

Research Article

Study on Turbulent Flow of Gas and Liquid Phase LPG in Tank under Fire Based on VOF Technology

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Abstract: The turbulent flow state of gas and liquid phase LPG in tank under fire is complex and the VOF technology and RNG k- ϵ model are applied to study it and the flowing rules of LPG in tank under fire can be obtained. First, the thermal response rules of gas and liquid phase LPG under fire are discussed. Second, turbulent flow model of gas and liquid phase LPG in tank under fire, the RNG k- ϵ model and VOF model and solution algorithm are established. Finally, simulation of turbulent flow for gas and liquid phase LPG in tank under fire is carried out and the changing rules of different physical parameters of gas and liquid phase interface in LPG tank are obtained.

Keywords: Gas and liquid phase, LPG, turbulent flow, VOF technology

INTRODUCTION

LPG is an inflammable and explosive medium, which is stored in the LPG tank. When LPG tank suffers by the external fire, the internal pressure will increase and the strength of the tank wall will reduce, the LPG tank can break. If the leaking medium exposes to an ignition source, vapor explosion is caused. If this accident happens in large oil tank depot and the linkage exploration will happen, which causes economic losses and casualties. Under fire the gas and liquid phase LPG in tank in turbulent flow and RNG k- ϵ model can be used to describe this flow. And the gas and liquid phase LPG exist at the same time and the change into each other under fire and a large number of bubbles can produce, therefore VOF technology can be used to describe the two-phase flow of LPG.

In recent years, the VOF technology has been applied in analysis of the gas and liquid phase flow and some excellent achievements have been obtained. Bruno *et al.* (2012) Carciofi studied important parameters in the dynamics of vacuum impregnation and proposed a three dimensional model which predicted the impregnation step in apple samples. The excellent predicting ability of this mathematical model is verified by comparing the experimental and numerical results. Sudarshan *et al.* (2013) Tiwari studied gas and liquid phase flow over a large of Knudsen numbers inside the gas phase and the corresponding mathematical models of liquid phase and gas phase were established. Numerical analysis results showed that the coupled solutions obtained from the Boltzmann and the incompressible Navier-Stokes equations match with the solutions obtained from the

compressible and the incompressible Navier-Stokes equations. Ganguli *et al.* (2011) proposed a novel computational fluid dynamics based method, which incorporated interfacial mass transfer at moving interfaces. A test case study was carried out for a gas bubble rising in a stagnant liquid phase; the movement of the bubble was simulated based on the level set method and velocity vectors and concentration contours were demonstrated and analyzed. Sungkorn *et al.* (2011) proposed three-dimensional and time-resolved simulations of turbulent gas-liquid bubbly flows and the mathematical model was established, the presented modeling technique offered very good agreement with experimental data for mean and fluctuating velocity components. Senthilkumar *et al.* (2011) studied the influence of surface tension and the static contact angle on the dynamics of an ellipsoidal air bubble of equivalent diameter. The computational results were achieved with a Piecewise Linear Construction of the interface and are reviewed with reference to experimental measurements of bubble velocity and interface shape oscillations recorded based on a high speed digital camera. Rodrigo *et al.* (2012) Lopes performed VOF numerical simulations to evaluate how liquid flow modulations could improve the detoxification of liquid effluents by catalytic wet oxidation. The VOF computations had correctly handled the experimental observations both in terms of the axial conversion and temperature. Computed and experimental findings revealed a considerable improvement on the detoxification of organic matter highlighting the benefits of process intensification covered by the periodic liquid flow modulations. Mustafa and Erdogdu (2012) Tutar coupled VOF

