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Analysis of the explosive boiling process of liquefied gases due to rapid depressurization

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A B S T R A C T

It has been reported that the phenomena of explosive boiling always occur during the storage and transport of the liquefied gases such as hydrogen. The accident usually followed the rapid depressurization of the liquefied gas storage tanks, which was caused by the rupture of the tank or the opening of the safety valve, and could bring secondary hazards by the pressure re-built. The explosive boiling process involved a complicated coupling between the response of the pressure and the boiling of the liquefied gases. In this paper, a mathematical model was developed to predict the coupled response between the pressure and the unstable boiling of the liquefied gases. And good agreement was obtained between the experimental data and the simulated results of the pressure response. The mechanism of the coupled response between the pressure and the superheated liquid boiling, as well as the evolution of the two phase flow during the discharge were researched by analyzing the pressure transmission process, the vaporization rate contribution and the hydrodynamic field.

1. Introduction

With the development of industry, the boiling liquid expanding vapor explosion (BLEVE) has been more and more common among many areas, such as boiler operation, storage and transportation of liquefied gases, supercritical carbon dioxide sequestration and so on. In recent years, it also has drawn lots of attentions as a kind of propulsion technology.

In order to prevent the serious harm caused by uncontrollable vapor explosion and use the effective energy which it released, it is necessary to carry out further research on the microcosmic mechanism of BLEVE. The vapor explosion often originates from a rapid decompression of a liquid container. Cumber (2002) divided the pressure response process after the opening of the container into four stages: first, the gas begins to discharge and the pressure drops; then the liquid reaches into a superheated state and vaporizes, producing bubbles and swelling to the vapor space, which will make the pressure rise; the phase transition of the expanded superheated liquid was very quick and amount of two-phase flow moves to the outlet; eventually a lot of superheated liquid discharge and the liquid level drops.

R. C. Reid (1979) first proposed the theory of the superheat limit temperature for the occurrence of BLEVE, and later Prugh (1991) corrected it to that even if the initial temperature of the liquid is lower than its superheat limit temperature, BLEVE can also happens. But academia has reached a consensus that the consequences of BLEVE accidents are the most serious when the liquid reaches the superheat limit temperature. Based on the theory of non-equilibrium thermodynamics, Zeng and Liu built up a new mathematical model for bubble growth in a superheated liquid during rapid decompression, and derived out the chemical potential changes during the gas-liquid phase transition and the mathematical formula of critical bubble radius (Zeng and Wang, 1997; Liu and Zeng, 1998). Lin and Gu used the probability distribution of energy fluctuation to determine the homogeneous nucleation rate in superheated liquid by considering the rate of temperature or pressure changing (Lin et al., 2010). Numerous studies showed that the temperature rising rate or the pressure dropping rate played an important role in nucleate boiling process of superheated liquid, but the actual process is that not only the new bubbles will not form, but also the generated bubbles may be broken when it happens.

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In parallel with the theoretical analysis, many scholars launched a large number of experimental studies on the causes, factors of BLEVE and pressure rebound in the pressure relief process, in order to reveal the BLEVE accident regulation. Birk (1995, 1996); Birk et al. (2002; 2006) carried on 30 groups of BLEVE experiments on 400 L propane tanks, the effect of three control variables like the opening pressure of the safety valve, the tank wall thickness and the fire conditions on BLEVE were analyzed. Venart et al. (1993) carried out a vapor explosion using R11 by artificially processing cracks on the wall of the container at the gas side using a propane flame nozzle. After the pressure discharged for 200 μs, the pressure peak was higher than the initial pressure of about 0.175 MPa measured by the dynamic pressure sensor placed under the liquid surface, and then containers suffered catastrophic destruction. Lin et al. (2002a) used the heater band instead of the real flame, mounted a valve at the outlet of the pressure vessel, and simulated the real vapor explosion process by suddenly opening the valve. The results showed that: the sudden discharge process may indeed cause a rapid pressure increase, sometimes close to or even surpass the initial value. Chen (2007); Chen et al. (2008) built a small-scale experimental device that could lead to BLEVE. The experimental medium was water, which was heated in the form of internal heating, and the rupture disc was forced to open in the experiments. By changing the initial conditions of temperature, liquid level, size of opening, their impacts on the container overpressure were explored.

