

VENTING OF GASEOUS EXPLOSIONS: TURBULIZATION ASPECT

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ABSTRACT

The main goal of the present investigation is to discuss multiparametric dependence of turbulization factor χ on combustion and venting conditions in an vented vessels or other enclosures. More well grounded dimensionless formulae for minimal safe vent area calculation are cited, then those in the NFPA 68 "Guide for Venting of Deflagrations" (1988 Edition). Formula for turbulization factor χ dependence on the vessel volume V ; "true" vent ratio $(F/V^{2/3})$; maximum dimensionless internal pressure π_m , that can be withstood by the weakest structural element; maximum dimensionless explosion pressure developed in unvented vessel π_e ; and other conditions is given and discussed.

INTRODUCTION

According to *Industrial Risk Insurers* about 40% of the total explosions is a result of deflagration inside process equipment and buildings. Venting of deflagration - the main protection method, allowing to minimize structural and mechanical damage from combustion overpressure within an enclosures.

Practically all companies dealing with explosion protection systems, such as Fike Corp., Fenwal Inc. et al., use now for determination of the vent area NFPA 68 "Guide for Venting of Deflagrations". This document is based on large experimental material, but has some serious limitations. In particular it does not answer on the question: how initial turbulence, or turbulence-producing internal appurtenances influence on dynamics and hence on maximum pressure of explosion? Employment of NFPA 68 in such cases without new scientific knowledge will lead to catastrophes.

RESULTS AND DISCUSSIONS

The system of dimensionless differential equations, derived from energy and mass conservations laws, with "surface" turbulent combustion model was used by modeling¹. According to Michelson's principle the main factor of vented deflagration - turbulization factor χ is determined as ratio of real area of turbulent flame surface at some moment to surface area of sphere to which burned products may be collected at the same moment (turbulent burning velocity $S_f = (f_t/f_s) S_u = \chi S_u$, where S_u - laminar burning velocity). It is self-evident, that for laminar spherical flame propagation $\chi=1$. But really $\chi>1$, because flame front is disturbing by different phenomenons: wrinkling flame structure due to hydrodynamic², acoustic³ (or Taylor⁴) or diffusion-thermal⁵ instabilities; convective deformation of combustion edge; initial mixture turbulence or flame turbulence, produced by combustion products or obstacles and so on.

Origin and development of wrinkling flame structure gives $\chi=1.5+2$, as experiments in 70 m³ initial volume rubber bubble⁶ and our researches showed.

Under isotropic turbulence⁷ maximum value of turbulization factor is equal $\chi=4+6$. Further rise in the isotropic turbulence intensity causes flame extinction at the Karlovits criteria $\frac{v' \delta l}{S_u l} = 10+20$ (v' - pulsating velocity; δl - laminar flame front depth; l - turbulence scale).

A maximum ratio of visible burning velocity ahead of and behind three meshes (0.8 mm wire diameter, 1.6 mm mesh size) in laboratory conditions⁸ is equal to 12. For respectively large-scale experiments⁹ in 11 m³ volume vessel with only one grid (18 mm wire diameter, 125 mm mesh size) we obtain already $\chi=14$.

Dependence of safe vent area F , which contains in venting parameter W , on turbulization factor χ is given by our engineering dimensionless formulae, obtained on the base of system of exact differential equations, respectively for subsonic and sonic ($2 \leq \pi_m \leq \pi_e$) efflux:

$$W = \frac{\chi(E_i - 1)}{E_i^{1/2} \sqrt{\pi_m - 1}}, \quad (1)$$

$$W = 0.9 \frac{\chi (\pi_e - \pi_m)}{E_i^{1/2}}, \quad (2)$$

where dimensionless venting parameter $W = \frac{1}{(36\pi_o)^{-1/3} \sqrt{\gamma_u}} \frac{\mu F C_{ui}}{V^{2/3} S_{ui}}$ with π_o - "pi" number, μ - discharge coefficient, C_{ui} - speed of sound; E_i - combustion products expansion coefficient at initial conditions; $\pi_m = p_m / p_i$ - maximum dimensionless pressure, which a sheath of a vessel or other enclosure can withstand (maximum explosion pressure in case of inverse problem, when vent area is known); $\pi_e = p_e / p_i$ - dimensionless adiabatic explosion pressure in closed vessel. Relief vent diameter determination error when using formulae (1), (2) is near 10% in comparison with exact computer solution of system of differential explosion dynamics equations.

Hence, the mistaken choice of χ , for example in 5 times, will cause the same - in our case 5 times error in safe vent area determination. It's obviously the way to catastrophes.