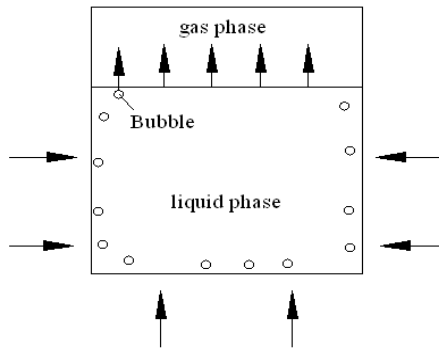


Fig. 1: The gas-liquid phase model in the first stage

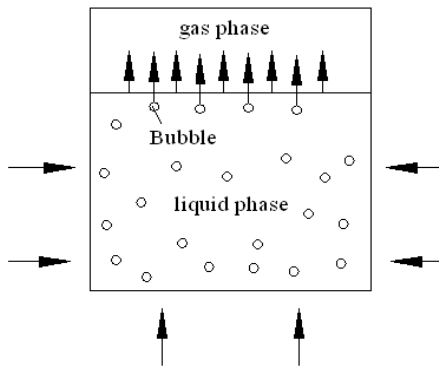


Fig. 2: The gas-liquid phase model in the first stage

element method with a finite volume discretization technique to simulate 2D two phase flow. Numerical results showed that two-phase flow patterns were significantly affected by increasing rotational speeds leading to distinguishable flow patterns in terms of air-liquid interface characteristics and associated headspace air bubble movement through the liquid phase.

According to the achievements obtained, the VOF technology can be applied in analyzing the turbulent flow, therefore the VOF technology is an effective means to describe the two-phase turbulent flow of LPG in tank under fire. In order to improve the precision of the turbulent flow analysis, the turbulent flow model is constructed through combining the RNG k-ε model with VOF technology.

There are two stages for the thermal response procession of gas and liquid phase LPG in tank under fire. The gas-liquid phase models in first and second stage are shown in Fig. 1 and 2 respectively.

The first stage is the start of heat transfer stage, heat transfer between the liquid zone and tank wall is carried out based on natural convection. When superheating ratio of the liquid phase LPG arrives to a certain degree, boiling heat transfer occurs on the inner wall surface of LPG tank locating on the liquid zone and lots of bubbles are formed on the wall surface and the bubbles exit the inner wall surface after they grow up and move to the gas-liquid interface, then enter to

the gas phase zone. The second stage happens when the liquid phase LPG is in overall superheated status, homogeneous phase boiling in liquid zone occurs and lots of bubbles produce and the bubbles arrive to the gas-liquid interface and enter into the gas zone.

MATERIALS AND METHODS

Because the flow field of gas and liquid phase in LPG tank under fire has big amplitude of variation in the different direction velocity and turbulence intensity, therefore RNG k-ε model can be applied in analyzing it. RNG theory offers an analytical formula considering low Reynolds number viscosity flow and a condition is added into k-ε formulation and the computing precision can be improved. RNG theory also considers the turbulent vortex and the corresponding precision is improved. RNG k-ε model has higher credibility and precision than standard k-ε model.

The governing equations of turbulent gas phase LPG is expressed as follows (Bruno *et al.*, 2012; Sudarshan *et al.*, 2013; Ganguli *et al.*, 2011):

$$\frac{\partial \vec{u}}{\partial t} + \vec{u} \cdot \nabla \cdot \vec{u} = -\frac{1}{\rho_g} \nabla \cdot P + \frac{2(\mu + \mu_T)}{\rho_g} \nabla \cdot \vec{S} \quad (1)$$

$$\nabla \cdot \vec{u} = 0 \quad (2)$$

$$\mu_T = \rho_g C_\mu \frac{k^2}{\varepsilon} \quad (3)$$

$$\frac{\partial k}{\partial t} + \vec{u} \cdot \nabla k = \frac{1}{\rho_g} \left(\mu + \frac{\mu_T}{\sigma_k} \right) \nabla^2 k + G - \varepsilon \quad (4)$$

$$\frac{\partial \varepsilon}{\partial t} + \vec{u} \cdot \nabla \varepsilon = \frac{1}{\rho_g} \left(\mu + \frac{\mu_T}{\sigma_\varepsilon} \right) \nabla^2 \varepsilon + C_1 \frac{\varepsilon}{k} G - C_2 \frac{\varepsilon^2}{k} \quad (5)$$

where,

\vec{u} = The mean velocity

P = The mean static pressure

ρ_g = The density of the gas phase LPG

μ = The molecular viscosity

μ_T = The turbulence viscosity

\vec{S} = The strain rate, which can be expressed as follows:

