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IMPACT OF INLET SLUG FLOW ON HORIZONTAL GAS-LIQUID SEPARATOR

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By

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IMPACT OF INLET SLUG FLOW ON HORIZONTAL GAS-LIQUID SEPARATOR

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November 2018

Chairman : Professor Thomas Choong Shean Yaw, PhD, P.Eng
Faculty : Engineering

This study has demonstrated that the current sizing criteria for a gas-liquid separator commonly used in the industry maybe inadequate. The sizing criteria has not taken into account the inlet flow pattern and fluid hydrodynamics inside the separator. In this study, the inlet flow pattern was showed to have significant impact in the separator sizing and the fluid hydrodynamics inside the separator. The experiment was conducted using a test rig consists of a horizontal gas-liquid separator operating at 45 °C. The liquid was constantly fed at 430 mL/min while the gas flowrate was adjusted to meet the requirement of inlet momentum from 200 to 2500 Pa. The liquid and gas phase used in the experiment were water and air, respectively. Experimental results demonstrated that the inlet flow was slug flow for inlet momentum of 200 to 1500 Pa, and the Mandhane's map could be used to predict the flow pattern.

Computational Fluids Dynamics (CFD) has demonstrated its function as an essential tools to simulate hydrodynamic inside the separator. However, the standard approach for Volume of Fluids (VOF) does not able to model the hydraulic jump in the inlet slug flow and additional User Define Function (UDF) using normal distribution equation was used at the inlet boundary to simulate the hydraulic jump. Another advantage was demonstrated using CFD in this study is the complex calculation such as kinetic energy of turbulence can be solved easily. Realizable $k - \varepsilon$ turbulence model has provided good agreement with experimental result and is recommended for this type of application.

At inlet momentum of 800 Pa and lower, the sloshing does not occurred in the separator and the Souders-Brown constant from the guidelines is still valid for gas phase section sizing for horizontal gas-liquid separator which provided acceptable

low level liquid carryover at gas phase. For inlet momentum of 1000 Pa and higher, the impact of inlet slug flow initiated the separator sloshing phenomena. Sloshing was found to increase the liquid carryover in the gas phase. Kinetic energy of turbulence at liquid phase shall be kept below 15 m^2/s^2 to avoid any sloshing in the separator. The sloshing phenomena in the separator can be avoided by lowering the liquid level in the separator which is a very economical approach in retrofitting gas-liquid separator and to avoid expensive separation internals. Additional recommended liquid level from this study was suggested in the gas-liquid separator sizing in order to mitigate the sloshing phenomena in the separator.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

KESAN OLEH ALIRAN SLUG DI DALAM PEMISAH GAS-CECAIR MENDATAR

Oleh

LEE SIONG HOONG

November 2018

Pengerusi : Professor Thomas Choong Shean Yaw, PhD, P.Eng
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Kajian ini telah menunjukkan kriteria saiz semasa pemisah gas-cecair yang biasa digunakan dalam industri yang berdasarkan momentum masuk, pemalar Souders-Brown dan masa pengekalan cair adalah tidak mencukupi. Kriteria saiz semasa tidak mengambil kira corak aliran masuk dan hidrodinamik cecair di dalam pemisah akibat daripada kesan corak aliran masuk. Dalam kajian ini, corak aliran masuk (inlet slug flow) menunjukkan kesan yang ketara dalam saiz pemisah dan hidrodinamik bendalir di dalam pemisah. Eksperimen ini dijalankan dengan menggunakan rig ujian dua fasa atmosfera yang terdiri daripada pemisah gas-cecair mendatar dan operasi pada suhu 45 ^{O}C. Aliran cecair yang digunakan adalah 430 mL/min manakala aliran gas disesuaikan dengan memenuhi syarat momentum masuk dari 200 hingga 2500 Pa. Fasa cecair dan gas yang digunakan dalam eksperimen adalah air dan udara masing-masing. Keputusan eksperimen telah membuktikan bahawa inlet slug flow berlaku di antara momentum masuk 200 hingga 1500 Pa dan peta Mandhane menunjukkan persetujuan terbaik dengan hasil eksperimen.

Dynamics Fluid Dynamics (CFD) telah menunjukkan fungsinya sebagai alat penting untuk mensimulasikan hidrodinamik dalam pemisah. Walau bagaimanapun, pendekatan standard untuk Volume Fluid (VOF) tidak dapat memodelkan lompatan hidraulik dalam inlet slug flow dan User Define Function (UDF) menggunakan persamaan edaran normal digunakan di sempadan masuk untuk mensimulasikan lompatan hidraulik. Kelebihan lain ditunjukkan dengan menggunakan CFD dalam kajian ini adalah pengiraan kompleks seperti tenaga kinetik turbulen boleh diselesaikan dengan mudah. Model turbulen k-ε yang boleh diperolehi telah memberikan persetujuan yang baik dengan keputusan eksperimen dan disyorkan untuk jenis aplikasi ini.