Because BLEVE is a complex physical process, it is difficult to fully reveal the microscopic mechanism of its occurrence only through experimental studies, so researchers have tried to carry out some numerical simulations on BLEVE on the basis of experiments already finished. Woodward and Mudan (1991) took single phase gas discharge as an example, established a mathematical model of a tank with a small hole to describe the process of pressure release, and gave a simple analytic formula about discharge rate varying with time. Nutter (1999) established a model of a small container filled with HCFC-22 with a small hole to describe the process, single gas critical flow and gas-liquid homogeneous equilibrium model were used to describe critical mass flux at the outlet and deduce the expression of the depressurization rate from thermodynamic principle. Fthenakis et al. (2003) pointed out that homogeneous equilibrium model overestimated the discharge mass flow in the situation of rapid discharge of large gap and can't describe the entire discharge process more accurately. On the basis of the available experimental data, Yu and Xiong (1995) presented a physical analysis on the vapor explosion phenomenon caused by a small hole on the top of the container, the preliminary mathematical model of gas-liquid pressure distribution and liquid phase volume expansion was established. And cooperating with Wuhan University of Technology and the Flame Science Center of University of New Brunswick (Canada), they developed the PLGS99 software to simulate the temperature and pressure responses of LNG tanks caused by BLEVE (Yu et al., 2013). Lin et al. (2002b) and Wang and Ma (2006) each established a mathematical model for the sudden discharge process which is caused by the crack in the vapor region sidewall and the liquid region sidewall of the container, and through the computation, the changing of pressure rebounding progress state parameter in different conditions has been attained, and finally the effects of initial condition, such as broken area and container scale on the physical process were analyzed. Shang (2012) established a two-dimensional physical model for the initial process of BLEVE, and the influence of initial temperature, liquid level, size of opening and different initial conditions to the changes of the characteristics of BLEVE were studied used a simplified model.

In conclusion, the present knowledge about the vapor explosion is mainly focused on the macroscopic rule. For example, liquid would be instantaneous superheated due to rapid decompression, and the pressure of the container would increase quickly when a lot of superheated liquid boil rapidly and massive energy will release instantly. In most of the researches, the vapor explosion is considered as explosive boiling in the case of homogeneous superheat, but in the actual explosion, the liquid medium is gradually superheated with the propagation of pressure wave. In addition, the initial temperature stratification of the liquid medium can also lead to uneven superheat. It is necessary to carry out further research on the micro mechanism of the vapor explosion caused by rapid decompression. This paper established a fine time scale numerical model to study the mechanism of non-uniform explosive boiling caused by rapid decompression, to find out the law of the delayed non-uniform superheat and the law of boiling phase transition of liquid medium in the process of buck wave propagation, and make a deeper explanation to the mechanism of superheated liquid's explosive boiling and of two phase flow injection in the vapor explosion process.

2. Simulation model

The explosive boiling process of the liquefied gases will influence and be influenced by the response of the tank pressure due to the coupling of the rapid overheating after energy release and the suppression of the vaporization under the limit of the tank space. These two mechanisms which respectively result in the increase and decrease of the tank pressure were involved in the simulation model.

Based on the analysis of the key factors, the following assumptions were adopt during the simulating: 1) the tank wall was regarded as adiabatic considering the short duration; 2) the computational domain was simplified to 2D axisymmetric for efficiency under the premise of the axisymmetric flow field and boundary conditions; 3) the phase transition enthalpy was determined by the saturation temperature under the local transient pressure.

2.1. The tank geometry

The simulating research work in this paper was conducted on the 50 L vertical cylindrical liquefied gas tank used in Yang's experiments (2012), and the geometry details of it were shown in Fig. 1. As can be seen, the tank diameter was 325 mm and the total length was 812 mm with a 156 mm long vent duct weld at the top of the tank. The pipe was sealed by rupture disk before the pressure release, and the orifice can be adjusted from 0 to 100 mm with the line *AB* stood for the pressure outlet. Two pressure monitoring points of p_1 and p_2 were respectively set at the inner head and side wall of the cylinder.

2.2. The governing equations

The explosive boiling was regarded as a result of the homogeneous nucleation of the overheated liquid, and the following two phase flow was considered homogeneous. Based on this consideration, the Mixture multiphase model developed by the ANSYS Fluent, which treated the different phases mathematically as interpenetrating continua and still can describe phase slip, was adopted to simulating the multiphase flow of this problem. The main governing equations of the model are:

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