$$\vec{S} = \frac{1}{2} (\nabla \vec{u} + (\nabla \vec{u})^T) \quad (6)$$

G denotes the kinetic energy, which can be defined by Sungkorn *et al.* (2011):

$$G = \frac{2}{\rho_g} \mu_T \vec{S} : \nabla \vec{u} \quad (7)$$

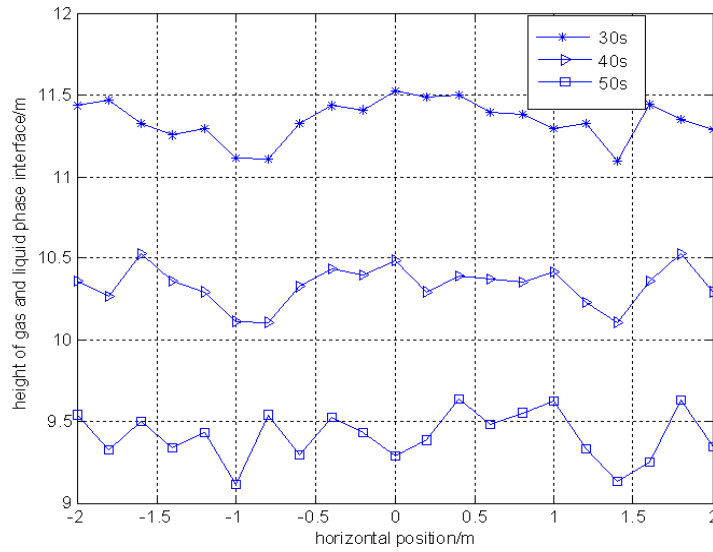


Fig. 3: Changing rules of height for the gas-liquid phase with time

C_1 is a constant, which is defined by:

$$C_1 = 1.42 - \frac{\eta(1 - \eta/\eta_0)}{(1 + \beta\eta^3)} \quad (8)$$

where, η be calculated based on the following expression:

$$\eta = \frac{\sqrt{2\bar{S} : \bar{S}k}}{\varepsilon} \quad (9)$$

Constants C_{μ} , C_2 , σ_k , σ_ε , β and η_0 are empirical constants.

The governing equations of turbulent gas phase LPG can be obtained through changing ρ_g to ρ_l , where ρ_l denotes the density of liquid phase LPG.

The interface between gas phase LPG and liquid phase LPG can be traced through calculating the volume fraction occupied by individual phase in each cell. The gas phase or liquid phase volume V in a cell can be computed by the following expression (Senthilkumar *et al.*, 2011):

$$V = \phi V_c \quad (10)$$

where, V_c denotes the volume of each cell, ϕ denotes the liquid volume fraction, $0 \leq \phi \leq 1$, $\phi = 0$ represents a liquid phase cell, $\phi = 1$ represents a gas phase cell, $0 < \phi < 1$ represents the liquid/gas interface.

The liquid volume fraction can be obtained according to the following continuous equation, which is expressed as follows Rodrigo *et al.* (2012):

$$\frac{\partial \phi}{\partial t} + \bar{u} \nabla \cdot \phi = 0 \quad (11)$$

The physical characteristics of LPG can be decided by the liquid volume fraction and the value of the mean density ρ_m and the mean dynamic viscosity μ_m can be computed based on the following expressions:

$$\rho_m = \phi \rho_l + (1 - \phi) \rho_g \quad (12)$$

$$\mu_m = \phi \mu_l + (1 - \phi) \mu_g \quad (13)$$

The variable density BCG method is used to simulate the interface flow and it has the two order time and space precision because the Godunov pattern is used to compute the convection term. And the multi-grid method is applied in speeding up the convergence of RNG k- ε model. And the corresponding algorithm equations are listed as follows Mustafa and Erdogdu (2012):

$$\frac{\bar{u}^* - \bar{u}^n}{\Delta t} = [-\bar{u} \cdot \nabla \cdot \bar{u} + \frac{2(\mu + \mu_r)}{\rho_g} \nabla \cdot \bar{S}]^{n+\frac{1}{2}} - \frac{1}{\rho_g^n} \nabla \cdot P^n \quad (14)$$

$$\frac{\bar{u}^{n+1} - \bar{u}^*}{\Delta t} = -\frac{1}{\rho_g^{n+1}} \nabla \cdot (P^{n+1} - P^n) \quad (15)$$

$$\frac{\nabla \bar{u}^*}{\Delta t} = \nabla \left[\frac{1}{\rho_g^{n+1}} \nabla \cdot (P^{n+1} - P^n) \right] \quad (16)$$

