INTERNATIONAL JOURNAL OF HYDROGEN ENERGY XXX (2018) 1–22

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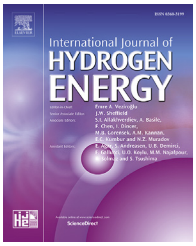

Deflagrations of localised homogeneous and inhomogeneous hydrogen-air mixtures in enclosures

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ARTICLE INFO

Article history:
Received 21 December 2017
Received in revised form
27 February 2018
Accepted 22 March 2018
Available online xxx

Keywords:
Hydrogen
Localised flammable mixture
Vented deflagration
Inhomogeneous mixture
Engineering correlation
Validation

ABSTRACT

Two original models for use as novel tools for the design of hydrogen-air deflagration mitigation systems for equipment and enclosures are presented. The first model describes deflagrations of localised hydrogen-air mixtures in a closed space such as a pressure vessel or a well-sealed building while the second model defines safety requirements for vented deflagrations of localised mixtures in an enclosure. Examples of localised mixtures include ‘pockets’ of gas within an enclosure as well as stratified gas distributions which are especially relevant to hydrogen releases. The thermodynamic model for closed spaces is validated against experiments available from the literature. This model is used to estimate the maximum hydrogen inventory in a closed space assuming the closed space can withstand a maximum overpressure of 10 kPa without damage (this is typical of many civil structures). The upper limit for hydrogen inventory in a confined space to prevent damage is found to be equivalent to 7.9% of the closed space being filled with 4% hydrogen. If the hydrogen inventory in a closed space is above this upper limit then the explosion has to be mitigated by the venting technique. For the first time an engineering correlation is presented that accounts for the phenomena affecting the overpressure from localised vented deflagrations, i.e. the turbulence generated by the flame front itself, the preferential diffusion in stretched flames, the fractal behaviour of the turbulent flame front surface, the initial flow turbulence in unburnt mixture, and the increase of the flame surface area due to the shape of an enclosure. Validation of the new vented deflagration model developed at Ulster has been carried out against 25 experiments with lean stratified hydrogen-air mixtures performed by the Health and Safety Executive (UK) and Karlsruhe Institute of Technology (Germany).

Introduction

Deflagration of inhomogeneous, e.g. stratified, fuel-air mixtures in an enclosure, where fuel concentration varies mainly in vertical direction, is a realistic accident scenario for both industrial environment and domestic premises [1,2]. This scenario may result from a slow release of heavier or lighter than air flammable gas, or a spill of

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https://doi.org/10.1016/j.ijhydene.2018.03.159
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Nomenclature

A	fraction of vent area occupied by combustion products, or coefficient in equation (49)
B	coefficient in equation (49)
Br_t	turbulent Bradley number, $Br_t = (\sqrt{E_i/\gamma}\,\mu F c_{ui})((36\pi_0)^{1/3}\,\Xi V^{2/3} S_{u_i}\,(E_i - 1))$
Br_t^*	parameter for scaling overpressure in equation (60)
c_p	specific heat at constant pressure in equations (8) and (12) (J/kg/K)
c_v	specific heat at constant volume in equation (20) (J/mol/K)
c_{ui}	speed of sound in unburnt mixture (m/s), $c_{ui} = \sqrt{\gamma RT/M}$
D	fractal dimension
e	energy per unit mass (J/kg)
E_i	combustion products expansion coefficient, $E_i = M_{ui}T_{bi}/M_{bi}T_{ui}$
F	vent area (m^2)
G	mass flow rate (kg/s)
H	height (m), or enthalpy (J)
ΔH_c	heat of combustion (J/mol)
Δh_c	heat of combustion (J/kg)
h	enthalpy per unit mass (J/kg)
L	length (m)
M	molecular mass (g/mol)
m	mass (kg), or burning velocity temperature index (Table 7)
n	mass fraction, or burning velocity baric index (Table 7)
p	pressure (Pa abs)
q	heat per unit mass (J/kg)
R	flame radius (m), or universal gas constant, $R = 8314$ (J/K/kmol)
$R^{\#}$	non-dimensional venting parameter, $R^{\#} = \{\,(2\gamma)/(\gamma-1)\,\pi\sigma\,[(1/\pi)^{2/\gamma} - (1/\pi)^{1+1/\gamma}]\,\}^{1/2}$
R_0	critical radius for transition from laminar to fully turbulent flame propagation regime (m)
S_t	turbulent burning velocity (m/s)
S_u	laminar burning velocity (m/s)
T	temperature (K)
t	time (s)
u	internal energy per unit mass (J/kg)
V	volume (m^3)
v	specific volume (m^3/kg)
W	width (m), or non-dimensional venting parameter, $W = \mu\, F c_{ui}/[(36\,\pi_0)^{1/3}\sqrt{\gamma_u}\,V^{2/3}\,S_{ui}]$
w	mechanical work of gas per unit mass (J/kg)
x_{H_2}	volumetric fraction of hydrogen in entire enclosure, $x_{H_2} = \phi\cdot\Phi$
Z	non-dimensional number, $Z = \gamma_b[E_i - (\gamma_u/\gamma_b)(\gamma_b - 1)/(\gamma_u - 1)]\,\pi^{(1-\gamma_u)/\gamma_u} + (\gamma_u - \gamma_b)/(\gamma_u - 1)$

Greek

Φ	volumetric fraction of localised flammable fuel-air mixture in enclosure
Φ^*	volumetric fraction of the fastest burning fuel-air mixture in enclosure
γ	adiabatic index, $\gamma = c_p/c_v$
φ	volumetric fraction of fuel in localised fuel-air mixture, and number of moles in equations (9)–(11)
μ	discharge coefficient
π	non-dimensional pressure $\pi = p/p_i$
π_0	“Pi” number, 3.14159
Ξ/μ	deflagration-outflow interaction (DOI) number, $\Xi/\mu = \Xi_K\Xi_{LP}\Xi_{FR}\Xi_{u'}\Xi_{AR}\Xi_O$
Ψ	empirical coefficient
Ξ_K	wrinkling factor to account for the turbulence generated by the flame front itself
Ξ_{LP}	wrinkling factor to account for the leading point flame acceleration mechanism
Ξ_{FR}	wrinkling factor to account for the fractal increase of the flame surface area
$\Xi_{u'}$	wrinkling factor to account for the initial flow turbulence in unburnt mixture
Ξ_{AR}	wrinkling factor to account for the aspect ratio of the enclosure
Ξ_O	wrinkling factor to account for the presence of obstacles
ρ	density (kg/m^3), $\rho = pM/(RT)$
σ	relative density, $\sigma = \rho/\rho_i$
τ	non-dimensional time, $\tau = tS_{u_i}/c_{u_i}$
ω	volume fraction in enclosure

Subscripts

air	air
b	burnt mixture
corr	correlation value
exp	experimental value
f	fuel
H_2	hydrogen
i	initial conditions
MAX	maximum
MIN	minimum
m	flammable mixture
t	turbulent
u	unburnt mixture
0	initial thermodynamic state (before combustion)
1	thermodynamic state 1 (on completion of adiabatic isochoric combustion)
2	thermodynamic state 2 (on completion of adiabatic expansion)

Superscripts

‘	value in flammable mixture

Acronyms

BOS	Background Oriented Schlieren
CFD	Computational Fluid Dynamics
DOI	Deflagration-Outflow Interaction
LES	Large Eddy Simulation
RHS	Right-Hand Side
SGS	Sub-Grid Scale

Please cite this article in press as: Makarov D, et al., Deflagrations of localised homogeneous and inhomogeneous hydrogen-air mixtures in enclosures, International Journal of Hydrogen Energy (2018), https://doi.org/10.1016/j.ijhydene.2018.03.159