Venting of Deflagrations: the Dependence of Turbulence Factor on Enclosure Volume and Vent Ratio

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ABSTRACT

The universal correlation for vented deflagrations in coordinates "dimensionless maximum explosion overpressure-turbulent venting parameter" was obtained for the first time in 1995 for 10 experiments and verified on 39 tests in 1997. To use universal correlation somebody needs to know the dependence of effective turbulence factor on explosion conditions. Equations for calculation of effective turbulence factor in dependence on main explosion conditions in hollow enclosure, i.e. volume and its vent ratio, are given for wide range of parameters, including volumes up to 4000 m^3.

NOMENCLATURE

A	Radius of spherical vessel of equivalent volume
c_{ui}	Speed of sound, m/s
D	Diameter of the vent, m
F	Vent area, m^2
p	Pressure, Pa
Re	Reynolds number
S_u	Laminar burning velocity, m/s
S_{ui}	Laminar burning velocity at initial pressure and temperature, m/s
T	Temperature, K
t	Time, s
V	Volume of enclosure, m^3
W_c	Venting parameter of Crescitelli et al.
W_t	Turbulent venting parameter

Greek

γ	Ratio of specific heats
μ	Generalized discharge coefficient
π_o	"pi" number

π Dimensionless explosion pressure, $\pi = p/p_i$
π_{red} Dimensionless explosion overpressure, $\pi_{red} = (p-p_i)/p_i$
ρ Density
χ Turbulence factor

Subscripts
apr Approximate
cs cellular structure
i Initial state
ipm Inverse problem method
f Flame front
s Spherical
u Unburnt gases
v Venting

INTRODUCTION

Huge property loss and risk of life from internal deflagrations remains the topycal issue. Fo example, the average number of gaseous explosions in domestic premises, estimated fron samples of fire brigade reports in United Kingdom, is relatively high - about 190 explosion per annum. Why dreadful destructions go on? The main reason is the imperfection of ven sizing guidelines because of the lack of knowledge on explosion dynamics.

The long-term theoretical, experimental and analytical research of author and colleagues fror various Russian research organizations was aimed to obtain new knowledge on the physics c turbulent vented deflagrations and overcome limitations of existent guides, the main of whic is NFPA 68 "Guide for Venting of Deflagrations", for the benefit of fire safety engineerin This principally new approach to vent sizing takes into account previously obtained physicall sound results on the dependence of two main processes of vented deflagration - turbuler gaseous combustion and gasdynamics of outflow, as well as their interrelation in accordanc with discovered analog of the Le Chatelier-Brown principle, on explosion dynamics.

The developed for years approach based on a lumped parameter model and huge experiment data processed by inverse problem method, including fuel tanks with inertial vent coverin bullet and jet ignition as well as real plant buildings with equipment inside and volumes up t 8000 m^3 [1-7].

After attempts to find general correlation, the most famous of which is the work of Bradle and Mitcheson [8], in 1995 the universal correlation for vented deflagrations was obtained fc the first time in coordinates "dimensionless reduced overpressure-turbulent ventin parameter". It was justified on 39 tests in 1997 [6]. The turbulent venting parameter

$$W_t = \frac{1}{(36\pi_0)^{1/3}\sqrt{\gamma_u}} \frac{\mu F}{V^{2/3}} \frac{c_{ui}}{\chi S_{ui}} \tag{1}$$

depends on the only unknown parameter of the theory - effective turbulence factor χ/μ, whic is the ratio of turbulence factor to generalized discharge coefficient. Generalized dischar coefficient μ (cited below as discharge coefficient) accounts not only for the non-ideality (the efflux through the vent, but also for the difference between the real non-zero flow veloci before the vent in the course of explosion and the assumed zero flow velocity when standa orifice equations derivation. According to discovered and described earlier [3] analog of the Le Chatelier-Brown principle the gasdynamics of turbulent combustion is coupled with the gasdynamics of outflow and hence the turbulence factor χ is in interdependency with the discharge coefficient μ.

SOME PREVIOUS RESULTS AND RECENT FINDINGS

Pressure-time traces from experiments on vented deflagration in hollow vessels of different volume and vent ratio ($F/V^{2/3}$) carried out by different authors were processed by inverse problem method [3] with the use of the corresponding computer programe, based on the theory [1, 5], to obtain the best fit for theoretical pressure-time dependences and to determine corresponding values of χ and μ. The results are given in the Table.

