CFD SIMULATION OF LIQUEFIED NATURAL GAS (LNG) BEHAVIOR DURING TANK FILLING

FU FANG XIONG

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

SUPERVISOR DECLARATION

"I hereby declare that I have read this thesis and in my opinion this report in sufficient in terms of scope and quality for the award of the degree of Bachelor of Mechanical Engineering (Thermal-Fluids)."

Signature: ……………………………..
Supervisor: ……………………………..
Date: ……………………………..

CFD SIMULATION OF LIQUEFIED NATURAL GAS (LNG) BEHAVIOR DURING TANK FILLING

FU FANG XIONG

This report is submitted in partial fulfillment of degree requirement for the award of Mechanical Engineering (Thermal-Fluids)

Faculty of Mechanical Engineering
Universiti Teknikal Malaysia Melaka

JUNE 2013

DECLARATION

"I hereby declare that the work in this report is my own except for summaries quotations which have been duly acknowledged."

Signature: ………………………

Author: ………………………

Date: ………………………

ACKNOWLEDGEMENT

It would not have been possible without the kind support and sincere guidance of many individuals and organizations within this Project Sarjana Muda (PSM) period. Author would like to extend sincere thanks to all of them.

First and foremost author offering sincerest gratitude to PSM supervisor, Mr Mohamad Shukri Bin Zakaria, who guide and support author with his patience and knowledge whilst allowing the room of mistake for author. Author also would like to express his special gratitude and thanks to entire PSM Organization Faculty of Mechanical Engineering UTeM for management of PSM to all the students. Great deals appreciated go to author's parent for giving author the strength to perform responsibilities and encouragement when facing problems.

ABSTRACT

Rollover happen when two stratified Liquefied Natural Gas (LNG) reaches density equilibrium and release large amount of vapor in short period causing over-pressurization of the storage tank. The novelty of the present work is to study the relationship between stratification effect with the independent parameter of filling rate, density condition and initial depth of heel LNG by using Computational Fluids Dynamic (CFD) software. A brief of LNG in term of formation, composition, advantages and current LNG market were presented at the first section. Present study also focuses on the review of stratification, different composition effect, filling method and behavior, heat leakage and rollover in both numerical and experimental way. For validity, Koyama (2008)'s paper was selected to perform validation test by using ANSYS Fluent software and a relative percentage error of 8.76 was obtained showing well agreement between present study simulation with experimental result did by Koyama(2008). The independent parameters (filling rate, initial depth of heel LNG, and density condition) effect on stratification was discussed detailed at the result and discussion session. Generally, case study simulation result shows that lower filling rate, deeper height of heel LNG, and smaller initial density difference between two LNG are recommended to reduce stratification level. This present study was end with the conclusion of finding and recommendation of future study.

ABSTRAK

"Rollover" berlaku ketika dua LNG berlapis mencapai keseimbangan ketumpatan dan melepaskan jumlah wap yang besar dalam masa yang singkat menyebabkan tekanan dalam tangki simpanan melebihi maksimum had tekanan. Tujuan kajian ini adalah untuk mengaji hubungan antara stratifikasi dengan kadar mengisi, keadaan ketumpatan dan ketinggian awal LNG dalam tangki simpanan dengan menggunakan CFD. Kajian ini bermula dengan pengenalan tentang fomasi, kebaikan dan pasaran LNG sekarang. Seterusnya, kajian illmiah memberi tumpuan dalam stratifikasi, komposisi berbeza, cara mengisi, kebocoran haba dan haba dengan cara kajian numerik dan eksperimen. Kertas Koyama(2008) telah terpilih untuk melaksanakan ujian validasi dengan menggunakan perisian ANSYS Fluent dan kesilapan peratusan relative 8.76% telah diperolehi. Ini menunjukkan perjanjian baik antara simulasi kajian ini dengen keputusan eksperimen yang telah dilakukan oleh Koyama(2008). Kesan kadar mengisi, keadaan ketumpatan dan ketinggian LNG terhadap stratifikasi telah dibincangkan dalam sesi perbincangan. Secara umumnya, keputusan simulasi kajian menunjukkan bahawa kadar mengisi yang lebih rendah, ketinggian LNG yang lebih tinggi dan perbezaan ketumpatan yang kecil adalah dicadangkan untuk mengurangkan tahap stratifikasi Kajian ini akhir dengan kesimpulan dan cadangan untuk kajian masa depan.

