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A CFD based model to predict film boiling heat transfer of cryogenic liquids

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A B S T R A C T

Following an accidental spill of cryogenic liquid (*e.g.*, LNG) on a solid substrate (*e.g.*, concrete), the vapor generation corresponds to different boiling regimes *i.e.*, film boiling, transition boiling, and nucleate boiling. As film boiling phenomena dictate the vapor generation in the early stage of the spill, it is considered as the most important boiling regime in the context of cryogenic (*e.g.*, LNG) source-term estimations. This paper presents CFD simulations of cryogenic film boiling for liquid nitrogen (LN_2) and LNG as pure methane. Different aspects of CFD modeling such as vapor-liquid interface morphology, the behavior of heat flux at the heated surface, the effect of wall superheats on bubbles generation frequency and bubbles departure diameter are presented. Based on the results of CFD simulations, a first principle model is applied to correlate the wall heat flux in the film boiling regime. This model can be used to enable a faster estimation of wall heat flux when CFD simulations and use of empirical correlations are not feasible.

1. Introduction

Due to the technological break-through of shale gas exploration, LNG industries in the USA and other countries are booming (FERC, 2016). Once an importing country, USA is turning to be LNG exporting nation. As a result, LNG manufacturing activities related to liquefaction, storage, transportation and re-gasification have increased. Experts (Havens and Spicer, 2007) and government agencies (United States Government Accountability Office, 2007) emphasized the need for better risk assessment procedures associated with these operations. Standards such as (NFPA 59A, 2013), therefore, recommend accurate estimation of LNG spill consequence via validated models. Consequences of a LNG release include asphyxiating vapor cloud, fire (flash and pool), vapor cloud explosion (in highly congested area), and rapid phase transition (RPT). It is to be noted that a RPT occurs due to very fast evaporation of LNG on water, causing a pressure wave, is unique to the spill on water and therefore will not occur during a spill on land (Bubbico and Salzano, 2009).

A loss of containment of storage tanks, pipes or hoses carrying cryogenic liquid *e.g.*, LNG will result in the formation of the liquid pool on spilled substrate. Heat transfer from the surrounding to the pool results in vapor formation which disperses and may cause flammable and/or asphyxiating cloud in the dispersed area. Ignition condition and congestion level in the dispersed area dictates whether the dispersed cloud may escalate to consequence type such as vapor cloud explosion, flash fire or pool fire. The size of the cloud, or in other words, the amount of vapor formed from the boiling pool, determines the severity of the consequence phenomena. Thus, estimations of vapor formation from a boiling pool, also known as source-term, an input to dispersion model, is the key to accurate estimation of consequence severity of a loss of containment event (Webber et al., 2010).

The sources of heat to an on-land cryogenic pool are conductive heat from the ground, convective heat from the atmosphere and solar radiation or radiative heat from the fire. Among the different heat sources, conductive heat contributes the most to vapor formation during the early stage of the spill (Véchot et al., 2013). In general, three different regimes of the conductive heat are recognized during a spill of a cryogenic liquid: film boiling at the beginning, nucleate boiling towards the end of the spill and transition boiling between these two. A pictorial depiction of boiling phenomena, owing to the conductive heat transfer from the substrate, is presented in Fig. 1. A large temperature gradient during

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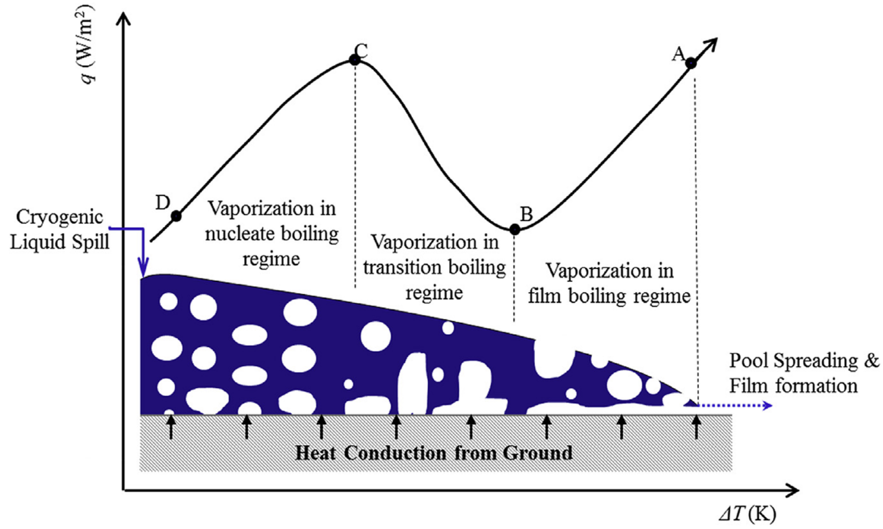

