The University of Nottingham
UNITED KINGDOM · CHINA · MALAYSIA

Agunlejika, Ezekiel O. and Langston, Paul A. and Azzopardi, Barry J. and Hewakandamby, Buddhika N. (2016) Subatmospheric boiling study of the operation of a horizontal thermosyphon reboiler loop: Instability. Applied Thermal Engineering, 109 (A). pp. 739-745. ISSN 1873-5606

Subatmospheric boiling study of the operation of a horizontal thermosyphon reboiler loop: Instability

Ezekiel O. Agunlejika, Paul A. Langston*, Barry J. Azzopardi, Buddhika N. Hewakandamby

Manufacturing and Process Technologies Research Division, Faculty of Engineering,
University of Nottingham, NG7 2RD, United Kingdom

Abstract

Distillation and chemical processing under vacuum is of immense interest to petroleum and chemical industries due to lower energy costs and improved safety. To tap into these benefits, energy efficient reboilers with lower maintenance costs are required. Here, a horizontal thermosyphon reboiler is investigated at subatmospheric pressures and low heat fluxes. This paper presents detailed experimental data obtained using Wire Mesh Sensor in a gas-liquid flow with heat transfer as well as temperatures, pressures and recirculation rates around the loop. Flow regimes which have been previously identified in other systems were detected. The nature of the instability which underpins the mechanisms involved and conditions aiding instability are reported. Churn flow pattern is persistently detected during instability. The nature of the instability and existence of oscillatory churn flow are interconnected.

Keywords: Horizontal thermosyphon reboiler, Geysering instability, Subatmospheric boiling, Start-up, Wire Mesh Sensor, Two-phase heat transfer

*Corresponding author: P.Langston@nottingham.ac.uk (P. Langston) Tel.: +44 115 951 4177; fax: +44 115 951 4115. ezekiel_agunlejika@mail.com (EO Agunlejika)

1 Introduction

Distillation is still one of the major units for separations in the chemicals and oil refining industries. It is also one of the largest users of energy. It is only in providing more efficient equipment in this area that energy savings will be made. It must be remembered that a distillation column consists not only of the column itself but also of the associated reboiler and condenser, the providers of vapour and liquid to the column. Improved design of these associated units will yield energy savings. One way to achieve improvements is by better understanding of their operation. A majority of the reboiler operate as thermosyphons, liquid is driven through the heat exchanger via a density difference created by heat input to the system. At the outlet of the exchanger there is usually a two-phase gas-liquid mixture with a lower density than the liquid descending from the distillation column. This density difference drives the flow. Thermosyphon reboilers have lower operating and maintenance costs than other reboiler types due to their simplicity and the absence of a mechanical pump. They are characterized by high heat transfer rates and low fouling tendencies, can be operated over a range of pressures and have proven to be adequate for heavy heat duties in petroleum and nuclear industries. Thermosyphon reboiler usage is fundamentally attractive because of the high heat fluxes. This imply a smaller heat transfer area and hence capital expenditure and also lower process liquid inventory compared to other reboilers as reported by Japikse et al. (1973). Also horizontal thermosyphon reboilers have been judged, through research, to be superior in thermal performance to vertical thermosyphon and kettle reboilers (Yilmaz, 1987). This is due to their higher circulation, local boiling temperature differences and heat transfer rates. Notwithstanding the merits, the presence of two-phase flow initiates complications. Researchers and designers have to consider many aspects including pressure drop, flow regime prediction, realistic boiling curves, and flow instabilities (McKee, 1970).

Horizontal thermosyphon reboilers are much more effective at low temperature differences than kettle and vertical thermosyphon units. Vertical thermosyphons are also less attractive than horizontal type when heat transfer area requirements are large due to mechanical considerations (e.g. distillation column height). Fluids with moderate viscosity boil better in horizontal thermosyphon than in vertical units. It is possible to use low-finned and enhanced boiling tubes on the shell side of horizontal thermosyphon reboilers. The vertical height of the riser between the horizontal thermosyphon and the column discharge nozzle allows for very flexible hydraulic design. The static head requirements are lower for horizontal thermosyphon reboilers than for vertical units. And because of their high circulation rates, the temperature rise for boiling fluid across horizontal thermosyphon reboilers is lower than that for kettle reboilers. Yilmaz (1987) reports that this leads to higher local boiling temperature differences and higher heat transfer rates for horizontal thermosyphon. Their size is not limited with respect to length of tubes and weight; thus the requirements for high surface area are in their favour. They handle the process fluid on the shell side; a scheme which many applications favour, particularly where the heating fluid has fouling tendency. They also offer easier access for mechanical cleaning of tubes by pulling the bundle as noted by Collins (1976).

In industry, the advantages of operating such equipment under vacuum, such as in low pressure distillation include: higher thermodynamic efficiency; reduced energy consumption; processing of heat sensitive materials at low temperature and achieving better separation. The low temperatures will allow cheaper materials of construction to be used (Benson et al., 2004). Nowadays, many applications in distillation are looking to use subatmospheric pressure operation to lower energy costs and improve safety (Alane and Heggs, 2007). Distillation under vacuum is also a commonly desired process in the chemical industry for extraction of essential oils, deodorisation of vegetable oils and purification and drying of chemicals. This is because there are favourable advantages over atmospheric pressure distillation which include: (1) use of lower process temperatures as a result of reduction in boiling points and hence shorter time of thermal exposure of the distillate so that thermally sensitive substances, like vitamin and hormones, can be processed easily, (2) reduction of energy consumption as a result of lowered boiling point, (3) increase in relative volatility of materials resulting in higher production rates, (4) change in position of the azeotropic point enables separation of hard-to-separate materials, (5) reduction of oxidation losses of the feed stock, and (6) reduction in stripping steam requirements for de-odourisation process of oil due to increased specific volumes (of steam), enhanced agitation and stirring of the oil. However, vacuum operation makes the thermosyphon system more susceptible to instabilities due to lowered system pressure and this initiates oscillatory flow. The improved vaporization rate results in high vapour mass flux, which was noted by Benson et al. (2004), makes the subatmospheric pressure boiling systems prone to instability.

