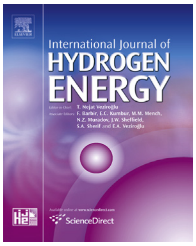
INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 40 (2015) 1256–1266

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/he



Hydrogen–air deflagrations: Vent sizing correlation for low-strength equipment and buildings

V. Molkov [a], M. Bragin [b,*]

[a] Hydrogen Safety Engineering and Research Centre (HySAFER), University of Ulster, Shore Road, Newtownabbey, BT37 0QB, Northern Ireland, UK
[b] Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University, Epinal Way, Loughborough, LE11 3TU, UK

ARTICLE INFO

Article history:
Received 22 August 2014
Received in revised form
8 November 2014
Accepted 12 November 2014
Available online 4 December 2014

Keywords:
Hydrogen
Vented deflagration
Experimental data
Correlation
Validation

ABSTRACT

This paper aims to improve prediction capability of the vent sizing correlation presented in the form of functional dependence of the dimensionless deflagration overpressure on the turbulent Bradley number similar to our previous studies. The correlation is essentially upgraded based on recent advancements in understanding and modelling of combustion phenomena relevant to hydrogen–air vented deflagrations and unique large-scale tests carried out by different research groups. The focus is on hydrogen–air deflagrations in low-strength equipment and buildings when the reduced pressure is accepted to be below 0.1 MPa. The combustion phenomena accounted for by the correlation include: turbulence generated by the flame front itself; leading point mechanism stemming from the preferential diffusion of hydrogen in air in stretched flames; growth of the fractal area of the turbulent flame surface; initial turbulence in the flammable mixture; as well as effects of enclosure aspect ratio and presence of obstacles. The correlation is validated against the widest range of experimental conditions available to date (76 experimental points). The validation covers a wide range of test conditions: different shape enclosures of volume up to 120 m^3; initially quiescent and turbulent hydrogen–air mixtures; hydrogen concentration in air from 6% to 30% by volume; ignition source location at enclosure centre, near and far from a vent; empty enclosures and enclosures with obstacles.

Introduction

Venting of deflagration is the most wide spread technique to reduce overpressure during flammable mixture deflagration indoors or in a system like fuel cells. Different empirical and semi-empirical models were developed and applied for vent sizing of deflagration mitigation systems and published elsewhere. A recent overview of equations for vent sizing and their inter-comparison and comparison against experiments with various hydrocarbon-air and hydrogen–air mixtures can be found in Ref. [1].

The vent sizing technique that is advanced further in this study has been under development since 1995 and its

---

* *Corresponding author*. Tel.: +44 1509227684.

E-mail addresses: v.molkov@ulster.ac.uk (V. Molkov), m.bragin@lboro.ac.uk (M. Bragin).

http://dx.doi.org/10.1016/j.ijhydene.2014.11.067
0360-3199/

Nomenclature

A_{EW}	area of enclosure internal surface, m^2
A_W	area of the sphere with volume equal to enclosure volume, m^2
Br	Bradley number
Br_t	turbulent Bradley number
c_{ui}	speed of sound, m/s
D	fractal dimension
E_i	combustion products expansion coefficient, $E_i = M_{ui}T_{bi}/M_{bi}T_{ui}$
e, g	empirical coefficients in equation (6)
F	vent area, m^2
M	molecular mass, g/mol
P_i	initial pressure, Pa abs
P_{max}	maximum absolute pressure, Pa abs
P_{red}	reduced pressure, Pa gauge
P_{stat}	static activation pressure, Pa gauge
R	flame radius (maximum), m
R_u	universal gas constant, 8.31 J/K/mol
R_0	critical radius, m
S_t	turbulent burning velocity, m/s
S_{ui}	initial laminar burning velocity, m/s
T	temperature, K
V	volume of enclosure, m^3
$V_{\#}$	dimensionless volume (numerically equal to enclosure volume in cubic meters)
X	hydrogen mole fraction