Pada momentum masuk 800 Pa dan ke bawah, sloshing tidak berlaku dalam pemisah dan pemalar Souders-Brown untuk fasa gas masih berada di dalam lingkungan garis panduan yang ditetapkan, oleh itu, pengalihan cecair pada fasa gas berada di tahap rendah yang boleh diterima. Fenomena sloshing berlaku akibat dripada inlet slug flow untuk momentum masuk 1000 Pa ke atas. Tenaga kinetik turbulens pada fasa cair hendaklah disimpan di bawah 15 m2/s2 untuk mengelakkan fenomena sloshing di dalam pemisah. Fenomena sloshing di dalam pemisah boleh dielakkan dengan menurunkan tahap cecair di dalam pemisah dan merupakan pendekatan yang sangat ekonomik semasa pengubahsuaian pemisah gas-cair dan mengelakkan penggunaan pemisahan dalaman yang mahal. Tahap cecair tambahan yang dicadangkan dari kajian ini untuk pemisah gas-cecair dapat melenyapkan fenomena sloshing di pemisah.

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This thesis was submitted to the Senate of the Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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LIST OF ABBREVIATIONS

API	American Petroleum Institute
ASTM	American Society for Testing and Materials
BS&W	Basic Sediment and Water
CFD	Computational Fluid Dynamics
CPU	Central Processing Unit
DIN	German Institute for Standardization
GPSA	Gas Processors Suppliers Association
GVF	Gas Volume Fraction
ISO	International Organization for Standardization
K	Souders-Brown Constant, $\frac{m}{s}$
LPH	Liter per Hour
mLPM	milliliter per Minute
MMSCF	Million Standard Cubic Feet
MMSCM	Million Standard Cubic Meter
N	Normal
PETRONAS	Petroliam Nasional Berhad
PISO	Pressure-Implicit with Splitting of Operators
PTTEP	PTT Exploration and Production
PVC	Polyvinyl Chloride
RANS	Reynolds Average Navier-Stokes
Re	Reynolds Number
RNG	Renormalized Group
UDF	User Define Function
VOF	Volume of Fluids

ρ_m	Mixture density, $\frac{kg}{m^3}$
u_m	Mixture velocity, $\frac{m}{s}$
v	Terminal gas velocity or maximum gas velocity, $\frac{m}{s}$
ρ_g	Gas density, $\frac{kg}{m^3}$
ρ_l	Liquid density, $\frac{kg}{m^3}$

CHAPTER 1

INTRODUCTION

1.1 Upstream Production

A typical schematic diagram of an upstream oil and gas production facility is shown in Figure 1.1. The equipment or systems at a production facility are integrated, each having their own functionality. For example, a compression system is used to increase the gas pressure to its delivery pressure, glycol system is designed for gas dehydration which remove water moisture from the gas stream and amine system is installed to remove the acidic components in the gas such as carbon dioxide and hydrogen sulfide (Arnold, 2007; Arnold & Stewart, 1999). One of the basic yet essential equipment is separator. Separators are commonly found in pre and post treatment, primarily used to remove free liquid from the gas stream (Arnold & Stewart, 2008b). A receiving separator can be found in an upstream section which is in series arrangement for gas pretreatment and crude stabilization. These separators receive and separate incoming fluids using gravity separation (Arnold & Stewart, 2008a). In these separators, bulk phases such as gas and liquid will be separated before undergoing further treatment at the downstream processing. Therefore, under performance of a separator will directly impact its downstream equipment (Arnold & Stewart, 2008b).