These instabilities are magnified by decreasing: system pressure; mass flow rate; inlet resistance and inlet subcooling and by increasing: riser height (Durga Prasad et al., 2007). Of all the few articles published on thermosyphon under vacuum, none is centred on horizontal thermosyphon reboiler. This paper presents experimental data conducted on a horizontal thermosyphon reboiler loop at low heat fluxes and using Wire Mesh Sensor reports the nature of the instability and existence of interconnected oscillatory churn flow.

2 Experimental arrangements

2.1 Flow facility

The present work was carried out in an upgraded version of the facility employed by Hills et al. (1997) and Azzopardi and De Leon (2008) with detailed description presented by Agunlejika (2014) and Agunlejika et al. (2016). It is shown schematically in Figure 1. The essential features are: the reboiler (a horizontal shell and tube heat exchanger with 16 “U” tubes heated by steam condensing on their inside, the steam was provided by the laboratory steam main.), a riser, a vertical column and a pair of condensers in series. The riser and column are made of borosilicate glass (possibly from QVF) to permit observation of the flow.

Valve, V8, is placed in the recycle line to provide an inlet flow restriction to enhance stability. A gate valve has been selected for this purpose rather than a globe valve so as to give a smaller restriction when fully open. The facility is instrumented with an electromagnetic flow meter in the recycle line to monitor the recirculation rate, five absolute pressure transducers (P0-P4) and twelve T-type Ni-Cr thermocouples (T0-T11) with positions as indicted in Figure 1.

