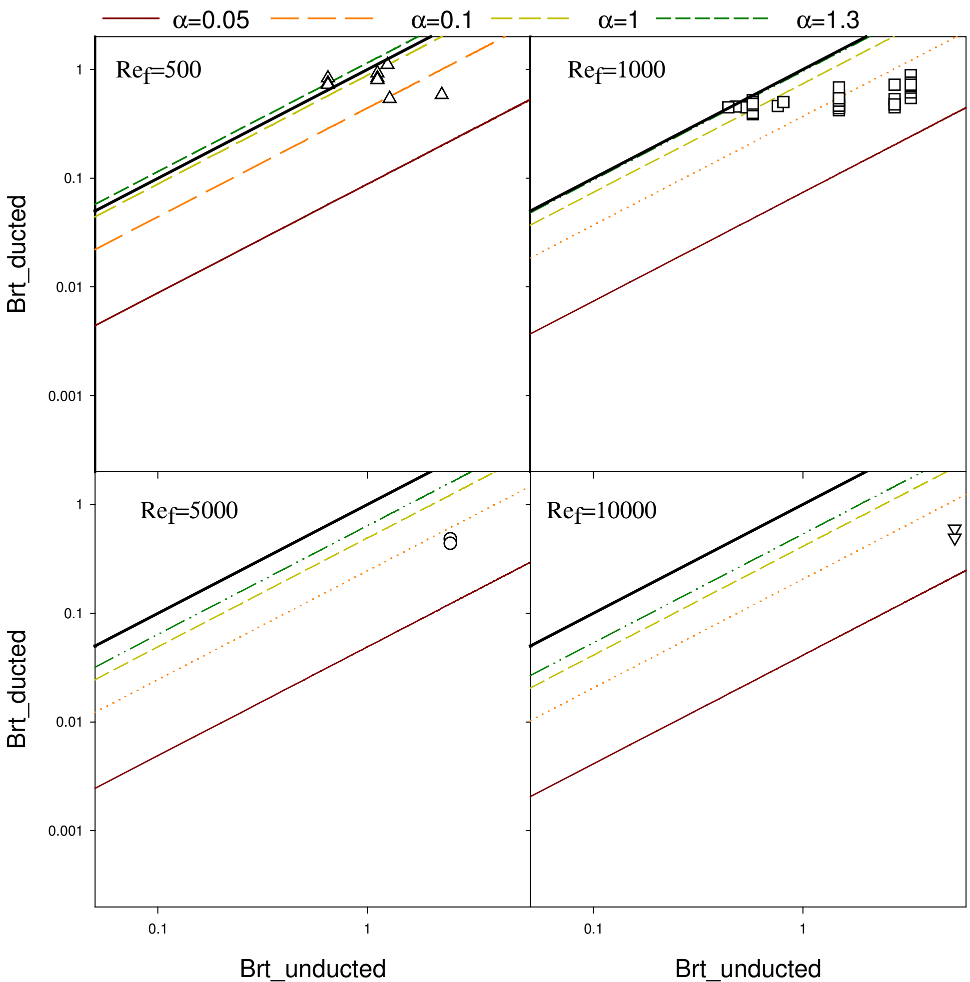

Figure 2. $Br_{t,\text{ducted}}$ vs $Br_{t,\text{un-ducted}}$ for different Re_f and parametrically with $\alpha = Br^{0.7}\ (L_t/D_t)_{-}^{0.006}$. Thick line: $Br_{t\ \text{un-ducted}} = Br_{t\ \text{ducted}}$. Points: experimental data.

From the data given in Table 2, it can be concluded that the ducted turbulent Bradley number is highly sensitive to the values of laminar Br number and to flame Reynolds number, whereas it is less sensitive to the ratio of L_t/D_t. These results are in good agreement with our previous findings which highlighted that frictional losses and gas column inertia are less relevant than burn-up effect quantified by the cited dimensionless number.

Figure 2 reports the maps of the ducted to the un-ducted turbulent Bradley number calculated according to the found function ϕ and considering factor $\alpha = Br^{a3}(L_t/D_t)^{a4}$ as a parameter, at different values of Re_f. These maps may be useful for engineering purposes in the evaluation of the turbulent Bradley number once the un-ducted Br number is known. In the same Figure, the experimental values of the $Br_{t,ducted}$ number are also showed. These values correspond to flame Reynolds numbers of the order of magnitude of the values indicated on the plots.