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURE

LIST OF SYMBOLS

Fr	=	Froude Number, $\frac{U}{((\frac{\Delta\rho}{\rho a})\cdot g\cdot d^{0.5})}$
Ra_s	=	Solutal Rayleigh number, $\frac{g\beta_S H^3 \Delta C}{\nu D}$
Ra_T	=	Modified Thermal Rayleigh number, $\frac{g\beta_T H^4 q}{\alpha\nu k}$
ρ	=	Density, kg/m^3
μ	=	Viscosity, Pa.s
λ	=	Conductivity, W/mK
C_p	=	Specific heat, kJ/kgK
T	=	Temperature, ^0C
H	=	Height,m
D	=	Diameter,m

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 OVERVIEW

Liquefied Natural Gas (LNG), which is produced from the natural gas via various cooling process to the temperature of -160 ^{0}C at atmospheric pressure of 101kPa(Wang, 2009)., The composition of LNG is similar to natural gas since LNG is produced from natural gas. LNG is not a pure substance but formed by various hydrocarbons and non-hydrocarbon like methane, ethane, propane, butane, nitrogen, carbon dioxide, and etc(Younger, 2004). Typically, methane with chemical formula CH_4 exists with a high fraction within the natural gas if compared to other components but the composition of the natural gas can vary widely depend on the gas source(Kastner, 2005).Table 1.1 show typical composition of natural gas which makeup from large volume of methane (> 85%) along with the other component. Different composition of LNG with respect to country is shows at Table 1.2. Bintulu, Malaysia produced highest percentage of methane(91.2%) among the other country

Table 1.1: Typical Composition of Natural Gas. (Mokhatab, 2006).

Name	Formula	Volume(%)
Methane	CH_4	> 85
Ethane	C_2H_6	3-8
Propane	C_3H_8	1-2
Butane	C_4H_{10}	<1
Pentane	C_5H_{12}	<1
Carbon dioxide	CO_2	1-2
Hydrogen sulfide	H_2S	<1
Nitrogen	N_2	1-5
Helium	He	<0.5

Table 1.2: Composition of LNG in Different Terminal Locations (Yang, 2003)

Component, mole %	Das Island, Abu Dhabi	Whitnell Bay, Australia	Bintulu, Malaysia	Arun, Indonesia	Lumut, Brunei	Bontang, Indonesia	Ras Laffan, Qatar
Methane	87.1	87.8	91.2	89.2	89.4	90.60	89.6
Ethane	11.4	8.3	4.28	8.58	6.3	6.0	6.25
Propane	1.27	2.98	2.87	1.67	2.8	2.48	2.19
Butane	0.141	0.875	1.36	0.511	1.3	0.82	1.07
Pentane	0.001	-	0.01	0.02	-	0.01	0.04

The main objective introduction of LNG is to solve the problem of transportation and storage (Bossier, 2011). Conventionally, natural gas is transmitted to user from production plant by using insulated pipeline (Thomas & Dawe, 2003) and it is become a problem when there is a long distance transmission in term of costing and unmanageable pipeline work. LNG with the liquid volume 600 times smaller than its corresponding original volume provided a strongpoint for ease of storage and transportation by using tanker or ship (Chandler et al, 2002). Figure 1.1 shows the comparison between natural gas, LNG and Compressed Natural Gas (CNG) as well and the volume ratio of natural gas to LNG and CNG is 600:1:3.

During low period, LNG is stored at the isolated cryogenic storage tank at atmospheric pressure to serve the demand during peak periods (Flynn, 2005).

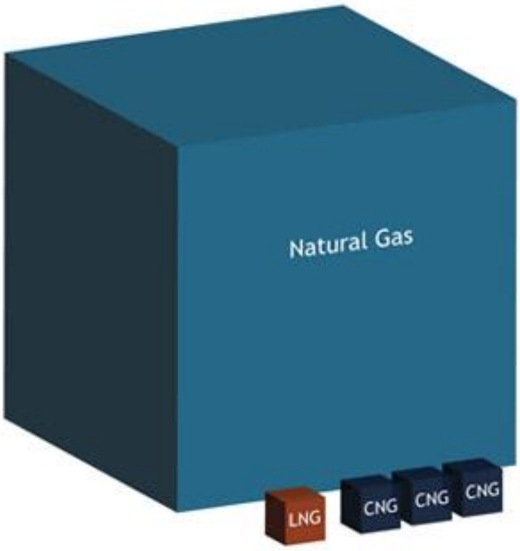

Figure 1.1:The Comparison of Volume Between Natural Gas, LNG and CNG. (Neptune, 2012)