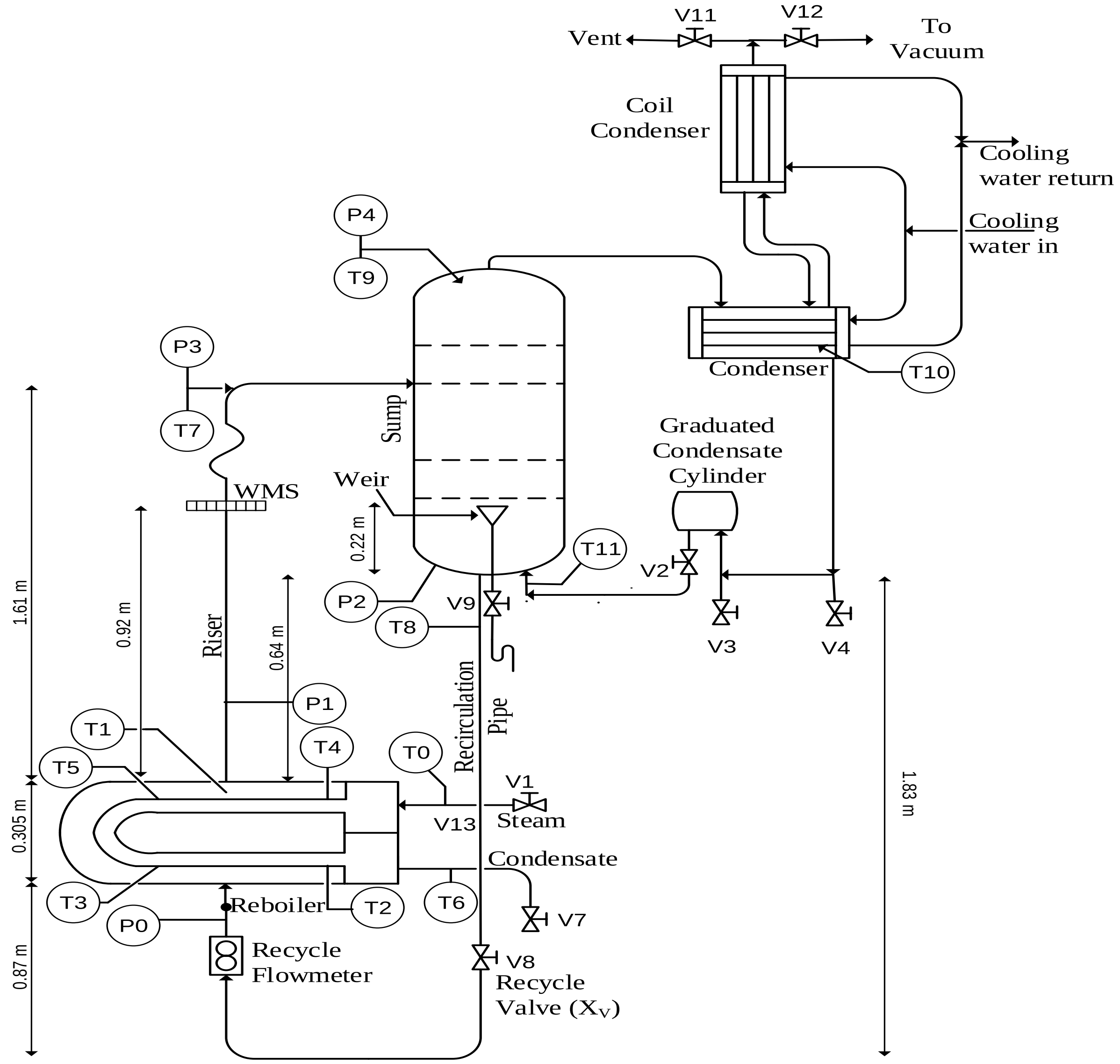


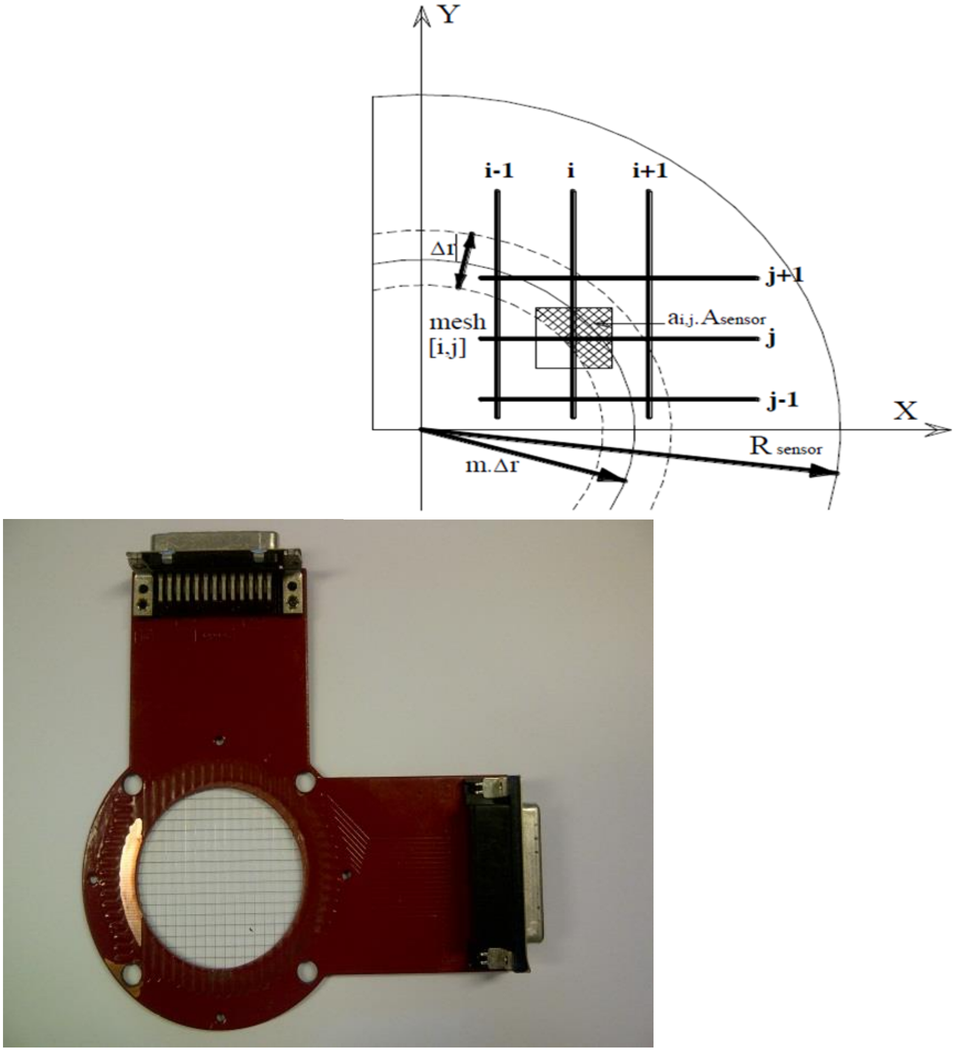
Figure 1. Horizontal thermosyphon reboiler loop with modifications for sub-atmospheric operation.

The continuous output of all of these is monitored at 100 Hz by a data logger connected to PC which also stores the data. In addition, the flow rate of the condensed heating steam and the condensed process fluid are measured over a timed interval. The accuracy of the measurements have been assessed to be: pressure, ±2%; temperature ±1%; recirculation rate ±4%. Apart from the upgrade in instrumentation relative to that employed by Hills et al. (1997) and Azzopardi and de Leon (2008) the other major change in the facility for its use in the present work is the provision of valves and connections which enable vacuum to be applied to the process side.

2.2 Wire Mesh Sensor

The Wire-Mesh Sensor (WMS) is a high speed imaging technique which can be used to quantify the location of the phases with high spatial and temporal resolution of the flow based on the relative permitivity measurements made at the wire crossing points. The principle is based on a matrix-like arrangement of the measuring points whereby the wire mesh subdivides the flow channel cross-section into a number of independent sub regions, where each crossing point represents one region as in Figure 2(b). Two arrays of wires; transmitters and receivers, are stretched along chords of a cross-section with a small axial separation, 1.5 mm, between them and the arrays are orthogonal to each other. The measuring cycle involves, one of the transmitter wires being activated successively while all the others are kept at ground potential. All the receiver wires are sampled in parallel and the collected raw data were processed offline. The output reading of a wire mesh sensor is in the form of a data matrix V (i, j, k) representing the voltage measured at each (i, j) crossing point with $i \in$ (1,...,0.16) and $j \in$(1,...,0.16) and at a given time step k. These voltage readings are proportional to the relative permittivity of two-phase mixture ε_m according to Da Silva et al. (2010) from $\varepsilon_m(i,j,k) = exp\left[\left(\frac{V(i,j,k)-V^G(i,j)}{V^L(i,j)-V^G(i,j)}\right) ln\varepsilon_{r,L}\right]$ and the void fraction is estimated using gas and liquid relative permitivities $\varepsilon_{r,G}, \varepsilon_{r,L}$ and mixture measurements from $\alpha(i,j,k) = \frac{\varepsilon_{r,L}-\varepsilon_m(i,j,k)}{\varepsilon_{r,L}-\varepsilon_{r,G}}$.

