Experimental Thermal and Fluid Science 88 (2017) 93–102

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs

Experimental and modeling studies on the transient pressurization in response to boiloff vapor recondensation in liquefied gas storage tanks

Zhongdi Duan, Tao Ren, Guoliang Ding *

Institute of Refrigeration and Cryogenics, Shanghai Jiao Tong University, Shanghai 200240, China

ARTICLE INFO

Article history:
Received 22 November 2016
Received in revised form 13 May 2017
Accepted 21 May 2017
Available online 23 May 2017

Keywords:
Boiling liquid expanding vapor explosion
Boiloff vapor recondensation
Modeling
Liquefied gas
Pressurization

ABSTRACT

The boiling liquid expanding vapor explosion (BLEVE) is a most common hazard in liquefied gas storage and transportation. The explosion is resulted from tank overpressure under external thermal attack, and its prevention depends on accurate prediction of the boiling liquid pressurization. This paper presents a mathematical model to simulate the boiling liquid pressurization in liquefied gas storage tank. The model includes a semi-empirical equation to calculate the critical subcooled degree at the onset of pressurization, an energy equation of bubble condensation to calculate the net vapor generation rate in storage tank, a thermal-response equation of the subcooled boiling liquid to calculate the transient temperature of bulk liquid, and an isochoric equation to predict the transient pressure of boiloff liquefied gas. Comparison of the model predictions with experimental data shows that the maximum deviations of the predicted transient pressure and temperature are within 15 kPa and 3 °C, respectively.

1. Introduction

Hydrocarbon mixtures (e.g. natural gas, petroleum gas) are widely used as clean fuels in the global energy system for power generation and heating industries [1]. These fuel gases are liquefied before storage and transportation to enlarge storage capacity and reduce transportation cost [2]. The liquefied gas contains large potential energy and suffers the danger of boiling liquid expanding vapor explosion (BLEVE), which has been reported frequently in recent decades [3]. BLEVE is a type of thermally-induced explosion described as a sudden release of a large mass of pressurized superheated liquid to the atmosphere [4]. Emergency measures including on-site personnel evacuation, fire mitigation actions and sufficient water supply are implemented to prevent the explosion and avoid casualties [5]. The emergency measures should be executed in time before BLEVE occurs, and the key point of managing the measures is to estimate the duration from the initial time of thermal attack to BLEVE occurring [6].

The duration from the initial time of thermal attack to BLEVE occurring can be estimated by predicting the pressurization in storage tanks. The liquefied gas is originally at the atmospheric pressure, and is pressurized to a high pressure leading to BLEVE due to external thermal attack [7]. Most of cases indicate that BLEVE occurs when the internal pressure exceeds the saturated pressure corresponding to the superheat limit temperature (SLT) of liquefied gas [8]. The interval time from the original pressure to the BLEVE pressure represents the minimum duration time before BLEVE occurs. In order to estimate the duration time in the previous stage of BLEVE, the pressurization in storage tanks under external thermal attack should be predicted [9,10].

The pressurization in a storage tank under external thermal attack is resulted from the vapor mass gain in the system [11]. The vapor mass gain comes from two parts: (1) the vapor generated from the surface evaporation at the liquid-vapor interface; (2) the vapor generated from the heating wall surfaces due to liquid boiling. The surface evaporation induced pressurization is in response to the thermal convection in liquid region. The thermal convection increases the temperature at the liquid-vapor interface and enhances the surface evaporation rate, leading to pressurization [12]. The boiling induced pressurization is in response to the nucleate boiling of subcooled liquid [13], where the liftoff bubbles are partly condensed and partly entering into the vapor zone, leading to pressurization. In order to predict the pressurization in storage tanks, the models of surface evaporation induced pressurization and boiling induced pressurization are needed.

The surface evaporation induced pressurization can be predicted by existing models [14–17]. These models are developed by determining the temperature at the liquid-vapor interface, and expressing the pressure as a function of the interface temperature based on the assumption that the liquid and vapor at the interface are in thermodynamic equilibrium. Early surface-evaporation

* Corresponding author.
E-mail address: gldingsjtu.edu.cn (G. Ding).

http://dx.doi.org/10.1016/j.expthermflusci.2017.05.020
0894-1777/

Nomenclature

A	cross-section area (m^2)
C	coefficient
D	bubble diameter (m)
g	acceleration of gravity (m/s^2)
H	liquid level height (m)
h	enthalpy (kJ/kg)
M	vapor mass (kg)
P	pressure (kPa)
q	heat flux (W)
T	temperature (K)
t	time (s)
u	bubble lifting velocity (m/s)

