Journal of Loss Prevention in the Process Industries 42 (2016) 70–81

Contents lists available at ScienceDirect

Journal of Loss Prevention in the Process Industries

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

Quantification of turbulence in cryogenic liquid using high speed flow visualization

Nirupama Gopalaswami, Delphine M. Laboureur, Ray A. Mentzer, M.Sam Mannan*

Mary Kay O'Connor Process Safety Center, Artie McFerrin Department of Chemical Engineering, Texas A&M University, College Station, TX 77843-3122, USA

ARTICLE INFO

Article history:
Received 6 April 2015
Received in revised form
15 August 2015
Accepted 21 August 2015
Available online 25 August 2015

Keywords:
LNG
Turbulence
Vaporization
High speed camera
Flow visualization
Source term

ABSTRACT

A high speed flow visualization experiment was conducted to characterize the boiling induced turbulence when a cryogenic liquid is released on water. The advective transport of turbulent structures traversing through the liquid was captured and reconstructed using image processing software to obtain information on velocity components. The numerical results obtained from image processing were used to determine turbulence parameters like turbulent intensity, turbulent kinetic energy and eddy dissipation rate. An interesting aspect of the study was the formation of wavy structures called 'thermals' which were characteristic of turbulent convection. The thermals were found to act as a catalyst in increasing heat transfer and turbulence between water and cryogenic pool. The turbulent intensity was influenced by the turbulent velocity and had direct effects on the vaporization flux. Among the turbulence parameters, increase in turbulent kinetic energy resulted in faster vaporization of cryogenic liquid through enhanced mixing, whereas variations in the eddy dissipation rate had weak dependence on vaporization. Additionally, the initial height of cryogenic liquid was also found to strongly affect the vaporization mass flux.

1. Introduction

An essential part of consequence analysis of Liquefied Natural Gas (LNG) spills on water requires understanding of pool spreading and vaporization behavior, which is often studied as source term modeling. The quantification of turbulence in the cryogenic liquid pool, when it comes in contact with water, is an important step in LNG source term modeling. Recent modeling approaches involve Computational Fluid Dynamics (CFD) codes with different types of turbulence models to perform various aspects of LNG consequence analysis. In spite of the increasing use of turbulence parameters in CFD, only a few researchers have tried to quantify the turbulence characteristics through experiments. One of the early attempts made to quantify turbulent intensity of vaporizing LNG was through analysis of video images of experiments (Gavelli et al., 2009). In this study, the spreading velocity of the pool was utilized to quantify the turbulent intensity. In another study, the effect of water turbulence on the cryogenic liquid was studied by varying the turbulent intensity of the water (Morse and Kytömaa, 2011). This approach was classified as free-surface turbulence and it utilized a controlled jet velocity of water in its study. Their study concluded that the vaporization rate was dependent on the height of cryogenic liquid. However, the underlying mechanism for the dependence of height on vaporization rate was not completely understood. A theoretical study was also performed based on a parameter called turbulence factor which was used to model the instability of the thermal film when LNG contacted water (Hissong, 2007). The turbulence factor reflected the turbulence produced in water due to an LNG spill and was given by the ratio of heat transfer coefficient between water and LNG to the heat transfer coefficient of quiescent water from correlations. Most of work done by researchers was focused on turbulence generated in water. It should be noted that there is presence of bubbly vaporization even when LNG is spilled on still water. However, the question remains as to whether turbulence, characterized by bubbly vaporization of cryogenic liquid, arises due to water or cryogenic liquid. Despite numerous theoretical models for pool spreading and vaporization, the number of models accounting for turbulence that is associated vaporization is less. This is attributed to the fact that turbulence is a complex three dimensional phenomenon and it is difficult to develop and incorporate a turbulence model in pool spreading and vaporization models. In addition to it, the nature of turbulence

* Corresponding author.
E-mail address: mannan@tamu.edu (M.Sam Mannan).

http://dx.doi.org/10.1016/j.jlp.2015.08.005

structures that are present inside the cryogenic liquid during vaporization are yet to be studied. Overall, this paves the way to determine sub-grid scale turbulence and examine its effect on vaporization.

To address these concerns, the present study investigated the turbulence generated during cryogenic liquid vaporization process. The purpose of the study is to describe a comprehensive and quantitative characterization of velocity and turbulence measurements of cryogenic liquid boiling on water. To achieve this, high speed flow visualization technique was used in the first phase of study to quantify the interfacial turbulence in the boiling phenomenon. Based on the experimental results, image analysis techniques were used to obtain the velocity components. From the velocity measurements turbulence parameters were determined from correlations. In addition, the interaction of the turbulence structures in the underlying flow field was investigated, which is important for understanding the turbulent effects on heat and mass transfer between water and cryogenic liquid.