One sensor was positioned in the 51 mm diameter riser, 18 pipe diameters above the top of the thermosyphon reboiler. The sensor used, shown in Figure 2(a), is a 16x16 wire configuration; i.e. 256 cross points which are equally spread over the cross section.



(a) (b)

Figure 2. The Wire-Mesh Sensor; (a) 16 x 16 configuration, (b) Weights coefficients for the cross-section averaging of local void fractions, Prasser et al. (2002)

Only 242 of these points are available for measurements because others are located outside the circular cross section. Each wire has a diameter of 0.12 mm. The spatial resolution is 3 mm which also equals the pitch of the wires. The technique has been tested by carrying out simultaneous measurements with other techniques, i.e., using Electrical Capacitance Tomography (Azzopardi et al., 2010), gamma-ray absorption (Sharaf et al., 2011), ultrafast X-ray tomography Zhang et al. (2013) and found to produce good agreement between the instruments.

2.3 Operational conditions and constraints

Prior to the operation of the facility at subatmospheric conditions, the process side liquid was degassed by vacuuming down to 0.35 bar. The facility was operated in close loop mode under sub-atmospheric pressure conditions in Table 1. The parameters that were varied were the steam pressure (which controls the heat flux), the recycle valve setting (which controls the inlet flow restriction and hence recycle flow rate), and overflow weir height (which alters the static liquid head and hence the subcooling). The steam pressure employed were in the range between 1.14 and 1.34 bar(a) for equivalent heat flux range between 9 and 17 kW/m^2. Recycle valve setting between 9.1 and 100 % of fully open were used. However, it is noted that a gate valve was used and so even when fully open it still constitutes a restriction. For steady state measurements the system was allowed to warm up for at least 1 hour to allow for the long term dynamic mode to be achieved from start-up before data were recorded. Also a step increase in heat flux was used to quantify the response of the system in circulation rate, temperature and pressure.

Table 1. Parameters for experimental conditionss

Parameter	**Value (Unit)**	**Symbol**
Operating pressures	0.35, 0.4, 0.5, 0.9, 1.013 bar(a)	P_O
Equivalent boiling points	72.5, 75.9, 81.4, 96.7 100 ºC	T_B
Utility steam pressures	1.14, 1.21, 1.28, 1.34 bar(a)	P_S
Equivalent heat fluxes	9, 11, 14, 17 kW/m^2	q
Equivalent saturated temperatures	103.3, 105.0, 106.7, 108.0 ºC	T_{sat}
Valve positions	0.091, 0.136, 0.182, 0.25, 0.5, 0.75, 1 (0 = fully shut, 1 = fully open)	X_V
Static liquid head	1.165 – 1.265 m	h_W

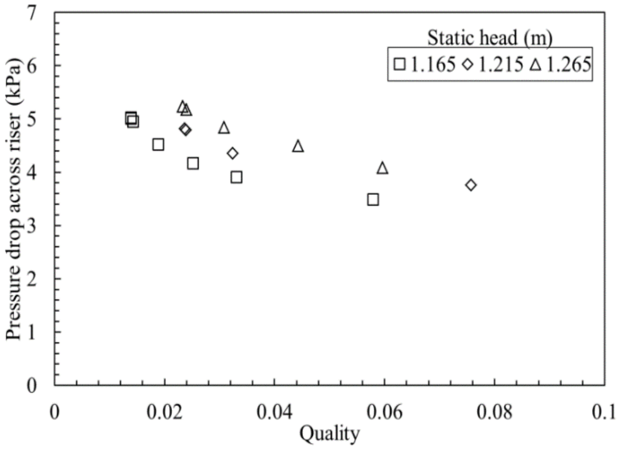
At each set condition, the pressures, temperatures and recirculation flow rate data were logged for 200 s at a frequency of 100 Hz. The WMS data was sampled at 1000 Hz for 30 s. Data were taken at different process side pressures, at atmospheric and subatmospheric conditions. The processed results were compared to clarify under which condition the system is most productive or susceptible to instability. The effects of heat flux and flow rate on vapour production rate are also investigated. A high speed camera has been employed to record the flow to assist in identifying phenomena and flow patterns.

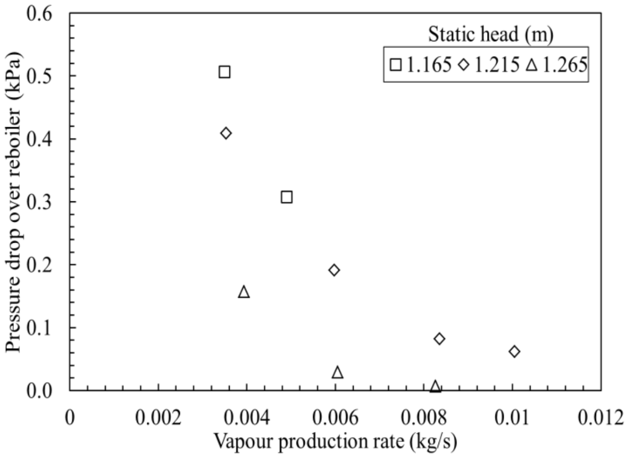
3 Results and discussion

Both process side and steam pressures strongly affect the performance of a thermosyphon reboiler. Quality and vapour production rate are used as measure of efficiency. Overall, vacuum operation improves vaporization and hence separation efficiency although instability is more pronounced.