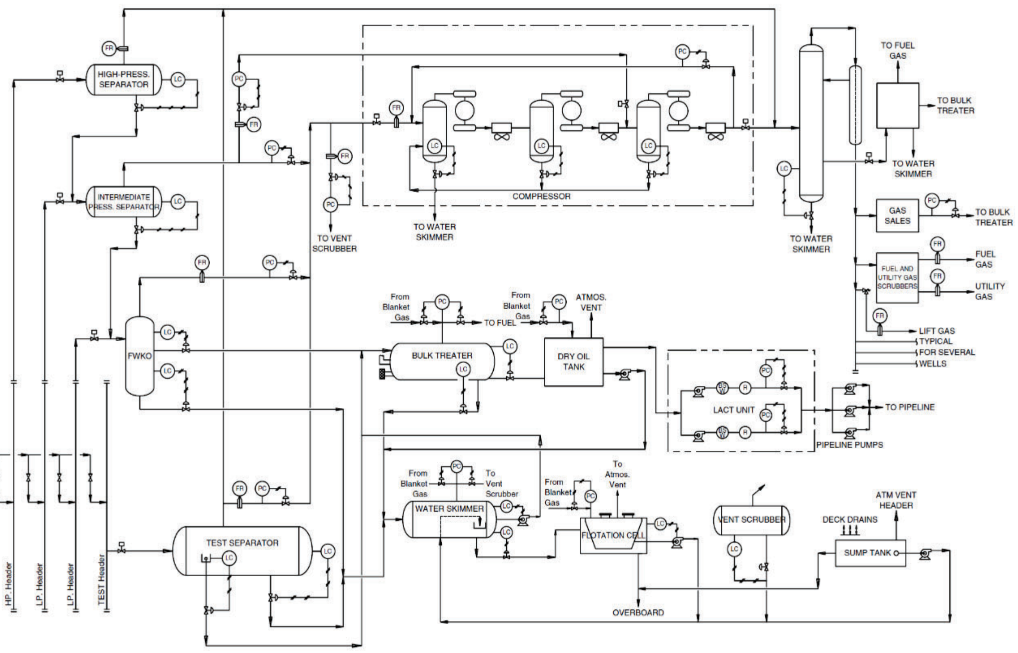

Figure 1.1: Typical Schematic Diagram of a Production Facility
(Arnold & Stewart, 2008a)

1.2 Gas-Liquid Separators in Production

The primary function of a gas-liquid separator is to separate bulk phases using gravitation concept. To ensure a separator to perform as it is, Hansen (2001) has proposed several important criteria for sizing:-

1. Provide sufficient time to allow the immiscible gas and liquid phases to separate by gravity.
2. Provide sufficient time to allow for the coalescence of gas bubbles in the bulk liquid phase to improve degassing.
3. Allow for variation in the flow rates of gas and liquid without adversely affecting separation efficiency. This variation in flow rates is often represented using inlet momentum.

These sizing criteria will be further explained in Section 2.2.

A separator shall be robust in handling incoming fluids. The incoming fluids from a subsurface flowline enters a separator at different momentum and the magnitude of the incoming fluids are subjected to reservoir pressure, fluids mixture and overall production plan. An ideal separator is designed to withstand and dampen this inertia or commonly known in the industry as inlet momentum.

The performance of a separator is measured in amount of liquid carryover to the gas phase. Liquid carryover in the gas phase from a separator is one of the major issue in an upstream production facility. A liquid carryover to the compressor will lead to imbalance of the impeller and excessive vibration. An excessive liquid carryover may eventually lead to mechanical failure in the long run (Prabhudharwadkar et al., 2010; Ezzell, 2017). In gas processing system such as glycol and amine system, an excess condensate carryover will cause uncontrollable foaming in the contactors (Ezzell, 2017). Moreover, excessive liquid carryover in the flaring system will damage the flare tip and lead to more downtime due to maintenance work and incomplete combustion.

Information on hydrodynamics inside a separator is crucial to unlock the uncertainties in sizing a new separator or retrofitting an existing unit. Besides physical experiment study, numerical simulation can be used to model the phenomena happened in a separator. Computational Fluid Dynamics (CFD) can be a useful tool to review the design or retrofitting of a separator (Laleh et al., 2011b).

1.3 Problem Statement

As mentioned by Bothamley (2013a), many two-phase separators in the oil and gas industry were reported to underperform, most likely due to inadequate sizing methodology. One of the weakness associated with the current sizing methodology is the lack of quantification of feed flow, where the impact of flow pattern on the performance of a separator is not incorporated.

The current practice, provided by vendor, in rectifying excessive liquid carryover in a gas-liquid separator is often by the installation of advanced separation internals such as inlet device, vane type coalescer and demisting cyclones. However, this approach involves a high retrofitting cost and also adds more weight to the equipment which is unfavorable to the production operators. Note that an investment of millions of ringgit is often required for a major retrofitting (Chin, 2015a; Chin et al., 2015; Morillo et al., 2016; Bothamley (2017)).

