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BLEVE fireball modeling using Fire Dynamics Simulator (FDS) in an Algerian gas industry

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ABSTRACT

BLEVE is one of major accidents observed in gas industry causing severe damage to people and environment. Its effects are manifested in three ways: shock wave propagation, fireball radiation and fragments projection. To assess these effects, risk decision-makers often use Quantitative Risk Analysis (QRA). In most cases, QRA data are obtained from empirical correlations. However, these correlations are not very satisfactory because they generally overestimate BLEVE effects and do not take into account geometry effects. In order to overcome the limitations of these empirical approaches, CFD modeling appears as a powerful tool able to provide more accurate data to better realize QRA. In this paper, the objective is to develop a CFD methodology in order to predict BLEVE thermal effects. Numerical simulations are carried out using the CFD code FDS. A sensitivity analysis of numerical models is performed in order to choose the right parameters allowing to model the fireball dynamics. The models retained are based on a single-step combustion using EDC model coupled with a LES turbulence model. Predictions show good agreement in comparison with results issued from three large-scale experiments. Furthermore, a case study on a propane accumulator in an Algerian gas processing unit is carried out.

1. Introduction

For several years, the consequences of major accidents with severe impacts on people, equipment and environment remain a primary concern for decision-makers and industrial experts. The three main most commonly encountered types of accidents in the chemical and petrochemical process industry are: fires, explosions and toxic releases.

With the technological growth of existing and emerging facilities, it is necessary to enhance the safety of these facilities by optimizing and improving the risk analysis methods. For this, risk analysts often use quantitative risk analysis (QRA) (Sellami and Nait-Said, 2017), which is based on understanding and quantifying the consequences of accidental phenomena (thermal radiation, overpressure, toxicity dose).

Among the accidental phenomena most observed in the process industry is the Boiling Liquid Expanding Vapor Explosion (BLEVE). It corresponds to a violent vaporization of explosive nature following the rupture (loss of confinement) of a reservoir containing a liquid at a temperature significantly higher than its normal boiling point at atmospheric pressure (CCPS, 2010).

A simple accident analysis can demonstrate the potential destruction of a BLEVE. Indeed, the 80-odd major BLEVEs that have occurred between 1940 and 2005 have costed more than 1000 lives and have injured more than 10000 persons in addition to harming property worth billions of dollars (Abbasi et al., 2007). BLEVE effects on the environment are characterized by a propagation of shock wave, projection of fragments and formation of a fireball if the gas is flammable. Therefore, it is important to estimate the potential damage that would be caused by such an explosion.

In this context, considerable efforts have been made to study the mechanisms of BLEVE. Several researchers published articles on various aspects of this accident.

Roberts (1981) worked on the thermal radiation hazards associated with LPG releases from pressurized storage. He established correlations that describe the fuel mass influence on the fireball characteristic parameters (diameter, lifetime and heat flux). Based on these ideas, Crocker and Napier (1988) evaluated mathematical models for fire and explosion hazards of LPG. They shown that these models overestimate the risks associated with jet fires, fireballs and BLEVE blast effects.

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Nomenclature

c	Constant Coefficient of Vreman
C	Corrective factor
C_d	Discharge coefficient
C_nH_{2n+2}	Alkane
CO_2	Carbon dioxide
c_p	Specific heat (kJ/(kg·K))
C_{RNG}	Constant Coefficient of RNG model
C_s	Constant Coefficient of Smagorinsky
C_{UFL}	Volume concentration corresponding to UFL
C_v	Constant Coefficient of Deardorff
D^*	Characteristic fire diameter (m)
d_C	Source diameter (m)
D_{k*}	Diffusion coefficient of the specie $k*$ (m^2/s)
D_{FB}	Fireball diameter (m)
E_p	Surface emissive power (kW/m^2)
F_v	View factor
g	Gravitational acceleration (m/s^2)
h	Enthalpy (kJ/kg)
H_2O	Water
H_{eav}	Heaviside unit step function
H_{FB}	Height of fireball center (m)
I_b	Radiation blackbody intensity (kW/m^2)
$I_{b,d}$	Radiation blackbody intensity of the particles (kW/m^2)
I_υ	Radiation intensity at wavelength υ (kW/m^2)
$I(x, s')$	Spectral integrated intensity in the direction s' (kW/m^2)
k_{sgs}	Subgrid kinetic energy (m^2/s^2)
L	Distance from the fireball center to the target at ground level (m)
L_{ij}	Germano identity
M	Fuel mass (kg)
$\dot{m}$	Mass loss rate (kg/s)
$\dot{m}_{O2}$	Oxygen mass loss rate (kg/s)
n	Atom number, integer
N_2	Nitrogen
O_2	Oxygen
p	Pressure (Pa)
P_0	Vessel pressure before explosion (MPa)
P_w	Water partial pressure (Pa)
$\dot{Q}$	Heat Release Rate (kW)
$\dot{q}'''$	Heat release rate per unit volume (kW/m^3)
$\dot{q}_r''$	Radiative heat flux (kW/m^2)
R_H	Relative humidity (%)
r_s	Mass stoichiometric coefficient for air
ρ	Density (kg/m^3)
s, s'	Unit vectors in direction of radiation intensity
S	Strain rate (1/s)
S_{ea}	Ejection surface (m^2)
T	Temperature (K)
t_{FB}	Fireball lifetime (s)
t	Time (s)
t_C	Release time (s)
U	Total integrated radiant intensity (kW/m^2)
u	Velocity in the direction of x (m/s)
v	Velocity in the direction of y (m/s)
V	Volume (m^3)
w	Velocity in the direction of z (m/s)
Y	Mass fraction (kg/kg)

Greek letters

Δ	Filter width (m)
δ_x	$x$nominal mesh size (m)
δ_y	$y$nominal mesh size (m)
δ_z	$z$nominal mesh size (m)
ΔH_c	Heat of combustion (kJ/kg)
ΔH_{O2}	Oxygen heat of combustion (kJ/kg)
κ	Absorption coefficient (1/m)
κ_d	Particle absorption coefficient (1/m)
χ_r	Radiative fraction
λ	Thermal conductivity (W/(m·K))
μ	Dynamic viscosity (kg/(m·s))
μ_{eff}	Effective eddy viscosity (kg/(m·s))
μ_S	Smagorinsky dynamic viscosity (kg/(m·s))
$\dot{\omega}'''$	Production rate per unit volume ($kg/(m^3 \cdot s)$)
$\Phi(s, s')$	Scattering phase function
σ	Boltzmann constant = $5.67 \cdot 10^{-11}$ $kW/(m^2 \cdot K^4)$
σ_d	Particle scattering coefficient
τ_a	Atmospheric transmissivity
τ_{mix}	Mixing time (s)

Subscripts

a	Ambient air
g	Fuel or gas
i, j, k	Cell indexes
$k*$	Species index
∞	Ambient condition
l, m, n	Integers
t	Time
x, y, z	Location indexes

Acronyms

BAM	Bundesanstalt für Materialforschung und -prüfung
BLEVE	Boiling Liquid Expanding Vapor Explosion
CFD	Computational Fluid Dynamics
CFT	Critical Flame Temperature
CPU	Central Processing Unit
EDC	Eddy Dissipation Concept
FDS	Fire Dynamics Simulator
FFT	Fast Fourier Transforms
FVM	Finite Volume Method
HRR	Heat Release Rate
HSL	Health and Safety Laboratory
JIVE	Jet-fire Interaction with VEssels
LES	Large Eddy Simulation
LNG	Liquefied Natural Gas
LOC	Limiting Oxygen Concentration
LPG	Liquefied Petroleum Gas
MPI	Message-Passing Interface
NIST	National Institute of Standards and Technology
PDE	Partial Differential Equation
QRA	Quantitative Risk Analysis
RANS	Reynolds-Averaged Navier-Stokes
RMSE	Root-Mean-Square Error
RNG	Renormalization Group
RTE	Radiation Transport Equation
SGS	Sub-Grid Scale
UFL	Upper Flammable Limit
UVCE	Unconfined Vapor Cloud Explosion