3.1 Pressure drop over reboiler and across riser

The feedback relationship between pressure drop and flow rate makes it important to system stability. In Figure 3(a), pressure drop over reboiler as a function of vapour production rate shows the effect of static head. The plot shows general trend of decline with higher pressure drop at low static head. Pressure drop across riser as a function of quality with the effect of static head is shown in Figure 3(b). At low qualities, the pressure drop is mainly due to gravity. Hence the data appears to approach a minimum where the influence of friction begins. Looking at the data trend, pressure drop across the riser also depends on flow rate.



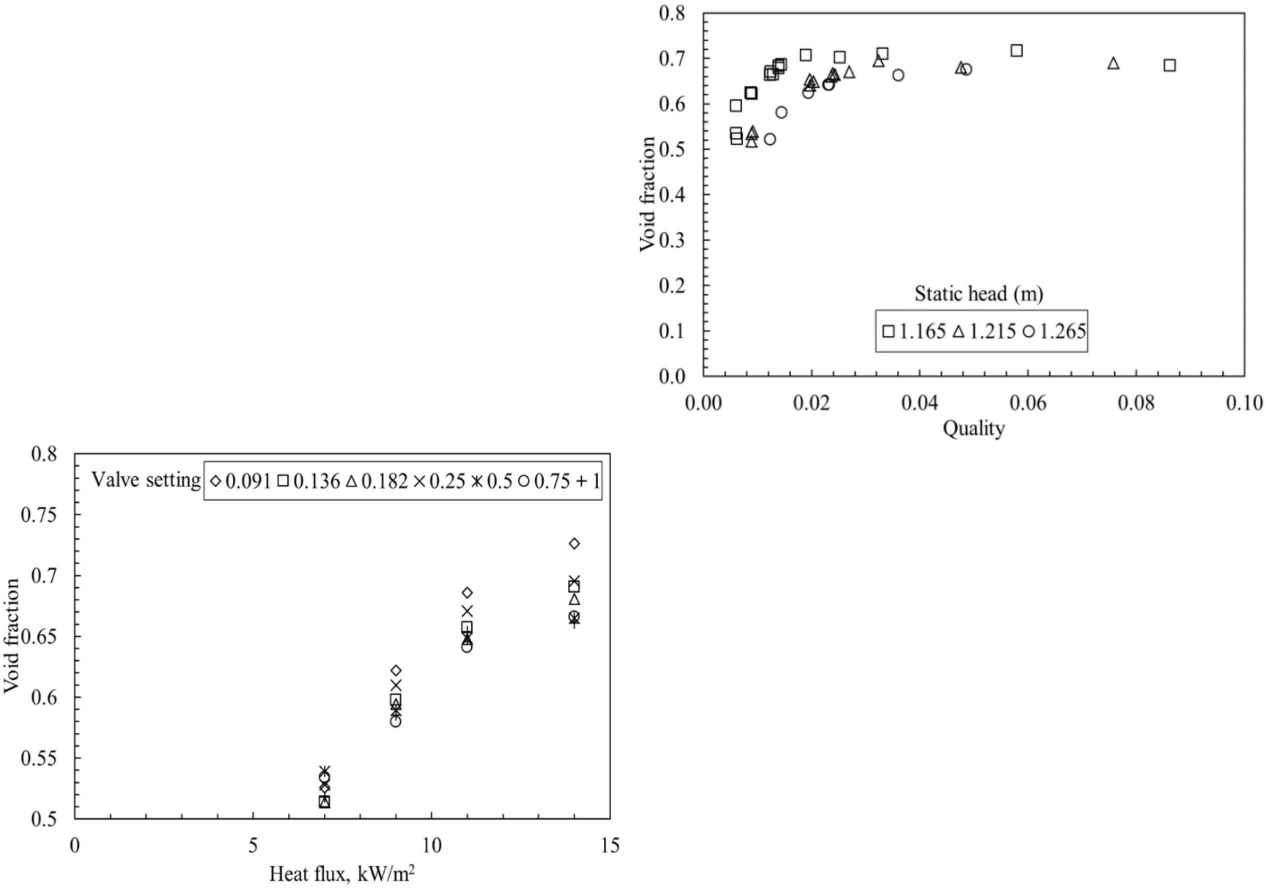


(a) (b)

Figure 3. Pressure drops over reboiler and across riser at different static head, process side pressure = 0.5 bar(a)

3.2 Void fractions and flow structures obtained using WMS

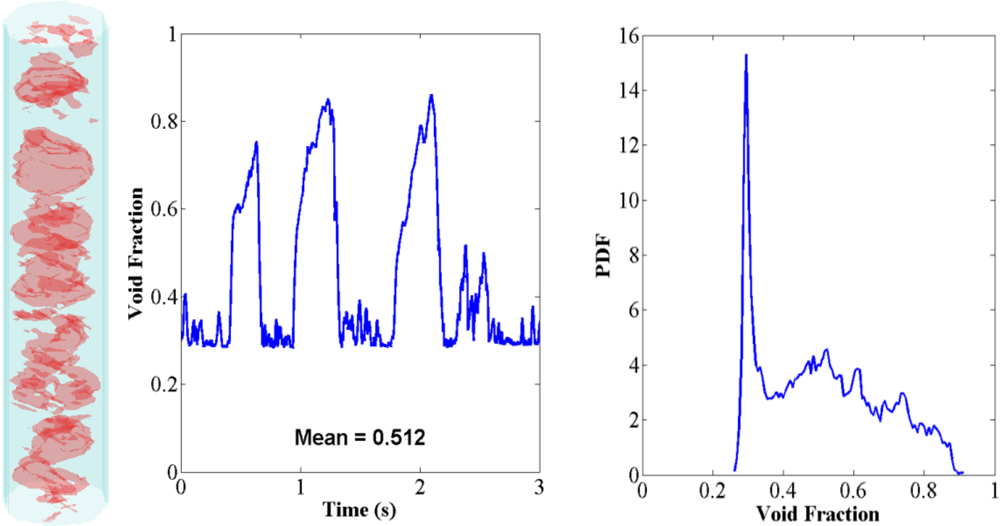
Time series cross-sectionally averaged void fraction as a function of quality and heat flux are shown in Figure 4(a & b). Void fraction increases with flow restriction and heat flux in Figure 4(a). This is expected since flow restriction reduces the transient heat load. The effect of static head on void fraction as a function of quality is seen in Figure 4(b).