Recent year, due to liberalization of global gas market, it leads to the whole gas market under transition from long term rigid contract to sort term contract. Besides that, diversification of LNG supply sources increase result in complicating reception terminal to handle and store the LNG inside separate tank according to its source respectively. To deal with greater variety of incoming LNG, the storage tank at reception terminal must be fully utilized by mixing varies type of LNG inside one tank to reduce costing and capital.(Versluijs, 2010) The consequence of mixing varies LNG qualities inside a storage tank is density stratification and in the end lead to serious safety concern named rollover.

1.2 PROBLEM STATEMENT

Rollover is a very importance safety concern inside the LNG storage tank. During tank filling, sudden mixing incoming LNG with residual LNG inside the storage tank will result in stratification of LNG due to inequality in term of density (Bates & Morrison, 1996). When stratified LNG come to equilibrium (density of two liquid become equality due to convection), the interface between two layer become unstable and mixes rapidly in the end. In this moment, liquid from the lower layer that is superheated gives off a large amount of vapor that rises to the surface, which may exceed the safety venting capability of tank and cause seriously damage. However, the effect of stratification can be minimized by using correct filling method depend on the circumstances. So present study is focus on evaluate and simulate the filling behavior to minimize the density difference (stratification) in order to reduce the consequence of rollover.

1.3 OBJECTIVE

1. To evaluate rapid pressure rise inside the LNG storage tank due to rollover.
2. To study and simulate behavior of LNG during tank filling.

1.4 SCOPE

1. Study of phenomenon when mixing 2 different density of LNG inside a tank.
2. Simulation of LNG behavior during tank filling in term of density by using Computational Fluid Dynamics (CFD).
3. Evaluation of the effect of residual LNG in different initial depth, density condition and filling rate to the stratification.

CHAPTER 2

LITERATURE REVIEW

2.1 OVERVIEW

Literature review for present study is focus on the stratification, LNG composition, filling method, rollover and heat leakage in order to provide the required knowledge and information to achieved the objectives.

2.2 STRATIFICATION

Shi et al (1993) presented his result as the migration of the interface and rapid mixing of the remaining fluid are the two stages have involved when mixing two stratified fluid during flow visualization experiments. Besides that, Shi et al (1993) stated that the base to side heat flux ratio provide significant contribution to rollover with the directly proportional relationship. Large base heat flux will balance the entrainment rates between two phase and lead to non-interface movement to approach density equilibrium, result in serious rollover phenomenon.

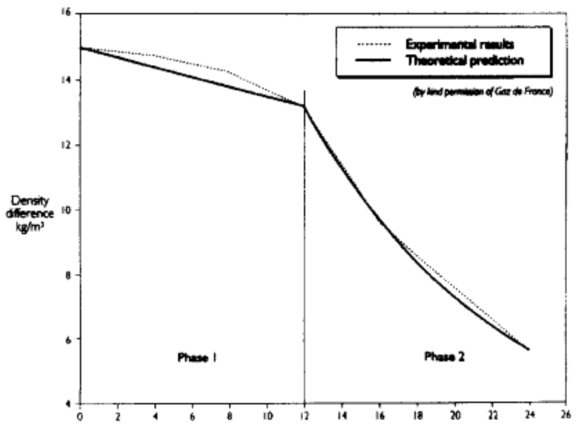

Figure 2.1: Density Difference Across An Interface (Bates & Morrison, 1996)

Study had presented by Bates & Morrison (1996) to modeling the behavior of stratified LNG on tank experimentally and mathematically. In his paper, he classified the evolution of stratification into two stages which is quiescent, stable phase (phase 1) and migrating interface. Bates & Morrison's result agreed with the result did by Shi et al (1993) by using flow visualization experiments. For mathematical modeling, governing equation was used and parametric solution is derived for phase 1 and a series of penetrative convection equation have been introduced in phase 2. The experimental result was compared to the mathematical model showing a good agreement. A small negative gradient of density different is showing in phase 1, but there is a sharp drop of density different when come into phase 2 and culminating in a rollover.(Bates & Morrison, 1996)