In order to achieve a simpler and a more economical solution, a deeper understanding on the behavior of inlet flow and its impact on hydrodynamics inside a separator is necessary. However, there are very few literature reporting the details of inlet flow and its hydrodynamics inside a separator. A detailed study in this particular field is required to realize this approach. The focus of this research will be on slug flow as it is the most common flow pattern encountered in two-phase flow. As mentioned recently by Bothamley (2017), a proper quantification of feed inlet and a proper understanding of hydrodynamics is crucial to prevent liquid carryover in a separator.

1.4 Objectives

This project was designed to study the inlet flow behavior and hydrodynamics inside a separator. A bare separator was used here in order to achieve a simple and economical solution. The specific objectives of this research were as follows:-

1) To study the type and impact of inlet flow on liquid surface movement inside a separator using an in-house gas-liquid separation test rig.
2) To simulate the impact of inlet flow on liquid surface movement inside a separator using CFD simulation – ANSYS Fluent.
3) To simulate and predict the performance of a gas-liquid separator using an experimental validated CFD model. The performance of a separator is quantified using the amount of liquid carryover. A practical guideline for mitigating the liquid carryover is proposed.

1.5 Scope of the Research

In this study, the focus is on a two-phase or gas-liquid separator as experimental study of a three phase separator involves liquid-liquid phase separation which may require the use of actual crude oil. The Gas Volume Fraction (GVF) for the incoming fluids mixture is in the range of 0.90 to 0.99 where inlet slug flow occurred. The GVF range adopted in this research is commonly found in most separators for both associated and non-associated gas fields. Most of the first separator for associated and non-associated gas fields in this region have operating temperature no more than 45 ºC. In this study, experiments were performed at atmospheric pressure and air, and water were used as gas and liquid phase. Furthermore, this work focused on the primary sizing criteria for horizontal gas-liquid separator, in which droplet size of carryover was not included. The droplet size is an additional aspect covered by the secondary sizing criteria for separator. However, this criteria is not mandatory in the industry standard. The experiment in this study was designed to achieve the American Petroleum Institute (API) 17 N Technology Readiness Level 3 for research to prove feasibility where concept was proved by experimental or simulation. (Banke, 2017 and Grethe et. al., 2016)

REFERENCES

Abbruzzese G., Gómez, M. and Cordero-Gracia, M. 2018. Unstructured 2D Grid Generation Using Overset-Mesh Cutting and Single-Mesh Reconstruction. *Aerospace Science and Technology* 78: 637-647.

Aker Solutions. 2010. *Process Datasheet - HP Separator (V-110).* Aker Solution Document No EP-CPP-10-DS-0001.

Al-Hadhrami, L. M., Shaahid, S. M., Tunde, L. O. and Al-Sarkhi, A. 2014. Experimental Study on the Flow Regimes and Pressure Gradients of Air-Oil-Water Three-PhaseFlow in Horizontal Pipes. *The Scientific World Journal*: 1-11.

Alves, G. E. 1954. Co-current Liquid/Gas Flow in a Pipeline Contractor. *Chemical Enigneering Program*: 449-456.

Alves, M. V. C., Waltrich, P. J., Gessner, T. R., Falcone, G. and Barbosa Jr, J. R. 2017. Modelling Transient Churn-Annular Flows in a Long Vertical Tube. *International Journal of Multiphase Flow* 89: 399-412.

Ambrosia, V. S. 2018. *How to Run Fluent Benchmark Cases. Retrived* 9 December 2018 from https://support.esss.co/hc/en-us/articles/205250955-How-to-Run-Fluent Benchmark-Cases

American Petroleum Institute. 2008. *Specification for Oil and Gas Separators.* 8th ed. American Petroleum Institute: Washington D. C.

Andreussi, P., Minervini, A. and Paglianti, A. 1993. Mechanistic Model of Slug Flow in Near-Horizontal Pipes. *AIChE Journal* 39: 1281-1291.

ANSYS Fluent. 2016. *Theory Guide Release 17.2.* SAS IP Inc.

Arnold, K. and Stewart, M. 2008a. *Surface Production Operations: Design of Oil Handling Systems and Facilities.* 3rd ed. United State of America: Gulf Professional Publishing.

Arnold, K. E. 2007. *Petroleum Engineering Handbook.* 1st ed. Texas: Society of Petroleum Engineers.

Arnold, K. and Stewart, M. 1999. *Surface Production Operations: Design of Gas-Handling Systems and Facilities.* 2nd ed. United States of America: Gulf Professional Publishing.

Arnold, K. and Stewart, M. 2008b. *Gas-Liquid and Liquid Liquid Separators.* United States of America: Gulf Professional Publishing.