TABLE. Data on vented explosion experiments in hollow enclosures and results of their processing

Test	Fuel	V, m^3	Shape	Obstacles	Ignition	F, m^2	π_V	χ	μ	W_t	π_{red}	χ/μ_{ipm}	χ/μ_{apr}
1l [1]	Acetone	0.0215	Cyl	No	C	0.0020	1.000	1.00	0.67	3.232	0.700	1.49	1.64
2l [1]	Acetone	0.0215	Cyl	No	C	0.0020	1.200	1.00	0.67	3.447	0.600	1.49	1.64
3l [1]	Acetone	0.0215	Cyl	No	C	0.0020	1.230	1.00	0.67	3.506	0.520	1.49	1.64
1p [1]	Acetone	2.0	Cyl	No	V	0.0314	1.150	1.75	0.92	2.010	2.330	1.90	2.41
2p [1]	Acetone	2.0	Cyl	No	C	0.0314	1.750	1.60	0.92	2.199	3.200	1.74	2.41
3p [1]	Acetone	2.0	Cyl	No	C	0.0314	2.900	1.20	0.96	3.059	3.270	1.25	2.41
A0 [9]	Propane	11.0	Cyl	No	R	1.36	1.050	5.00	0.60	5.987	0.090	8.33	5.71
B17 [10]	Propane	30.4	Rec	No	C	0.58	1.400	6.20	1.50	3.019	0.425	4.13	4.08
B6 [10]	NG	30.4	Rec	No	C	1.33	1.012	6.80	1.20	3.819	0.205	5.67	5.13
B7 [10]	NG	30.4	Rec	No	C	1.33	1.040	6.80	1.00	3.183	0.542	6.80	5.13
B5 [10]	NG	30.4	Rec	No	C	2.74	1.023	8.50	0.80	4.197	0.215	10.63	6.51
1S [11]	Propane	35.0	Rec	No	C	1.00	1.000	7.60	1.00	2.577	1.350	7.60	4.66
2S [11]	Propane	35.0	Rec	No	V	1.00	1.000	7.10	1.10	3.035	0.770	6.45	4.66
0M [12]	Methane	49.1	Cyl	No	Plane, R	3.46	1.000	5.50	0.60	4.462	0.120	9.17	6.71
H1 [13]	Propane	4000.0	Seg	No	R	563.00	1.000	-	-	20.600	0.010	20.50	26.65
H2 [13]	NG	4000.0	Seg	No	R	563.00	1.000	-	-	27.500	0.005	16.00	26.65
H3 [13]	Propane	4000.0	Seg	No	R	563.00	1.000	-	-	16.400	0.015	25.70	26.65

Notes: χ/μ_{ipm} - effective turbulence factor, determined by inverse problem method; χ/μ_{apr} - effective turbulence factor, determined by approximation formulas; Column "Fuel": NG - natural gas; Column "Shape": Cyl - cylindrical, Rec - rectangular, Seg - segment; Column "Ignition": C - central, V - near the vent, R - at rare wall.

Rationally designed explosion protection systems use the smallest safe vent area from possible. This is very important in some cases like necessity to save fuel for enclosure heating systems. For such explosion systems the second general pressure peak is equal or higher than the first pressure peak, including the influence of inertia of vent covers on the first pressure peak. Only the experiments which comply with this condition were processed to obtain universal correlation [6]. All other experiments will give results above the line of universal correlation. The correlation is correct both for hollow enclosures and enclosures with obstacles inside. The data on 48 explosions in volumes in the full range of practical interest from 0.0215 m^3 to 8000 m^3 for various conditions were processed. The best fit line for universal correlation complies with equation

$$\pi_{red} = 9{,}8 \cdot W_t^{-2,4} \quad (2)$$

Coefficient of universal correlation determination is 0,96 and residual mean square is 0,10.

Universal correlation is valid for both a low-strength and high-strength enclosures with subsonic and sonic outflow. Explosion protection system developer needs to make calculations with parameters entering into a turbulent venting parameter W_t. It is not difficult to determine with relatively high accuracy the ratio of specific heats for unburnt gases and the speed of sound in formula (1) as well as the value of laminar burning velocity S_{ui} for majority of premises.

The main issue for wider implementation of the universal correlation is the lack of information on effective turbulence factor χ/μ until now. In approximation of laminar spherical flame spread when χ=1 and widely used value of discharge coefficient μ=0,6 the effective turbulence factor is equal to 1,67. It differs significantly in some cases of practical interest to dangerous side from values of χ/μ shown in the Table, which reach for 27 even at hollow enclosures. As it is known the safe area is proportional to effective turbulence factor.