Tamura et al (1998) also study the effect of Froude number on the density profile during filling. Numerical result showed the directly proportional relationship between Froude number and density difference of LNG inside a tank. Tamura et al (1998) explained this behavior as the both y-axis momentum and filling rate increase due to increase in Froude number and resulting in large buoyancy effect. Therefore, low Froude number (low filling rate)during light fluid bottom filling provided large plume inertia force and well mixing mechanics between two fluids and reduced the density differences. Figure 2.2 shown the directly proportional relationship between Froude Number and the y-axis momentum(m) while Figure 2.3shown that increase in Froude number will results in increase of flow rate(q) directly proportional

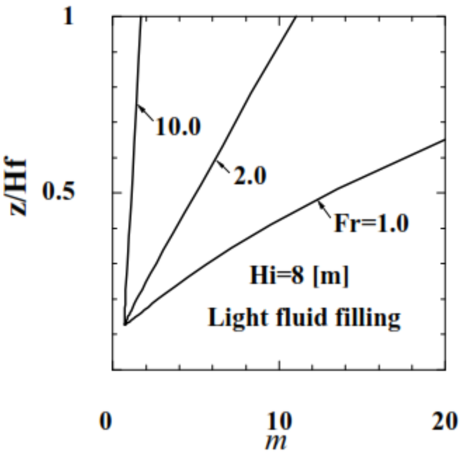

Figure 2.2: The relationship between Froude number with vertical momentum (m) (Tamura et al. 1998)

.

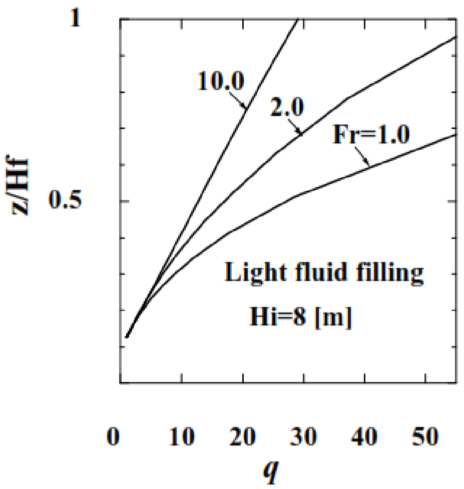

Figure 2.3: The relationship between Froude number with filling flow rate (q). (Tamura et al. 1998)

2.3 DIFFERENCE COMPOSITION

Bashiri (2006) had presented his paper which dealing with theoretical framework for rollover analysis and a case study of La Spezia Rollover incident was simulated. Bashiri (2006) emphasized the present of nitrogen inside LNG is the main contribution to density different due to its volatility (largest k-value among the other hydrocarbon component) and auto-stratification will occurs with conditions of more than 1% of nitrogen is present in LNG. Bashiri (2006) research go parallel with the research did by Hands (1998) which stated that evaporation of the other hydrocarbon component only result in slightly saturation temperature rises but not really much contribute to the liquid density change.

Lom (1974) in his book claimed that the impurity of LNG is the main reason contributed to stratification and stratification is not going to happen in a pure methane LNG. Existing of other compound like nitrogen, ethane and propane etc lead to stratification due to its respective volatility of each compound. Besides that, incompletely mixing the cargo LNG with heel LNG takes place of contribution to stratification. Lom (1974) also claimed that none of the filling method (top or bottom) provided a guarantee against stratification to occur but high discharge filling nozzle. Limit the range of LNG composition is the best way to reduce occurrence of stratification.

Maeda & Shirakama (2007) summarized some factors that contribute to stratification. These factors including tank dimension, position of feed and inlet, density difference of LNG, heel level, feed rate and heat transfer. Eulerian-Eulerian homogeneous multiphase option of CFX was used to analyze tank filling characteristic and behavior. From the density contour obtained by CFX, buoyancy effect drive the lighter density which filling from the bottom to reach the surface and forming a slow convective flow in the tank. The volume fraction contour showing the directly proportional relationship between final density different with initial density difference, feed rate and inversely proportional relationship with heel depth.