Austrheim, T., Gjersten, L. H. and Hoffmann, A. C. 2007. Is the Souders-Brown Equation Sufficient for Scrubber Design? An Experimental Investigation at Elevated Pressure with Hydrocarbon Fluids. *Chemical Engineering Science* 62: 5715-5727.

Austrheim, T., Gjertsen, L. H. and Hoffmann, A. C. 2008a. Experimental Investigation of the Performance of a Large-Scale Scrubber Operating at elevated Pressure on Live Natural Gas. *Fuel* 87: 1281-1288.

Austrheim, T., Gjertsen, L. H. and Hoffmann, A. C. 2008b. An Experimental Investigation of Scrubber Internals at Condition of Low Pressure. *Chemical Engineering Journal,* Volume 138: 95-102.

Baker, O. 1954. Simultaneous Flow of Oil and Gas. *Oil and Gas Journal* 53: 185-195.

Banke, J. 2017. *Techonology Readiness Demistified. Retrived* 8 December 2018 from https://www.nasa.gov/topics/aeronautics/features/trl_demystified.html

Banks, R. B. and Bhavamai, A. 1965. Experimental Study of the Impingement of a Liquid Jet on the Surface of a Heavier Liquid. *Journal of Fluid Mechanics* 23: 229-240.

Barth, T. J. and Jespersen, D. C. 1989. *The Design and Application of Upwind Schemes on Unstructured Meshes.* American Institute of Aeronautics and Astronautics.

Bonzanini, A., Picchi, D., Ferrari, M. and Poesio, P. 2018. Velocity Profiles Description and Shape Factors Inclusion in a Hyperbolic, One-Dimensional, Transient Two-Fluid Model for Stratified and Slug Flow Simulations in Pipes. *Petroleum.*

Boschee, P. 2014. Sand Separation in Surface Facilities for Heavy and Extra Heavy Oil. *Oil and Gas Facilities* October: 25-29.

Bothamley, M. 2013a. Gas/Liquid Separator: Quantifying Separation Performance. *Oil and Gas Facilities* August: 21-29.

Bothamley, M. 2013b. Gas/Liquid Separator - Part 2: Quantifying Separation Performance. *Oil and Gas Facilities* October: 35-47.

Bothamley, M. 2013c. Gas/Liquid Separator - Part 3: Quantifying Separation Performance. *Oil and Gas Facilities* December: 34-47.

Bothamley, M. 2017. *Quantifying Oil/Water Separation Performance in Three-Phase Separators - Part 2. Retrived* 9 June 2018 from https://spe.org/en/print-article/?art=2835

Brauner, N. and Ullmann, A., 2002. Modelling of Pase Inversion Phenomenon in Two-Phase Pipe Flows. *International Journal of Multiphase Flow* 28: 1177-1204.

Campbell, J. M. 1992. *Gas Conditioning and Processing.* 7th ed. Oklahoma: Campbell Petroleum Series.

Cheslak, F. R., Nicholls, A. J. and Sichel, M. 1969. Cavities Formed on Liquid Surfaces by Impinging Gaseous Jets. *Journal of Fluid Mechanics* 36: 55-63.

Chin, R. 2015a. The Savvy Separator Series: Part 2 - The Effect of Inlet Geometries on Flow Distribution. *Oil and Gas Facilities* August: 26-31.

Chin, R. 2015b. The Savvy Separator Series: Part 4 - The Ghosts of Separators: Past, Present and Future. *Oil and Gas Facilities* December: 18-23.

Chin, R., Asperen, V. V., Reisenberg, J. M. and McVinnie, G. 2015. The Savvy Separator Series: Part 3 - Scrubber Debottlenecking October: 22-27.

Chisholm, D. 1967. A Theoretical Basis for the Lockhart-Martinelli Correlation for Two-Phase Flow. *Internaltional Journal of Heat and Mass Transfer* 10: 1767-1778.

Escue, A. and Cui, J. 2010. Comparison of Turbulence Models in Simulating Swirling Pipe. *Applied Mathematical Modelling* 34: 2840-2849.

Ezzell, G. 2107. *Transtech Fabrication.* Retrived 25 May 2018 from https://www.transtechfabrication.com/news/liquids-carry-over-elimination-for-high-liquid-loads.

Farzad, B.-T. and Hamed, Z. 2010. Presumed PDF Modeling of a Reactive Two-Phase Flow in a Three Dimensional Jet-Stabilized Model Combustor. *Energy Conversion and Management* 51: 225-234.

Frankiewicz, T. and Lee, C. M. 2002. *Using Computational Fluid Dynamics (CFD) Simulation to Model Fluid Motion in Process Vessels on Fixed and Floating Platforms.* San Antonio: Society of Petroleum Engineres Inc.