Let us give a critical review of the data available in the literature with respect to effective turbulence factor. Munday had obtained in 1963 [15] for sonic outflow only that for propane-air mixtures in the initial pressure range of 1-3 atm the turbulence factor $\chi \propto$Re, and $\chi \propto \mathrm{Re}^{1/2}$ for hydrogen-air mixtures, where Reynolds number was determined through the speed of sound, density, and dynamic viscosity of initial mixture and vent diameter D. Unfortunately with the use of Munday's approach it is impossible to utilize results when not only one vent is used in explosion protection system, as well as when outflow is not sonic and velocity changes considerably during explosion. Besides above mentioned this approach has limited range of applicability, because the experimental data obtained in relatively small facilities were processed only.

In 1976 Rasbash et al. [18] recommended for laboratory rooms χ=2 if, following a leakage or spillage, an explosion should propagate through an initially quiescent mixture. The worst conceivable incident would appear, according to opinion of the authors [18], to be an explosion following a high pressure leakage of LPG from one of the test rigs, or even from a fractured supply line. In this event a value χ=8 seems to authors more appropriate, although if the laboratory space were to be partially filled by tall test rigs, χ=10 would be a better value to take [18]. In 1980 Solberg et al. [11] gave more severe recommendations on turbulence factor for room-like enclosures than in [18]. According to their conclusions a turbulence factor χ in the range 2,5-5 will be necessary if the vessel is considered spherical or in the range 7-11 if the vessel is considered to be prismatic. With the grids present, the turbulence factor must be doubled. Unfortunately there is no any information on dependence of turbulence factor on the volume and the vent ratio of enclosure in papers [11, 18].

In 1980-81 Crescitelli, Tufano and Russo [16, 17] carried out the research on finding of effective turbulence factor correlation on vent release pressure π_V and vent area F. These data refer to three different hydrocarbon-air mixtures (methane, propane and pentane), over a range of vent release pressures ($1 < \pi_V < 6$), disc areas (about $50 < W_C < 600$) and vessel volumes ($1 < V < 60$ m^3). They obtained the correlation as follows [17]:

$$\chi/\mu = 0{,}51 \cdot W_C^{0,6} \exp(-0{,}27/\pi_v^3),$$

where the venting parameter of Crescitelli et al. [24] $W_C = \frac{\mu F A}{V}\frac{c_{ui}}{S_{ui}}\sqrt{\frac{2}{\gamma - 1}}$.

According to correlation of Italian colleagues the increase of volume will not results in the increase of effective turbulence factor if the vent ratio remains the same.

There is no clearness on correlation between effective turbulence factor and vent release pressure until now. According to [17] χ/μ grows with π_V until $\pi_V < 1{,}625$ and then doesn't depend on vent release pressure. According to experimental data of Zalosh [14] and our theoretical data [7] the pressure at the second pressure peak doesn't depend on vent release pressure even in the range $\pi_V < 1{,}6$. Hence it might be concluded that it is impossible now to give sound correlation for general dependence of effective turbulence factor on vent release pressure.

In 1983-1984 some papers on vented deflagrations with the use of turbulence factor, changing during the course of explosion, were published. After Swift's work in 1983 [19] Chippett in 1984 [20] made the attempt to pick out three components of turbulent combustion - cellular structure, initial turbulence and turbulence induced by venting. Such approach has its own disadvantages. Namely, to avoid the use of adjustable parameters to allow for the effects of turbulence Swift [19] used "maked up" r.m.s. turbulent velocity as 5% of maximum outflow velocity. It is well known that gasdynamic situation in the vessel during venting of deflagration differs from isotropic one. There is also no recommendations on how to use this approach in the case of obstacles presence inside the enclosure. After attempts to employ changing during explosion turbulence factor, Swift with his colleagues [21] have made an important conclusion: "it seems best to employ a constant turbulence correction factor and gain the corresponding simplicity, rather than to carry more elaborate equations through a train of numerical computations whose accuracy is also limited to only a narrow range of experimental conditions".

The work of Canu et al. [22] appears in 1990 again with turbulence factor changing in course of explosion. The development of flame front surface due to cellular structure is taken into account like in the work [20] by the factor

$$\chi_{CS} = 1, \quad \text{if } \mathrm{Re}_f < 4000, \qquad \text{and} \quad \chi_{CS} = \left(\frac{\mathrm{Re}_f}{4000}\right)^{0,39}, \quad \text{if } \mathrm{Re}_f > 4000,$$

where Re_f defined through parameters of unburnt mixture before flame front and flame radius. The effect of turbulence and flame shape distortion is accounted for by empirical parameter

$$\chi_v = 1{,}23 \cdot \left(\frac{\mathrm{Re}_v}{10^6}\right)^{\frac{0{,}0487}{S_u}\frac{V_f}{V}},$$

where outflow Reynolds number Re_v defined with the use of parameters of unburnt mixture, vent radius and flow velocity through the vent, and V_f is the volume of combustion products.

The best fit to a collection of about 160 literature experimental data, covering a range of vessel volumes 0,001-199 m^3, initial pressures 0,1-0,4 MPa, and vent release pressures 0,1-2,96 MPa, has the maximum relative error in the maximum explosion pressure prediction equal to 34%.

DEPENDENCE OF EFFECTIVE TURBULENCE FACTOR

Clearly, the effective turbulence factor depends on many parameters of the process, such as enclosure volume and shape, its vent ratio $F/V^{2/3}$, type and position of ignition source relatively to the vent and obstacles, vent release overpressure and inertia of vent covering, number of vents, presence and types of obstacles and others. It seems impossible today to determine all fine regularities for effective turbulence factor change with the change of above mentioned parameters would it be lumped parameter approach or CFD approach. But fire safety engineering requires sound correlations for effective turbulence factor determination by now.

Different factors influence on effective turbulence factor in different extent. Let us consider the dependence of effective turbulence factor on the main explosion conditions for hollow enclosures - the volume of enclosure and its vent ratio. The priority of these two factors follows from our previous preliminary results. Of course, the disregard of influence of other parameters will decrease the accuracy of sought correlation for effective turbulence factor calculation in dependence on explosion conditions.

Particular regularities were discovered in our previous research by inverse problem method, i.e. by comparison of experimental and calculated pressure-time histories with χ and μ as two adjustable parameters for different tests. For example, it was found that the shape of enclosure, with ratio of the largest to the smallest size up to 5:1, doesn't influence essentially on explosion dynamics and values of turbulence factor and discharge coefficient (especially in conditions of developed turbulence). It was shown also that jet ignition increases effective turbulence factor for about 1,5-2,0 relatively to a point ignition at the same conditions and so on.

It follows from our numerous previous results that the turbulence factor definitely goes up with increase of volume and vent ratio. It is physically clear that a level of turbulence and flame front area grow with size (Reynolds number) or, that is the same but practically more convenient, with enclosure volume. It is obvious also that the larger vent area the larger induced disturbance of the flame front and hence it will lead to the higher value of turbulence factor. Only the extent of enlargement is the question now.

The parameters of nearstoichiometric hydrocarbon-air mixtures are close enough from the point of view of present investigation. Hence let us look for correlation of effective turbulence factor on geometric parameters only. The data on effective turbulence factors, obtained by inverse problem method and shown in the Table, can be approximated by the next formula

$$\chi / \mu_{apr} = \left[\left(1 + 4V^{1/3}\right)\left(1 + 25F / V^{2/3}\right)\right]^{0,4} \tag{3}$$

The correlation between effective turbulence factor χ/μ_{ipm} and effective turbulence factor χ/μ_{apr}, calculated with the use of formula (3), is shown on Fig. The maximum relative error in the effective turbulence factor prediction equal to about 25%. It seems satisfactory in adopted assumptions.

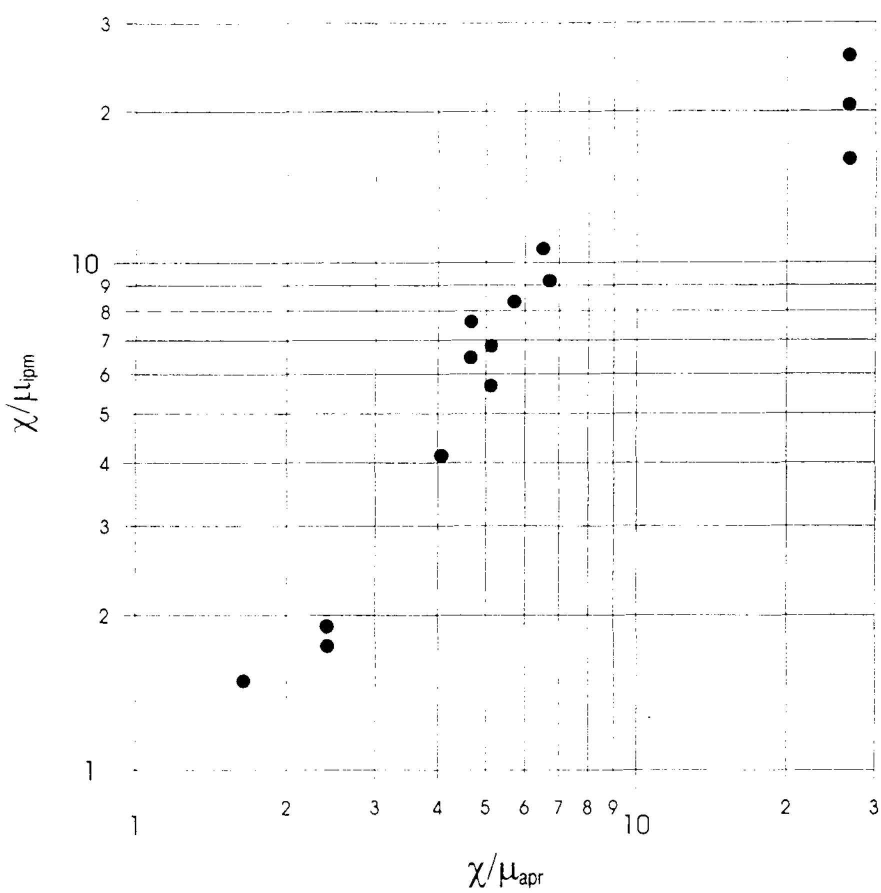

FIGURE. The correlation between effective turbulence factor χ/μ_{ipm}, determined by inverse problem method, and effective turbulence factor χ/μ_{apr}, calculated with the use of proposed approximation formula (3)

DISCUSSION AND CONCLUSIONS

It is easy to see that obtained correlation (3) for effective turbulence factor determination coincide in general with previous results of other authors. Thus our dependence on enclosure volume is very close to dependence of Canu et al. [22] on Reynolds number for flame front. The corresponding exponents equal to 0,40 and 0,39 respectively. The dependence of effective turbulence factor on vent area from our research and study of Tufano et al. [17] are close also (the corresponding exponents equal to 0,4 and 0,6).

Described in this paper results can be used for vent sizing and scaling of bench-scale data on large-scale enclosures. Universal correlation gives us the opportunity to obtain the unique value of turbulent venting parameter W_t corresponding to explosion overpressure π_{red}, to which the wall of enclosure could to withstand. To calculate the vent area F from this value of W_t we need to know the corresponding value of effective turbulence factor χ/μ. The last one can be calculated now.

For unknown parameters of the fuel the procedure is as follows. The first opportunity to solve the problem is to determine the parameters of the fuel-air mixture in special research and then carry out the procedures described above. The second way doesn't require the direct determination of fuel parameters in separate study. We need only to undertake experiments on vented deflagration in small-scale vented vessel. Through obtained value of experimental reduced overpressure we could determine from the universal correlation the corresponding value of turbulent venting parameter W_t. We can also calculate with the use of formula (3) the specific value of effective turbulence factor corresponding to this small-scale experiment. Such a way we can determine the unknown complex

$$\frac{1}{(36\pi_0)^{1/3}\sqrt{\gamma_u}}\frac{c_{ui}}{S_{ui}} \tag{4}$$

which characterizes the fuel.

After such operations it is easy to predict the vent area of explosion protection system for large-scale enclosure. Principally the same performance-based procedures can be used to predict the overpressure in hollow enclosures of different sizes with predetermined vent areas.

The advanced performance-based approach alternative to NFPA 68 is proposed for hollow enclosuress. It takes into account the dependence of vent area on reduced overpressure, volume of the enclosure and its vent ratio, on parameters of combustible mixture, on effective turbulence factor, as well as the dependence of effective turbulence factor on enclosure volume and its vent ratio is described.

There is satisfactory coincidence with the results obtained by other authors on dependence of turbulence factor on enclosure volume and vent area.

The simple engineering formula are proposed for prediction of effective turbulence factor for hollow enclosures. The maximum deviation $\pm$25% of the effective turbulence factor seems reasonable because of the range of χ/μ change is high enough 1-27 (2700%). Obtained accuracy of effective turbulence factor prediction 25% is less than 34% maximum error in explosion pressure prediction [22]. It should be underlined that our correlation can be used for wider range of explosion conditions. In particular, enclosure volume can be 20 times larger (4000 m^3 against 200 m^3).

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