2.4 FILLING BEHAVIOR

Experiment and numerical method have been used by Tamura et al (1998) to study bottom filling behavior with two different density- light fluid and heavy fluid. A replica tank with sixty times smaller than the original tank was used in experiment.

Laser visualization was introduced to study the mixing behavior of two miscible liquid and density profile obtained numerically.

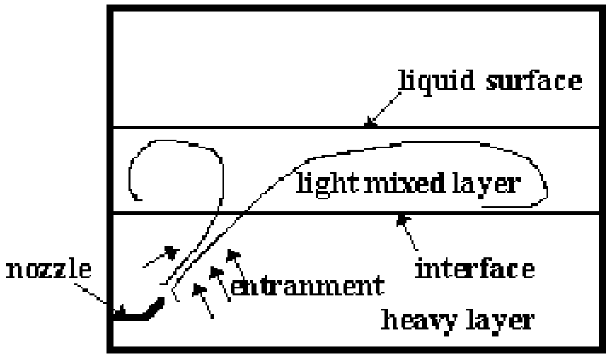

Figure 2.4: Mixing Mechanism In Light Fluid Filling. (Tamura et al. 1998)

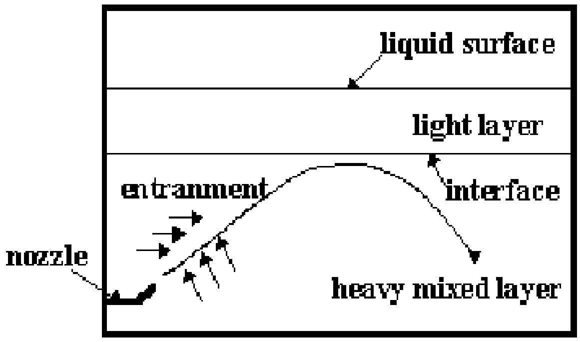

Figure 2.5: Mixing Mechanism in Heavy Fluid Filling. (Tamura et al. 1998)

Paper presented that entrainment of plume is the key to mix both new fluid and old fluid for both cases (light and heavy). For light fluid filling (Figure 2.4), due to both momentum and buoyancy of plume, light fluid exit from nozzle mixes, entrained, and penetrated with heavy fluid. For heavy fluid case (Figure 2.5), due to decrease in vertical momentum and gravitational force become large, heavy fluid's plume downward and unable to reach the lighter fluid even it reach at initial, LNG stratification occurs. Besides that, the position of the nozzle manipulated the probability of the occurrence of stratification. For light fluid filling, shorter the distance between nozzle outlet and tank bottom is preferable because lower unmixed layer can be vanish more easily due to natural convection. For heavy fluid filling, higher the distance must be introduced to increase the chance for heavy fluid's plume reach with light liquid surface, so stratification occur less.

Michael et al (2007) conducted a simulation of flow and process of water in a jet-mixed tank by using 3D URANS method. A comparison between CFD simulation, experimental data and other CFD result was present in term of jet velocity, nozzle diameter as well as nozzle angle. A nozzle with 45 degree incline position generated two circulation regions which provide good condition for mixing purpose if compare with 90 degree nozzle position which only provide a circulation area. In general, prediction mixing time result showing welcome to both experimental data and previous CFD result except the predicted concentration result of one probe location deviated from the experimental result.

2.4.1 CFD Simulation

Matice (1997) made use of computational fluid dynamics (CFD) software (volume of Fluid method) to simulate top filling behavior of two study case in order to understand the liquid-air interface inside the bottle when filling. The first case is study about the optimization of filling line to minimized occurrence of splash by using diving nozzle which location 1 cm above the bottom of the vial. For second cases, evaluation of bottle design was done by CFD simulation to elimination of foaming via redesign the bottle shape.

Chang et al (2010) validated a set of pervious density-gradient driven air ingress stratified flow experiment data by using ANSYS Fluent 2008 simulation to demonstrate the intrusion of heavy fluid into light fluid. Simulation was carried out to calculate front head speed and compared with result obtained by Richardson method when using air as the heavier fluid and helium as lighter gas. As a result, a percentage error of 4.8% between experiment and simulation result showed.

2.5 ROLLOVER

Flynn (2005) defined rollover as a phenomenon in which heat leak contribute the bottom portion of the liquid become superheated and spontaneously migrates to the surface with a large amount of vapor. Generally, heat is release to tank vapor