2. Flow visualization experiment

2.1. Flow visualization setup

The general experimental arrangement for flow visualization is presented in Fig. 1. The flow visualization set-up consisted of a high speed camera (Photron SA 5) capable of frame rates up to 150,000 frames per second. The camera was operated at a frame rate of 5000 frames/s and a shutter speed of 1/6000 s to provide a video of 4.37 s in each experimental run. The camera had an integrated personal computer, which was used to control the capturing and storage of images. A front end software called Photron Fastcam Viewer (PFV) captured the camera images and stored the information in the computer for image processing. The input parameters were speed of capture (frame rate), shutter speed of the camera and number of frames for storage after triggering the capture. A backlighting technique was used during the data acquisition stage to illuminate the liquid and vapor phases of cryogenic liquid appropriately. The advantage of this technique was that it provided high light intensity, which was needed for extremely short shutter times and high frame rates. The illumination source was provided by a tungsten lamp (60 W) operating with a light capacity of 900 lumens and luminous efficacy of 15 lumens per watt. The light from the lamp was diffused through an optical filter placed between the illumination source and test section to spread the high intensity light evenly on the region of influence.

2.2. Test conditions

The test section consisted of a 100 ml cylinder with a height of 24 cm and inner diameter of 2.7 cm. The cylinder was filled with 35 ml of water before the start of the experiment. In each experimental run, a known quantity of liquid nitrogen (LN_2) was poured instantaneously (~0.5 s) and the camera was triggered. The water was quiescent before liquid nitrogen (LN_2) was poured into the setup. The LN_2 was poured at the top of measuring cylinder at every run. This is equivalent to a distance of 24 cm elevation from the base of the setup. The spill was performed manually and was restricted to a consistent duration of less than 0.5 s in all the runs. A total of 21,850 images with a maximum resolution of 1024 × 1024 pixels were produced in each experimental run. The field of view was centered on the water–cryogen interface in all experimental runs. The experiment was repeated by spilling different amounts of liquid nitrogen on water. A summary of experiments and key results is provided in Table 1. The initial water temperature and cryogenic liquid height were varied in the experiment. These constitute the independent variables. The turbulence parameters were found to be influenced by the independent variables and they are considered as primary dependent variables. The vaporization flux is dependent on both independent variables and primary dependent variables (turbulence parameters) and is considered as secondary dependent variable. An additional note on salt content is included to denote its influence on ice formation.

3. Image processing and analysis

To quantitatively study the turbulence generated by the boiling of the cryogenic liquid on water, the high speed images were processed using the Large Scale Particle Induced Velocimetry (LS-PIV) technique (Laboureur et al., 2013). This technique allows the calculation of the flow velocity from an image pair using algorithms developed for Particle Image Velocimetry (PIV). The traditional PIV technique consists of introducing small particles in the flow to illuminate them with a laser sheet. A couple of successive images at two different instants are then taken with a camera. The velocity is then computed through the estimation of the displacement between the two images, using cross-correlation methods. In the LS-

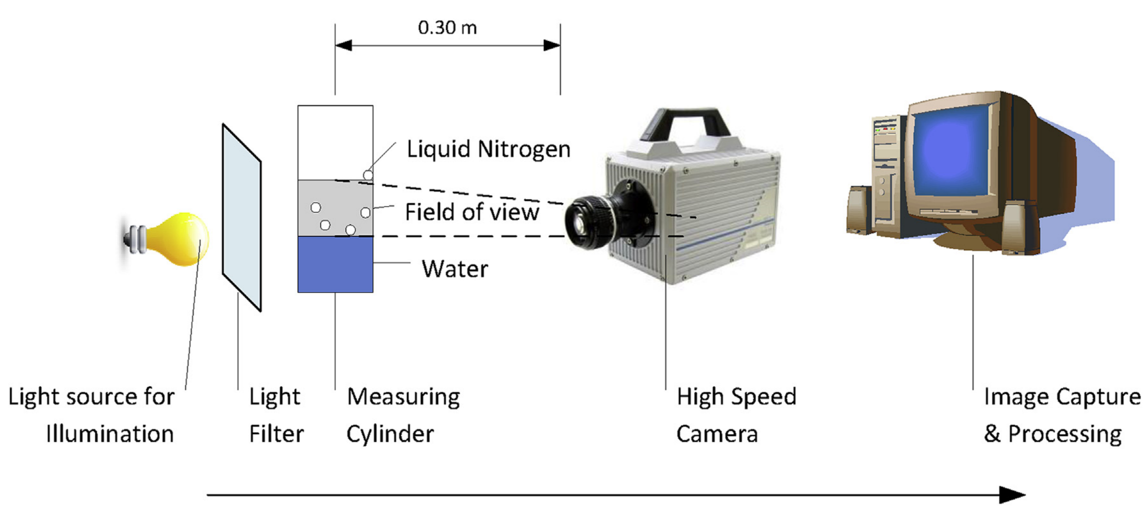

Fig. 1. Experimental setup for high speed flow visualization.