RESULTS AND DISCUSSION

The main parameters of LPG tank listed as follows: the height of LPG tank is 15.5 m, the diameter of LPG tank is 4.0 m and the filling rate of LPG tank is 75%,

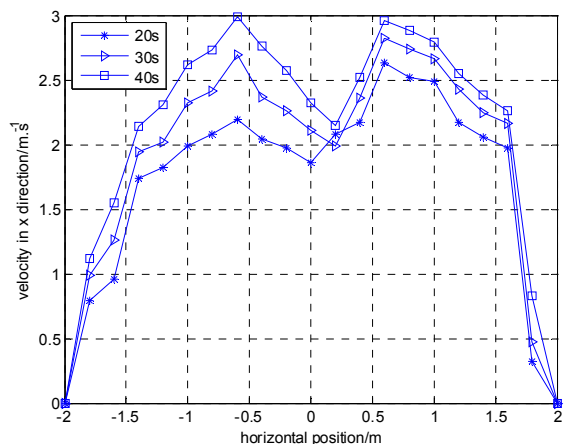


Fig. 4: Changing rules of velocity in x direction with time

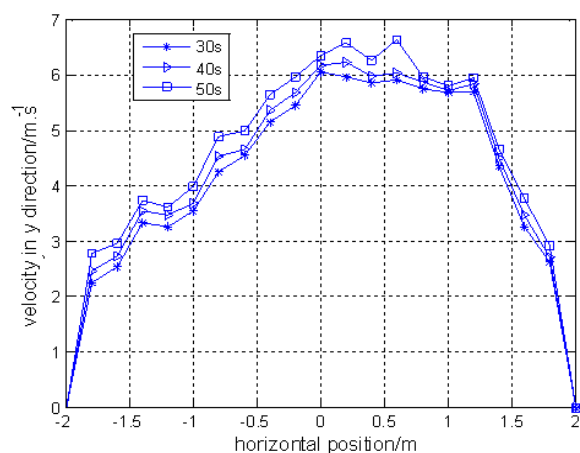


Fig. 5: Changing rules of velocity in y direction with time

the type of fire is pool fire. The simulation programmer is compiled by MATLAB software.

The height of the gas and liquid phase interface is a main parameter for describing the gas and liquid phase interface and the simulation results are shown in Fig. 3. As seen from Fig. 3, the height of the gas and liquid phase interface in LPG tank changes complexly and the gas and liquid phase interface flow belongs to turbulent flow. And the height of gas and liquid phase interface decreases with time prolonging. Under fire, the liquid phase LPG changes to the gas phase LPG and the interface will reduce.

The changing rules of velocity in x and y direction for gas and liquid phase interface in LPG tank is obtained through numerical analysis and the corresponding results are shown in Fig. 4 and 5. Figure 4 shows the changing rules of velocity in x direction for the gas and liquid phase interface in LPG tank and the velocity in x direction for the gas and liquid phase interface increases with time prolonging and distributed symmetrically relative the axis of

LPG tank. Figure 5 shows the changing rules of velocity in y direction and the velocity in y direction for the gas and liquid phase interface also increases with time prolonging and it is less than the velocity in x direction.

CONCLUSION

The VOF technology and RNG k-ε model are combined to analyze the turbulent flow of gas and liquid phase LPG in tank under fire and the corresponding mathematical models are established. The BCG method and multi-grid method are applied in simulating the gas and liquid phase interface in LPG tank. Simulation is carried out based on the theory model and the changing rules of the height, the velocity in x and y direction of the gas and liquid phase interface in LPG tank under fire are obtained.

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