Greek

$\alpha,\beta,\delta,\omega$	empirical coefficients in equation (6)
γ_u	specific heat ratio
π_0	"Pi" number, 3.141
$\pi_{i\#}$	dimensionless initial pressure (numerically equal to initial pressure in absolute atmospheres)
π_{red}	dimensionless reduced pressure, P_{red}/P_i;
π_v	dimensionless static activation pressure $\pi_v = (P_{stat} + P_i)/P_i$
χ/μ	deflagration–outflow interaction (DOI) number
Ψ	empirical coefficient
Ξ_K	wrinkling factor due to turbulence generated by the flame front itself
Ξ_K^{max}	theoretical maximum of Ξ_K
Ξ_{LP}	wrinkling factor due to leading point mechanism
Ξ_{LP}^{max}	maximum leading point wrinkling factor
Ξ_{FR}	wrinkling factor due to fractal increase of flame surface area
$\Xi_{u'}$	wrinkling factor to account for initial turbulence
Ξ_{AR}	wrinkling factor to account for aspect ratio of the enclosure
Ξ_O	wrinkling factor to account for the presence of obstacles

Subscripts

b	burned mixture
i	initial conditions
red	reduced
stat	static
t	turbulent
u	unburned mixture

Superscripts

max	maximum value

Acronyms

CFD	computational fluid dynamics
DOI	deflagration–outflow interaction
LES	large eddy simulation
SGS	sub-grid scale

developmental progress can be found in publications [2–6,8–11]. The correlation for low-strength equipment and buildings, i.e. when the deflagration overpressure or reduced pressure is below 0.1 MPa (initial pressure in such cases is usually atmospheric equal to 0.1 MPa), is presented by from our 1999 study [4] that is the best fit to experimental data

$$\pi_{red} = Br_t^{-2.4} (\pi_{red} < 1), \tag{1}$$

where π_{red} is the dimensionless reduced pressure, and Br_t is the turbulent Bradley number

$$Br_t = \frac{\sqrt{E_i/\gamma_u}}{\sqrt[3]{36\pi_0}} \cdot \frac{Br}{\chi/\mu}, \tag{2}$$

in which Br is the Bradley number defined as a product of a ratio of the vent area, F, to the enclosure surface area, $V^{2/3}$, and a ratio of the speed of sound, c_{ui}, to flow velocity in front of the flame, $S_{ui}(E_i - 1)$,

$$Br = \frac{F}{V^{2/3}} \cdot \frac{c_{ui}}{S_{ui}(E_i - 1)}, \tag{3}$$

where S_{ui} is the laminar burning velocity at initial conditions; E_i is the combustion products expansion coefficient at initial conditions; γ_u is the specific heat ratio for unburned mixture; π_0 is "pi" number; c_{ui} is the speed of sound at initial conditions of the deflagration; V is the enclosure volume; and χ/μ is the so-called deflagration–outflow interaction (DOI) number in which χ is the turbulence factor and μ is the generalised discharge coefficient that obey the Le Chatelier–Brown principle analogue for vented deflagrations [10,11]. In 1999 correlation (1) the same empirical coefficients were applied to both hydrocarbon–air and hydrogen–air mixtures.

To meet requirements of standard development organisations the conservative form of the correlation was published in 2001 [6,7] for hydrocarbon–air and hydrogen–air mixtures. This conservative correlation was updated in 2008 [9] for hydrogen–air mixtures only. For dimensionless reduced pressures below 1 the form of the conservative correlation 2008 is

$$\frac{\pi_{red}}{\pi_v^{2.5}} = 5.65 \cdot Br_t^{-2.5} \left(\frac{\pi_{red}}{\pi_v^{2.5}} < 1 \right), \tag{4}$$

where π_v is the dimensionless static activation pressure that is close to 1 for low-strength equipment and buildings and can be neglected. The conservative form of the correlation (4) between the dimensionless reduced pressure and turbulent Bradley number was validated against a wider range of vented