Gas Processors Suppliers Association. 2004. *GPSA Engineering Data Book.* 12th ed. Oklahoma: Gas Processors Suppliers Association.

Ghaffarkhah, A., Shahrabi, M. A., Moraveji, M. K. and Eslami, H. 2016. Application of CFD for Designing Conventional Three Phase Oilfield Separator. *Egyptian Journal of Petroleum* 26: 413-420.

Govier, G. W. and Aziz, K. 1972. *The Flow of Complex Mixtures in Pipes.* New York: Van Nostrand-Reinhold.

Govier, G. W. and Omer, M. M. 1962. The Horizontal Pipeline Flow of Air-Water Mixtures. *The Canadian Journal of Chemical Engineering*: 93-104.

Guha, D., Ramachandran, P. A. and Dudukovic, M. P. 2008. Evaluation of Large Eddy Simulation and Euler-Euler CFD Models for Solids Flow Dynamics in a Stirred Tank Reactor. *Wiley InterScience* 54: 766-778.

Gupta, A. and Kumar, R. 2007. Three-Dimensional Turbulent Swirling Flow in a Cylinder: Experimentals and Computations. *International Journal of Heat and Fluid* 28: 249-261.

Grethe, K., Thomas, M., Monica, B. and Ute, B. *TRL (Technology Readiness Level) Assessment of DREAM (Dose-related Risk and Effects Assessment Model) to Qualify its Use for Modelling of Produced Water and Drilling Discharges.* Stavanger: Society of Petroleum Engineres Inc.

Hansen, E. W. M. 2001. Phenomeological Modelling and Simulation of Fluid Flow and Separation Behaviour in Offshore Gravity Separators. *PVP-Vol.431, Emerging Technologies for FLuids, Structures and Fluid-Structure Interaction*: 23-29.

Höhne, T. and Hänsch, S. 2015. A Droplet Entrainment Model for Horizontal Segregated Flows. *Nuclear Engineering and Design* 286: 18-26.

Hoogendoorn, C. J. 1959. Gas-liquid flow in horizontal pipes. *Chemical Engineering Science* 9: 205-217.

Jack, 2009. *Oil & Gas Process Engineering.* Retrived 21 May 2018 from http://www.oilngasprocess.com/oil-handling-surfacefacilities/two-phase-oil-and-gas-separation/horizontal-two-phase-separator.html

Jawarneh, A. M., Tlilan, H., Al-Shyyab, A. and Ababneh, A. 2008. Strongly Swrling Flows in a Cylindrical Separator. *Minerals Engineering* 21: 366-372.

Jerzy, H. 2010. Phase Inversion in Liquid-Liquid Pipe Flow. *Flow Measurement and Instrumentation* 21: 284-291.

Johannessen, T. 1972. A Theoretical Solution of the Lockhart and Martinelli Flow Model for Calculating Two-Phase Flow Pressure Drop and Hold-Up. *International Journal of Heat and Mass Transfer* 15: 1443-1449.

Karadimou, D. P., Papadopoulos, P. A. and Markatos, N. C. 2017. Mathematical Modelling and Numerical Simulation of Two-Phase Gas-Liquid Flows in Stirred-Tank Reactors. *Journal of King Saud University - Science*: 1-9.

Katapodis, L. 1977. Oil and Gas Separation Theory, Application and Design. *Society of Petroleum Engineers*: 85-89.

Kharoua, N., Khezzar, L. and Saadawi, H. 2013. CFD Modelling of a Horizontal Three-Phase Separator: A Population Balance Approach. *American Journal of Fluid Dynamics*: 101-118.

Kim, S. E., Makarov, B. and Caraeni, D. 2003. A Muilti-Dimensional Linear Reconstruction Scheme for Arbitrary Unstructured Grids. *American Institute of Aeronautics and Astronautics*: 1-11.

Labus, T. L. and Aydelott, J. C. 1971. *Gas-Jet Impingement Normal to a Liquid Surface.* Washington D. C.: National Aeronautics and Space Administration.

Laleh, A. P., Svrcek, W. Y. and Monnery, W. D. 2011a. Computational Fluid Dynamics Simulation of Pilot-Plant-Scale Two-Phase Separators. *Chemical Engineering and Technology* 34: 296-306.

Laleh, A. P., Svrek, W. Y. and Monnery, W. D. 2011b. Design and CFD Studies of Multiphase Separators - A Review. *The Canadian Journal of Chemical Engineering*: 1-14.