Generalization of Russian and world experience in venting of deflagration field permitted us to obtain formula for turbulization factor dependence on the vessel volume V ; "true" vent ratio $F/V^{2/3}$; dimensionless maximum internal pressure π_m , that can be withstood by the weakest structural element; dimensionless maximum explosion pressure in closed vessel π_e

$$\chi = (1 + a_1 V) \left(1 + a_2 \frac{F}{V^{2/3}}\right) (a_3 + a_4 \frac{\pi_e - \pi_m}{\pi_e - 2}) \quad (3)$$

with empirical coefficients a_1, a_2, a_3, a_4 from Table for different conditions.

Table. Empirical coefficients for χ determination

Burning conditions	Empirical coefficients			
	a_1	a_2	a_3	a_4
Vessel volume $V \leq 10 \text{ m}^3$; vent ratio $F/V^{2/3} \leq 0.25$	0.15	4	1	0
Maximum explosion pressure $1 < \pi_m < 2$:				
- uncovered vent	0	0	2	0
- covered vent	0	0	8	0
Maximum explosion pressure $2 \leq \pi_m < \pi_e$:				
- uncovered vent	0	0	0.8	1.2
- covered vent	0	0	2	6

There is an influence of turbulization factor χ value on dynamics of vented deflagration shown on Fig.1 for laminar spherical ($\chi=1$) and turbulent ($\chi>1$) flame propagation. Pressure-time curves on Fig. 1 and 2 were obtained by using computer research program "DYNAMICS (Venting of Gaseous Explosions)", based on exact system of dimensionless differential equations of vented gas deflagration dynamics. Calculations for graphs on Fig.1 were made for near stoichiometric hydrocarbon-air mixture in 10 m^3 volume vessel with 0.5 m vent diameter and following parameters: initial and atmospheric pressure $p_i=p_a=0.1\text{ MPa}$; vent closure release pressure $p_v=0.11\text{ MPa}$; initial temperature and burning velocity respectively $T_i=298\text{ K}$ and $S_{ui}=0.34\text{ m/s}$; adiabatic factors $\gamma_u=1.365$ and $\gamma_b=1.248$;

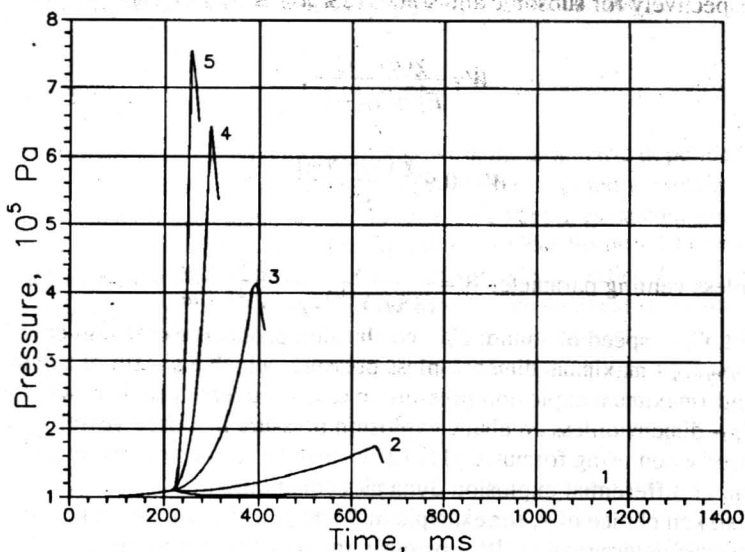


Fig.1 Dynamics of vented deflagration in 10 m^3 vessel with 0.5 m vent diameter for laminar (curve 1) and turbulent (curves 2-5) flame propagation: 1 - $\chi=1$; 2 - $\chi=2$; 3 - $\chi=4$; 4 - $\chi=8$; 5 - $\chi=16$.

thermokinetic factor $\epsilon=0.24$; expansion ratio $E_T=7.592$; mixture molecular mass $M=29.58$; discharge coefficient $\mu=0.8$; turbulization factor before vent closure release $\chi_o=1$.

There is strong dependence of maximum explosion pressure and explosion duration from turbulization factor χ on Fig.1. With $\chi=16$ the maximum pressure in vented vessel is near to it in unvented vessel.