Greek symbols

α	heat transfer coefficient (W/m^2 K)
λ	thermal conductivity (W/m K)
ν	viscosity (Pa s)
ρ	density (kg/m^3)
σ	surface tension (N/m)
ΔT	temperature difference (K)

Abbreviations

BLEVE	boiling liquid expanding vapor explosion
SLT	superheat limit temperature

Subscripts

0	initial
crit	critical
e	escape
ev	evaporation
f	fluid
g	gas
liq	liquid
p	constant pressure
s	sensible
sat	saturation
sh	single-phase heat transfer
sub	subcooling
v	vapor
∞	bulk liquid

models regard the entire liquid as a lumped zone [14], and the tank pressure is a function of the lumped liquid temperature. Thermal stratification in liquid is experimentally observed later [18,19], indicating that temperature gradient exists in the liquid region and the warmest liquid accumulates at the liquid-vapor interface. Thermal-stratification models [15–17] are then developed to calculate the liquid-vapor interface temperature rise by tracing the heat convection paths, and the transient pressure in the tank is depicted by the liquid-vapor interface temperature. The thermal-stratification models are experimentally validated, showing well agreement with the experimental data.

The boiling induced pressurization starts from the subcooled state of bulk liquid [20,21]. Neglecting the pressurization under subcooled boiling will result in as much as 50% underestimation of the transient pressure in the storage tanks [22]. The process of pressurization strongly depends on the subcooled degree of boiling liquid. Large subcooled degree of bulk liquid makes the bubbles totally condensed in liquid, resulting in zero pressurization rate. As the subcooled degree becomes smaller, the bubbles are just partially condensed and the rest enter into the vapor space [23], resulting in pressure rising. The subcooled degree of bulk liquid is a time-varying parameter in practical cases and is coupled with the internal pressure [24,25], leading to that the pressurization rate cannot be directly obtained. As a result, a model to predict the transient pressurization under subcooled boiling is needed.

The main challenge to build a model of the transient pressurization under subcooled boiling is resulted from the dynamics of boiloff vapor recondensation in bulk liquid [26]. The process of boiloff vapor recondensation in bulk liquid contains bubble generation, bubble departure and bubble recondensation [27]. The bubble generation and bubble departure in the transient pressure system are similar to the cases in stable pressure systems [28–29], and can be directly calculated by extending the models of stable pressure systems to transient pressure systems [30–32]. The bubble recondensation in transient system is more complex than that in stable system [33] due to two aspects: (1) The bulk liquid temperature will raise as the bubbles are condensed in subcooled liquid, resulting in less bubble recondensation and pressure increase [34]; (2) The bubbles in subcooled liquid become smaller and easier to be condensed as the pressure increases, resulting in more bubble recondensation [35]. In order to build a model of the transient pressurization, the boiloff vapor recondensation should be quantitatively described in the model.

The purpose of this paper is to propose a model to predict the transient pressurization in response to boiloff vapor recondensation in liquefied gas storage tank. The boiloff vapor recondensation is experimentally investigated and quantitatively described at first, and then the model of the transient pressurization in response to boiloff vapor recondensation is developed and validated by a pressurization test.

2. Technical approach

The basic idea of developing the model of pressurization in response to boiloff vapor recondensation is to figure out the pressurization rate under the time-varying liquid subcooled degree. The method is to firstly determine the onset of pressurization according to the critical subcooled degree; and then develop a model to calculate the pressurization rate under the current subcooled degree. The critical subcooled degree is defined as the minimum subcooled degree of bulk liquid capable to condense all amount of the boiloff vapor. The onset of pressurization is experimentally measured at first, and then quantitative determined by a semi-empirical model of the critical subcooled degree. The pressurization rate is modeled by establishing the equation of net vapor generation rate based on bubble condensation. The whole model is validated by an experimental test.

The experiment consists of two aspects: (1) the experiment for determining the onset of pressurization, including the observation of boiloff vapor recondensation and the measurement of the subcooled degree at the onset of pressurizationunder; (2) the experiment for model validation, which is conducted by measuring the pressure and temperatures during the entire pressurization process.

The model consists of four parts: (1) sub-model of the subcooled degree at the onset of pressurization; (2) sub-model of the net vapor generation rate; (3) sub-model of the transient tem-