Laleh, A. P., Svrek, W. Y. and Monnery, W. D. 2012. Computational Fluid Dynamics – Based Study of an Oilfield Separator - Part I: A Realistic Simulation. *Oil and Gas Facilities* December: 57-68.

Laleh, A. P., Svrek, W. Y. and Monnery, W. D. 2013. Computational Fluid Dynamics – Based Study of an Oilfield Separator - Part II: An Optimum Design. *Oil and Gas Facilities* February: 52-59.

Lienhard, J. H., 1968. Capillary Action in Small Jets Impinging on Liquid Surfaces. *Journal of Basic Engineering,* pp. 137-138.

Li, H., Li, J., Zhou, Y., Liu, B., Sun, B., Yang, D. and Fan, X. 2017. Phase Split Charaterictics of Slug and Annular Flow in a Dividing Micro-T-Junction. *Experimental Thermal and Fluid Science* 80: 244-258.

Lin, S., Chin, Y., Wu, C., Lin, J. and Chen, Y. 2012. A Pressure Correction-Volume of Fluid Method for Simulation of Two-Phase Flows. *International Journal for Numerical Methods in Fluids*: 181-195.

Lockhart, R. W. and Martinelli, R. C. 1949. Proposed Correlation of Data for Isothermal Two-Phase, Two-Component Flow in Pipes. *Chemical Engineering Progress*: 38-48.

Mandhane, J. M., Gregory, G. A. and Aziz, K. 1974. A Flow Pattern Map for Gas-Liquid Flow in Horizontal Pipes. *Int. J. Multiphase Flow* 1: 537-553.

Mata, C., Pereyra, E., Trallero, J. L. and Joseph, D. D. 2002. Stability of Stratified Gas-Liquid Flows. *International Journal of Multiphase Flow* 28: 1249-1268.

McCabe, W. L., Smith, J. C. & Harriott, P., 1993. *Unit Operations of Chemical Engineering.* 5th ed. Singapore: McGraw Hill Inc.

Miyoshi, M., Doty, D. R. and Schmidt, Z. 1988. Slug-Catcher Design for Dynamic Slugging in an Offshore Production Facility. *SPE Production Enigneering*: 563-573.

Moncho-Esteve, I. J., Gasque, M., González-Altozano, P. and Palau-Salvador, G. 2017. Simple Inlet Devices and Their Influence on Thermal Stratification in a Hot Water Storage Tank. *Energy and Building* 150: 625-638.

Morillo, E., Asperen, V. V. and Sander, B. 2016. The Savvy Separator Series: Underperforming Gas Scrubbers - How to Fix Them and How to Avoid Them April: 16-23.

NOV. 2018. *Inlet Separator - Process Data Sheet.* NOV Document No. 1526-NV-20-P-DS-00001.

Obara, T., Bourne, N. K. and Field, J. E. 1995. Liquid-Jet Impact on Liquid and Solid Surfaces. *Wear*: 388-394.

Ozan, A. Y. and Yüksel, Y. 2010. Simulation of a 3D Submerged Jet Flow Around a Pile. *Ocean Engineering* 37: 819-832.

Park, I. R., Kim, K. S. and Van, S. H. 2009. A Volume-of-Fluid Method for Incompressible Free Surface Flows. *International Journal for Numerical Methods in Fluids* 61: 1331-1361.

Pertamina. 2012a. *Process Data Sheet for Test Separator (SNO-V-1104 & SNO-V-1204).* Pertamina Document No SNO-R-DS-10-004 .

Pertamina. 2012b. *Process Data Sheet for Production Separator (SNO-V-1102 & SNO-V-1202).* Pertamina Document No SNO-R-DS-10-003.

PETRONAS Technical Standards. 2015. *PTS 16.52.09: Two Phase Gas and Liquid Separator.* Kuala Lumpur: PETRONAS Technical Standards.

Piela, K. et al. 2008. On the Phase Inversion Process in an Oil-Water Pipe Flow. *International Journal of Multiphase Flow* 34: 665-677.

Pozzetti, G., Jasak, H., Besseron, X., Rousset, A. and Peters, B. 2019. A Parallel Dual-Grid Multiscale Approach to CFD-DEM Couplings. *Journal of Computational Physics* 378: 708-722.

Prabhudharwadkar, D. M., More, R. Z. and Iyer, K. N. 2010. Experimental Study of Liquid Carryver in a Separator Drum. *Nuclear Engineering and Design* 240: 76-83.

PTTEP. 2012. *PTTEP Engineering General Specification (PEGS) - Process Sizing Criteria.* Thailand: PTT Exploration and Production Public Company Limited.