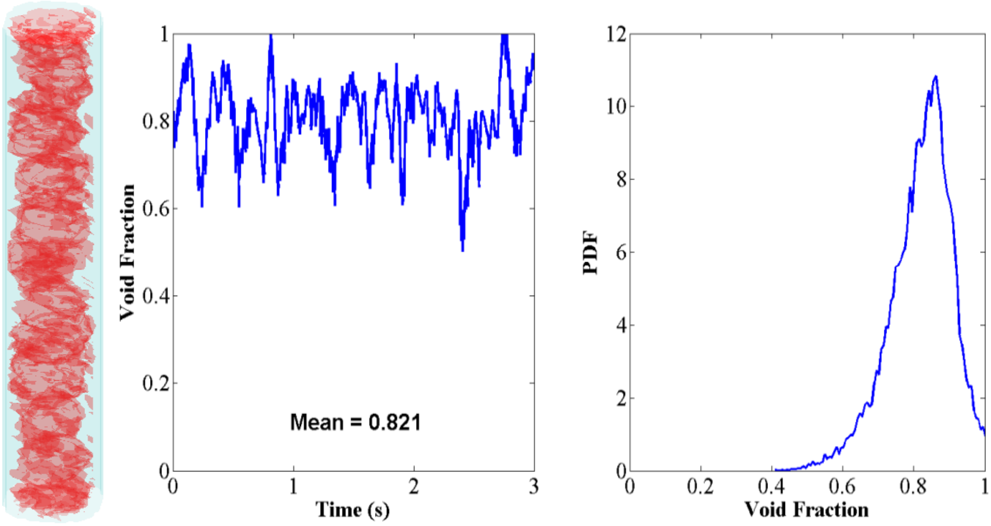
(a) (b)

Figure 4. Void fraction as a function of heat flux and quality

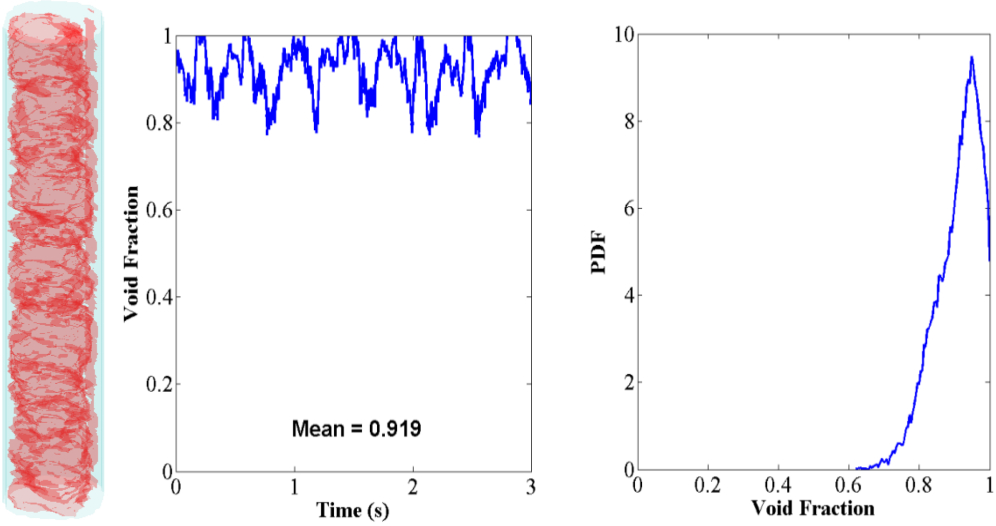
The two-phase flow patterns in the riser were observed and determined using the WMS and subsequent analysis on time sequences of the diametric void fraction distributions, the time series of cross-sectionally averaged void fraction and the Probability Density Function (PDF) of the latter are used in identifying the flow patterns. Example results for slug, churn and



Slug flow; valve setting = 1.0



Churn flow; valve setting = 0.5



Annular flow; valve setting = 0.182

Figure 5. Examples of void fraction and PDF of flow in the riser, heat flux 9 kW/m^2 (P_S = 1.14 bar(a)), static head = 1.265 m, process side pressure = 0.5 bar(a)