Fig. 1. Cryogenic spill phenomena and associated boiling regimes.

the early stage of the spill (189 K for LNG assuming ground at 300 K), result in a persistent vapor film between the substrate and the boiling liquid, and is known as film boiling. As shown in the schematic diagram under curve AB, generated bubbles completely cover the substrate surface forming a continuous film between the liquid and solid, which restrict the heat flux. With time, the surface temperature falls, reaching a lowest heat transfer rate (Leidenfrost point) as shown by point B in Fig. 1. Further decrease in temperature gradient cannot sustain a continuous film, the film breaks off, and boiling liquid comes in contact with the heated substrate, which is known as transition boiling regime. The behavior of heat flux as a function of wall superheat and schematic diagram of transition boiling are presented by the curve BC and corresponding area below, as shown in Fig. 1. With the contraction of intermittent vapor film, more and more liquid participates in convective heat transfer from the heated surface, causing an increase in heat flux as a function of decreasing wall superheat. The duration of boiling in this regime is very short compared to film boiling and nucleate boiling (CD). As a result, the cumulative amount of vapor generation in transition boiling regime is quite small compared to other boiling regimes. With the further decrease of wall superheats, in the nucleate boiling regime, bubbles become isolated from each other and detach from the nucleation sites of the substrate. Geometrical properties of the substrate, such as surface roughness play a major role in estimating vapor generation due to nucleate boiling. Point D in Fig. 1 represents the onset of nucleate boiling (ONB), below which the heat transferred to the pool contributes in free convection.

In the context of consequence analysis, consideration of film boiling regime is very important because of the fact that it corresponds to the highest temperature gradient at the beginning of spill. In 2004, U.S. Federal Energy Regulatory Commission (FERC) contracted ABS consulting to develop a case, to identify appropriate methods for performing consequence analysis of LNG release in water to estimate vapor dispersion and radiation hazards distance (FERC, 2004). The proposed methods have later become a "*de facto*" standard for consequence analysis of LNG release on water (Johnson and Cornwell, 2007). The detail computational methods have considered only the film boiling regime in estimating the vapor generation source-term. For the LNG release on land, 1-D heat transfer model is the most popular among the industries. However, this model does not consider the effect of heat transfer resistance due to the presence of different boiling regimes in the liquid phase. Thus, the estimation of vapor source-terms results inaccurate estimation of LNG spill consequence severity. Therefore, this study focuses in film boiling regime to facilitate better consequence analysis.

2. Literature review

The simplest of the vapor source-term model is based on 1-D heat conduction from the solid substrate. Reid utilized transient 1-D heat conduction equation to propose four different models as each model corresponds to different boundary conditions in estimating vapor generation rates (Reid, 1980). The most ideal of these models assumes a perfect contact between the liquid and solid-substrate. However (Reid, 1980), himself and others (Véchot et al., 2013) criticized this model for unrealistic assumptions and proposed to consider surface-thermal resistance due to the presence of film in the liquid solid interface. This is accounted via estimating heat transfer co-efficient from empirical film boiling correlations.

The first notable correlation to estimate film boiling heat transfer co-efficient on a flat boiling surface is credited to (Berenson, 1961). His formulation was based on the original work of Rayleigh-Taylor (R-T) hydrodynamic instability model of (Zuber, 1959) and expressed as Equation (1).

$$Nu = 0.425\left[\frac{\rho_v(\rho_l-\rho_v)gh_{fg}}{k_v\mu_v\Delta T}\right]^{1/4}\left[\frac{\sigma}{g\,(\rho_l-\rho_v)}\right]^{3/8} \quad (1)$$

Experimental works of (Holster and Westwater, 1962) confirmed the coherency of R-T instability during the film boiling on a horizontal surface. Water and Freon −11 (CCl_3F) systems were studied to validate the predictions of Berenson correlation.

A generalization of film boiling correlations on flat surface were proposed by (Klimenko, 1981). This proposed correlation was validated against different liquids including cryogens (Klimenko and Shelepen, 1982). The previously mentioned FERC "*de facto*" consequence analysis method has considered this correlation to estimate vapor formation source-term. For an upward facing geometrical system, according to this correlation, Nusselt number is predicted as follows: