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Blast wave from a high-pressure gas tank rupture in a fire: Stand-alone and under-vehicle hydrogen tanks

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ARTICLE INFO

Article history:
Received 23 May 2015
Received in revised form
30 June 2015
Accepted 1 July 2015
Available online 29 July 2015

Keywords:
Blast wave
Overpressure
Impulse
Deterministic separation distance
Hydrogen
Model

ABSTRACT

This study addresses one of knowledge gaps in hydrogen safety science and engineering, i.e. a predictive model for calculation of deterministic separation distances defined by the parameters of a blast wave generated by a high-pressure gas storage tank rupture in a fire. An overview of existing methods to calculate stored in a tank internal (mechanical) energy and a blast wave decay is presented. Predictions by the existing technique and an original model developed in this study, which accounts for the real gas effects and combustion of the flammable gas released into the air (chemical energy), are compared against experimental data on high-pressure hydrogen tank rupture in the bonfire test. The main reason for a poor predictive capability of the existing models is the absence of combustion contribution to the blast wave strength. The developed methodology is able to reproduce experimental data on a blast wave decay after rupture of a stand-alone hydrogen tank and a tank under a vehicle. In this study, the chemical energy is dynamically added to the mechanical energy and is accounted for in the energy-scaled non-dimensional distance. The fraction of the total chemical energy of combustion released to feed the blast wave is 5% and 9%, however it is 1.4 and 30 times larger than the mechanical energy in the stand-alone tank test and the under-vehicle tank test respectively. The model is applied as a safety engineering tool to four typical hydrogen storage applications, including on-board vehicle storage tanks and a stand-alone refuelling station storage tank. Harm criteria to people and damage criteria for buildings from a blast wave are selected by the authors from literature to demonstrate the calculation of deterministic separation distances. Safety strategies should exclude effects of fire on stationary storage vessels, and require thermal protection of on-board storage to prevent dangerous consequences of high-pressure tank rupture in a fire.

Abbreviations: CFRP, carbon fibre reinforced polymer; CNG, Compressed Natural Gas; HRR, heat release rate; IR, infrared; LPG, liquefied petroleum gas; OEM, Original Equipment Manufacturer; SUV, sport utility vehicle; TPRD, thermally activated pressure relief device.

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http://dx.doi.org/10.1016/j.ijhydene.2015.07.001

Nomenclature

a_g	speed of sound in compressed gas, m/s
a_s	speed of sound in surrounding gas, m/s
B	batch availability, J
b	co-volume constant, $b = 1.584 \times 10^{-5}$ m^3/mol, or $b = 7.69 \times 10^{-3}$ m^3/kg
c_v	specific heat at constant volume, J/kg/K
c_p	specific heat at constant pressure, J/kg/K
E_{ch}	total chemical energy, J
E_m	total mechanical energy, J
E_i	combustion products expansion coefficient of stoichiometric hydrogen–air mixture
H	enthalpy, J
H_c	heat of combustion, J/kg
I	impulse, Pa s
$\bar{I}$	non-dimensional impulse
L_{SUV}	length of SUV, m
M	molecular mass, kg/mol
M_{sh}	Mach number of the shock wave
m	mass, kg
m_g	mass of compressed gas, kg
n	number of gas moles, mol
ΔP	overpressure in a blast wave, Pa
$\bar{P}_{st}$	non-dimensional starting shock overpressure
$\bar{P}$	non-dimensional overpressure, $\bar{P} = P/p_s$
p	pressure, Pa
p_f	pressure at final stage of gas expansion, Pa
p_g	pressure of gas in a vessel, Pa
p_i	pressure of gas at initial state, Pa
p_s	surrounding pressure, Pa
R	universal gas constant, $R = 8.314$ J/mol/K
r	distance from a vessel, m
r_b	radius of hemisphere occupied by combustion products of burned stoichiometric hydrogen–air mixture, m
r_{sh}	radius of shock wave, m
r_u	radius of hemisphere occupied by unburned hydrogen–air mixture, m
r_v	radius of spherical vessel of equivalent volume, m
$\bar{r}$	non-dimensional distance from a vessel (non-dimensionalised for overpressure)
$\bar{r}_I$	non-dimensional distance from a vessel for impulse calculation
$\bar{r}_P$	non-dimensional distance from a vessel for overpressure calculation
$\bar{r}_v$	non-dimensional energy-scaled radius of spherical vessel
S	entropy, J/K
T	temperature, K
T_f	gas temperature at final stage of expansion, K
T_i	initial temperature of compressed gas, K
T_s	surrounding temperature, K
V	volume, m^3
V_b	volume of hemisphere occupied by combustion products of burned stoichiometric hydrogen–air mixture, m^3
V_f	volume of expanded gas, m^3
V_i	initial volume of compressed gas, i.e. vessel volume, m^3
V_{sh}	volume of hemisphere behind a shock, m^3
V_u	volume of a hemisphere occupied by stoichiometric hydrogen–air mixture, m^3
W	total work performed by gas, J
W_{SUV}	width of SUV, m

Greek

α	mechanical energy coefficient
β	chemical energy coefficient
γ	ratio of specific heats
π	"pi" number
ρ	density, kg/m^3
φ	"steady flow" availability, J

Subscripts

a	air
b	burned
ch	chemical
f	final
g	gas
I	impulse
i	initial
m	mechanical
P	overpressure
s	surrounding
sh	shock
st	starting shock
SUV	sport utility vehicle
u	unburned
v	vessel

Introduction

The use of alternative fuels like compressed natural gas (CNG), liquefied petroleum gas (LPG), and hydrogen raises the safety issues that have to be addressed. One of these issues is a blast wave strength that is needed to calculate a deterministic separation distance when high-pressure storage tank ruptures in a fire. Hydrogen safety engineering is a new discipline underpinning the technological safety of emerging hydrogen systems and infrastructure. It encompasses previously acquired and recent knowledge generated by the international hydrogen safety community that is published elsewhere [1]. The separation distance is an ultimate mitigation measure against hazards and associated risks during an accident that involves, in particular, compressed hydrogen storage. One of technical features that makes hydrogen systems different from others is very high storage pressure up to 100 MPa.

Deterministic separation distance from a hydrogen system or infrastructure is usually assessed by either hazards of unignited or ignited (fire) release from equipment or storage, or by hazards associated with a catastrophic failure (rupture)