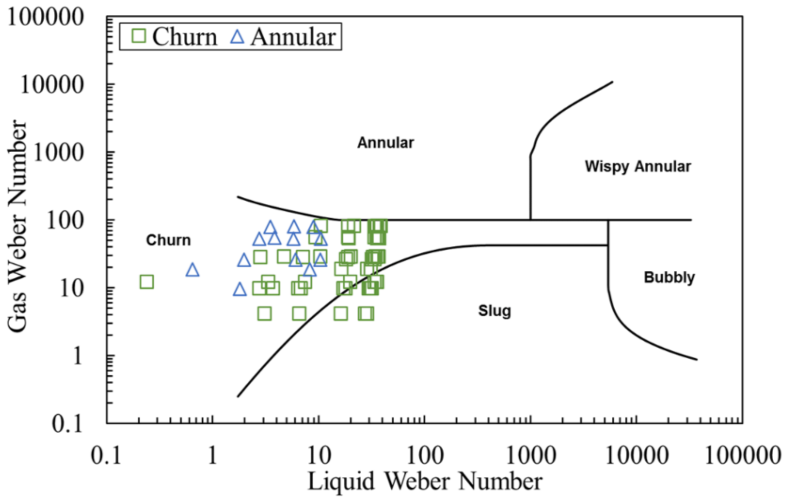


Figure 6. Two-phase flow pattern in riser on Hewitt and Roberts (1969) flow map, process side pressure = 0.5 bar(a)

annular flow are illustrated in Figure 5. The flow patterns determined for all the runs are shown in Figure 6 on a modified form of the Hewitt and Roberts (1969) flow map. The flow pattern for bulk of the data points is seen to be churn with occasional points at the churn-slug transition when the system is unstable. Flows at the churn-annular transition are observed mainly at moderate flow restrictions. Flow identified as annular are identified at high flow restriction when the system is stable. The shapes of the probability density functions (PDFs) and void fraction plots for the identified flow patterns in Figure 5 agree with the detailed description and classification by Costigan and Whalley (1997).

3.3 Observed characteristics of geysering instability

Agunlejika et al. (2016) presented and discussed experimental temperatures, pressures and flow rates data measured during the instability detected at atmospheric conditions. The results presented here concentrate on the instability inherent in the operation of the facility under sub-atmospheric conditions. At a process side pressure of 0.5 bar(a) and less, it was possible to apply a WMS which provided detail information about the flow in the riser. The WMS data were analysed to provide visual aid for the mechanism and characteristics of the instability. This can be divided into three stages as depicted in Figure 7 and follows the mechanism described by

Agunlejika et al. (2016)

Stage 1: The riser is filled with subcooled liquid and heating up is in progress. Small bubbles are soon seen but they are few. The flow is still except visible currents seen because of the difference in liquid density which show convection is taking place.

Stage 2: More bubbles are produced. The flow is still low until the bubbles generated begin to grow in size and coalesce to form Taylor bubbles and the flow is then essentially slug flow. As heating up continues, the Taylor bubbles start breaking up, the flow becomes chaotic and changes to churn. The resulting decrease in two-phase density results in recirculation.

Stage 3: The flow is fully developed and appears to be between churn and wispy annular flow. But it soon collapses within a period of 25 – 40 s, refilling with subcooled liquid takes place and the cycle starts over.