Rajagounder, R., Mohanasundaram, G. V. and Kalakkath, P. 2015. A Study of Liquid Sloshing in an Automotive FUel Tank under Uniform Acceleration. *Engineering Journal* 20: 71-85.

Rizzi, A. W. and Inouye, M. 1973. Time-Split Finite-Volume Method for Three-Dimensional Blunt-Body Flow. *American Institute of Aeronautics and Astronautics Journal* 11: 1478-1485.

Rosler, R. S. and Stewart, G. H. 1968. Impingement of Gas Jets on Liquid Surfaces. *Journal of Fluid Mechanics* 31: 163-174.

Shell. 2007. *Gas/Liquid Separators - Type Selection and Design Rules.* The Netherlands: Shell Global Solutions International B. V.

Shih, T. H. 1997. Some Developments in Computaional Modeling of Turbulent Flows. *Fluid Dynamics Research* 20: 67-96.

Shih, T. H., Liou, W. W., Shabbir, A., Yang, Z. and Zhu, J. 1994. *A New k-ε Eddy Viscosity Model for High Reynolds Number Turbulent Flows - Model Development and Validation.* Cleveland: Institute for Computational Mechanics in Propulsion and Center for Modeling of Turbulence and Transition, Lewis Research Center.

Sidi-Ali, K. and Gatignol, R. 2010. Interfacial Friction Factor Determination using CFD

Simulations in a Horizontal Stratified Two-Phase Flow. *Chemical Engineering Science* 65: 5160-5169.

Souders, M. and Brown, G. G. 1934. Design of Fractionating Columns - I. Entrainment and Capacity. *Industrial and Engineering Chemistry*: 98-103.

Spedding, P. L., Cooper, R. K. and McBride, W. J. 2003. A Universal Flow Regime Map for Horizontal Two-Phase Flow in Pipes. *Developments in Chemical Engineering and Mineral Processing* 11: 95-106.

Sun, X., Zhang, Z. and Chen, D.R. 2017. Numerical Modelling of Miniature Cyclone. *Powder Technology* 320: 325-339.

Swanborn, R. A., Koene, F. and De Graauw, J. 1995. New Separator Internals Cut Revamping Costs. *Journal of Petroleum Technology* 47: 688-692.

Taitel, Y. and Dukler, A. E. 1976. A Model for Predicting Flow Regime Transitions in Horizontal and Near Horizontal Gas-Liquid Flow. *AIChE Journal* 22: 47-55.

Tunstall, R., Laurance, D., Prosser, R. and Skillen, A. 2017. Towards a Generalised Dual-Mesh Hybrid LES/RANS Framework with Improved Consistency. *Computers & Fluids* 157: 73-83.

Total. 2012. *General Specification Process - Process Sizing Criteria.* Total.

Valencia, A., Paredes, R., Rosales, M., Godoy, E. and Ortega, J. 2004. Fluid Dynamics of Submerged Gas Injection into Liquid in a Model of Copper Converter. *International Communications in Heat and Mass Transfer* 31: 21-30.

Vallee, C., Lucas, D., Beyer, M., Pietruske, Schutz, P. and Carl, H. 2010. Experimental CFD Grade Data for Stratified Two-Phase Flows. *Nuclear Engineering and Design* 240: 2347-2356.

Wai, L. L., Valente, H., Nguyen, D. T., Thiam, T. W., Zhao, Y. and Vivek, K. P. 2016. Experimental Study of the Effect of Pressure and Gas Density on the Transistion From Stratified to Slug Flow in a Horizontal Pipe. *International Journal of Multiphase Flow* 85: 196-208.

Zheng, D., He, X. and Che, D. 2007. CFD Simulation of Hydrodynamic Characteristics in a Gas-Liquid Vertical Upward Slug Flow. *International Journal of Heat and Mass Transfer* 50: 4151-4165.

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LIST OF PUBLICATIONS

Lee Siong Hoong, Thomas S.Y. Choong, Luqman Chuah Abdullah, Mus`ab Abdul Razak, Ban Zhen Hong. Experimental and CFD Modelling: Impact of the Inlet Slug Flow on the Horizontal Gas–Liquid Separator. Energies (Q2), 2019, (Accepted)

Lee Siong Hoong, Thomas S.Y. Choong, Luqman Chuah Abdullah, Mus`ab Abdul Razak, Ban Zhen Hong. Impact of Incoming Flow Momentum on Hydrodynamics of a Horizontal Gas-Liquid Separator. Key Engineering Materials (Scopus), 2019, (Accepted)

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