What values of turbulization factor χ correspond to most widely using all over the world NFPA 68 "Guide for Venting of Deflagrations"? Comparison of NFPA 68 (4-3.1 paragraph) formula

$$F = \frac{CA_s}{(P_{red})^{1/2}} \text{ with our engineering formula (1) lead to equality for } C = \frac{1,86\chi S_{ui}}{T_{ui}^{1/2}} (\text{kPa})^{1/2}. \text{ For such}$$

gases as propane we have $C=0.45 (\text{kPa})^{1/2}$ from NFPA 68 table and with $S_{ui}=0.42\text{ m/s}$, $T_{ui}=298\text{ K}$ we can get for Low-Strength Enclosures (capable of withstanding not more than 0.01 MPa in NFPA 68 terminology) practically constant value nearby $\chi=10$. From one side it close to our value $\chi=8$, obtained for "undefined" vented deflagration conditions by comparison of engineering formula (1) with well grounded graphical recommendations of D.Bradley and A.Mitcheson¹⁰, based on large experimental material of different authors. But from other side, as last results of theory and experiments comparison showed⁹, the value of χ changes in wide range $\chi=1+14$ and even more. Because of safe vent area F is proportional to χ , as formulae (1) and (2) show, NFPA 68 gives in some cases large vent area ($\chi<10$) and in other cases fewer vent area ($\chi>10$). In both occurrences the user (cus-

tomers) will bear loss. The last case is the reason of catastrophes, when there is deflagration in an enclosure, if even there are vents.

There is an influence of vent area on explosion dynamics in 1000 m³ enclosure for constant turbulence factor $\chi=10$, corresponding to NFPA 68 recommendations, on Fig.2. Hence, according to NFPA 68 for 10m x 10m x 10m enclosure capable of withstanding 0.005 MPa ga the safe vent diameter must exceed 8.5 m (see Fig.2). It's near 60% of one side area of that enclosure. But it's wrong

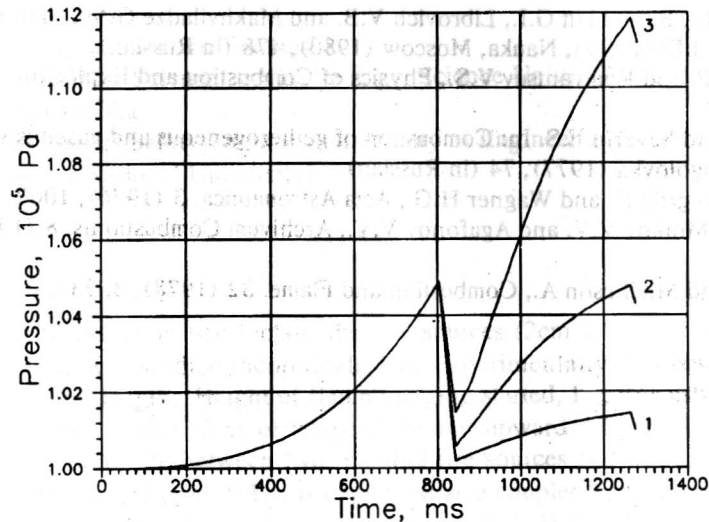


Fig.2 Dynamics of vented deflagration in 1000 m³ enclosure for turbulent flame propagation with $\chi=10$, corresponding NFPA 68, and different vent diameter: 1 - D=11.3 m (vent is one end of 10m x 10m x 10m enclosure); 2 - D=8.5 m; 3 - D=7 m.

for $\chi > 10$, what may be, for example, when there are obstacles within enclosure.

For High-Strength enclosures (reduced pressure P_{red} , i.e., the maximum pressure actually developed during a vented deflagration, is within the range 0.02-0.20 MPa in NFPA 68 terminology) the equality of formula $F=0,148 (V)^{0,703} e^{0,942 P_{stat}} P_{red}^{-0,671}$ from 6-1.1.1 paragraph of NFPA 68 and our formula gives dependence for turbulence factor

$$\chi = 0,0165 \frac{T_{ui}^{1/2}}{S_{ui}} \frac{V^{0,036}}{P_{red}^{0,171}} e^{0,942 P_{stat}}. \text{ For } V=10 \text{ m}^3 \text{ vessel and parameters: } S_{ui}=0.34 \text{ m/s; } T_{ui}=298 \text{ K;}$$

$P_{red}=0.1 \text{ bar ga; } P_{stat}=p_v-1=0.1 \text{ bar ga}$ we can get that NFPA 68 lead to value nearby $\chi=1.5$. It differs in dangerous side from value $\chi=5$, which can be obtained for such conditions by use of formula (3) with $F/V^{2/3}=0.25$ (notice, that given above formula for χ obtained on NFPA 68 base don't contain dependence on F or $F/V^{2/3}$, that is evidently wrong). For "undefined" conditions and respectively large volume we recommend $\chi=8$ for initially covered vents (see Table) and $\chi=2$ for uncovered vents without initial turbulence and turbulence-producing internal appurtenances. It's more than values, corresponding to NFPA 68 recommendations (for $V=10000 \text{ m}^3$ from NFPA 68 data we can get only $\chi=1.9$ for considering case).

To prevent catastrophes in industry NFPA 68 "Guide for Venting of Deflagrations" (1988 Edition) must be changed in maximum short time.

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