From Figure 2, it is clear that increasing the flame Reynolds number Re_f the deviation of $Br_{t,ducted}$ from $Br_{t\_un-ducted}$ is significant, and the expected reduced pressure increases correspondingly. Similar behaviour is observed by increasing the parameter α (i.e. by increasing Br or the ratio of duct length to diameter) as the value of $Br_{t,ducted}$ decreases significantly with respect to $Br_{t\_un-ducted}$.Finally, it can be deduced that the effects on of duct is particularly relevant for higher value of $Br_{t\_un-ducted}$, where the burn-up related phenomena my increase consistently the value of reduced explosion pressure. The plots show also that more experiments are needed at higher Re_f, and α, which appear the more severe regimes.

Figure 3 shows the P_{red} values obtained by the correlation of Yao (Eq. 6) versus the theoretical ducted turbulent Br number ($Br_{t\_ducted} = \phi g r_{t\_un-ducted}$). The agreement is quite satisfactory.

From the obtained results a procedure for the ducted-vent sizing has been then established. Indeed, by collecting all the data and correlation reported above it can be then written:

$$\frac{P_{\rm red}}{Po} = 0.081 Re_f^{0.8} \left(\frac{L_t}{D_t}\right)^{0.026} Br^{-0.36} \qquad (12)$$

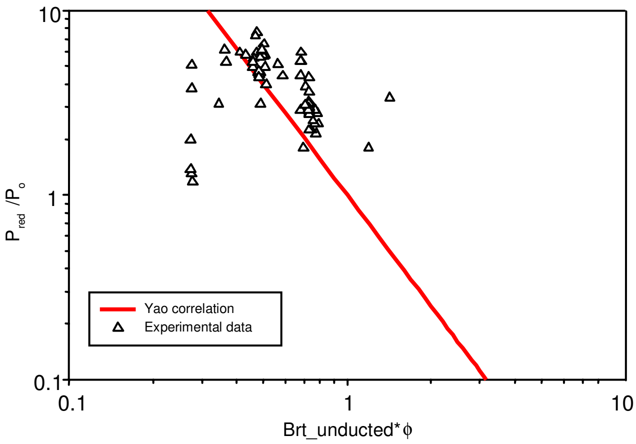

Figure 3. P_{red} vs. $Br_{t,\rm ducted}$ by using Yao assumption for $Br_{t,\rm un-ducted}$ (Eq. 7). Line: Theoretical.

Conclusions

The effect of the duct on explosions in vented vessel has been parametrically studied by using the experimental results available in literature. We started from the correlations which characterize simply vented vessel and addressed the effect of the duct to an enhancing function (ϕ). The ϕ function accounts for the increase of turbulization and frictional effects due to the presence of the duct. We then quantify this function with respect of the geometrical and reactivity properties.

Results have showed that the effect of duct is particularly important for very high values of vent ratio coefficient (or Bradley number, Br), i.e. when the characteristic time for the combustion reaction is very high with respect to the characteristic time for the discharge of hot combustion product through the vent section.

Design correlations and plots are proposed to quantify the link existing between the peak pressure enhancement due to the presence of the duct with respect to simply vented vessel, with respect to the geometrical properties and to the mixture reactivity. Further experiments are however needed for larger scale (i.e, larger Bradley number) and initial pressure greater than the atmospheric value.

Nomenclature

$A\prime$	reduced vent section [-]
Br	Bradley number [-]
Br_t	turbulent Bradley number [-]
C_D	discharge coefficient [-]
c_o	sound speed, [m s^{-1}]
D	diameter [m]
L	length, [m]
P_o	initial pressure [bar a]
P_{red}	reduced pressure [bar g]
P_v	vent set pressure [bar g]
Re_f	flame Reynolds number [-]
$S\prime$	flame Mach number [-]
S_u	burning or flame velocity [m s^{-1}]
T_{ad}	adiabatic combustion temperature [K]
T_o	initial temperature [K]
V	enclosure volume [m^3]

Greek Symbols

γ	adiabatic coefficient (c_P/c_V)
χ	turbulence factor, describing the flame stretch by turbulence [-]
μ	generalised discharge coefficient [-]
ρ	gas density [kg/m^3]
ϕ	duct to un-duct enhancement function [-]

Subscripts

c	chemical or combustion
ducted	referred to duct venting
s	referred to the internal surface of vessel
t	referred to the venting duct (tube) either ducted or unducted
u	unburned
un-ducted	referred to duct venting
v	vented or referring to a vent

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