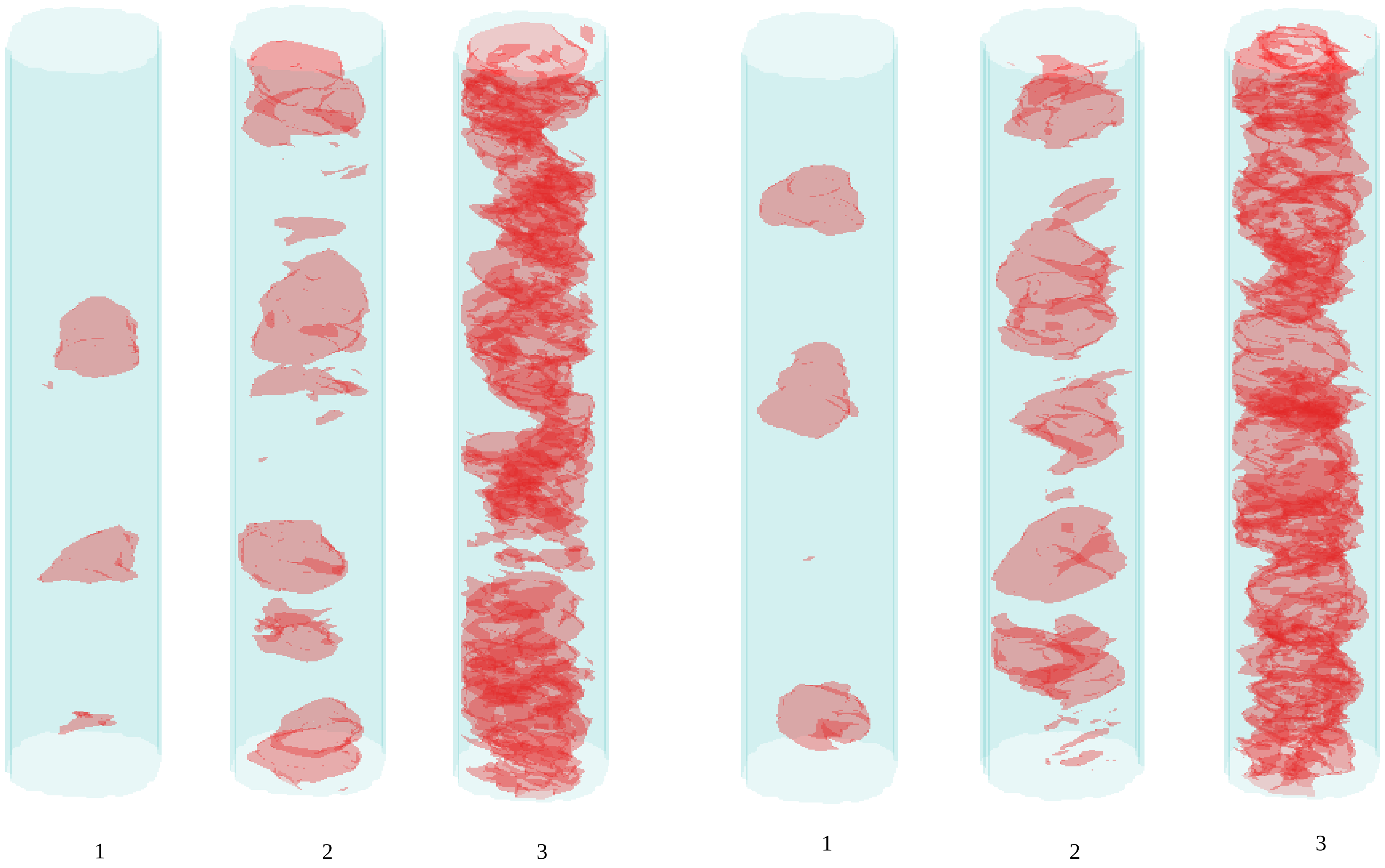


Figure 7. Pictorial view of geysering instability, heat flux 9 kW/m^2 (P_S = 1.14 bar(a)), Static head = 1.265 m, valve setting = 1.0, process side pressure = 0.5 bar(a)

4 Conclusions

Conclusions made from this study; Pressure drop across the riser shows dependence on flow rate. Using wire mesh sensor, void fraction data reveals the flows as fundamentally churn. However, slug and annular flows occur at very low and high heat fluxes respectively. Geysering instability is observed and documented. Gas pockets and flow pattern transition are involved. The mechanism is a mix of initiation, expulsion and refilling and exchange between heat transfer and flow rate in the system. Churn flow pattern is prevalently detected during instability. The nature of the instability and existence of oscillatory churn flow are interconnected.

References

Agunlejika, E.O., 2014. Experimental and simulation study of instabilities in a horizontal thermosyphon reboiler, PhD Thesis, Chemical Engineering. The University of Nottingham, Nottingham, United Kindgom.

Agunlejika, E.O., Langston, P., Azzopardi, B.J., Hewakandamby, B.N., 2016. Flow instabilities in a horizontal thermosyphon reboiler loop. Experimental Thermal and Fluid Science 78, 90-99.

Alane, A., Heggs, P.J., 2007. Experimental Study of Complex Two-Phase Instabilities for the Optimisation of Start-Up of a Vertical Thermosyphon Reboiler Operating Under Vacuum, *10th UK National Heat Transfer Conference , 10-11 September, 2007, Edinburgh, Scotland, UK.*

Azzopardi, B.J., Abdulkareem, L.A., Zhao, D., Thiele, S., da Silva, M.J., Beyer, M., Hunt, A., 2010. Comparison between Electrical Capacitance Tomography and Wire Mesh Sensor Output for Air/Silicone Oil Flow in a Vertical Pipe. Industrial & Engineering Chemistry Research 49, 8805-8811.

Azzopardi, B.J., De Leon, E., 2008. Instabilities in a Horizontal Thermosyphon Reboiler, HEAT 2008, Fifth International Confenrence on Transport Phenomena In Multiphase Systems, Bialystok, Poland.

Benson, H.R.S., Schnabel, T., Webb, D.R., Heggs, P.J., 2004. Operation of a Vertical Thermosiphon Reboiler Experimental Facility at Reduced Pressures. Chemical Engineering Research and Design 82, 445-456.

Collins, G.K., 1976. Horizontal Thermosyphon Reboiler Design. Chemical Engineering 83(15), 149-152.

Costigan, G., Whalley, P.B., 1997. Slug flow regime identification from dynamic void fraction measurements in vertical air-water flows. International Journal of Multiphase Flow 23, 263-282.

Da Silva, M.J., Thiele, S., Abdulkareem, L., Azzopardi, B.J., Hampel, U., 2010. High-resolution gas–oil two-phase flow visualization with a capacitance wire-mesh sensor. Flow Measurement and Instrumentation 21, 191-197.

Durga Prasad, G.V., Pandey, M., Kalra, M.S., 2007. Review of research on flow instabilities in natural circulation boiling systems. Progress in Nuclear Energy 49, 429-451.

Hewitt, G.F., Roberts, D.N., 1969. STUDIES OF TWO-PHASE FLOW PATTERNS BY

SIMULTANEOUS X-RAY AND FLASH PHOTOGRAPHY, Other Information: UNCL. Orig. Receipt Date: 31-DEC-69, p. Medium: X; Size: Pages: 28.

Hills, J.H., Jones, W.E., Ibrahim, A.K., 1997. The Behaviour of a Pilot-Scale Horizontal Thermosyphon Reboiler. Chemical Engineering Research and Design 75, 652-656.

Japikse, D., Thomas F. Irvine, Jr., James, P.H., 1973. Advances in Thermosyphon Technology, Advances in Heat Transfer. Elsevier, pp. 1-111.

McKee, H.R., 1970. Thermosiphon Reboilers - A Review. Industrial & Engineering Chemistry 62, 76-82.

Prasser, H.-M., Krepper, E., Lucas, D., 2002. Evolution of the two-phase flow in a vertical tube—decomposition of gas fraction profiles according to bubble size classes using wire-mesh sensors. International Journal of Thermal Sciences 41, 17-28.

Sharaf, S., Silva, M.D., Hampel, U., Zippe, C., Beyer, M., Azzopardi, B., 2011. Comparison between wire mesh sensor and gamma densitometry void measurements in two-phase flows. Measurement Science and Technology 22, 104019.

Yilmaz, S.B., 1987. Horizontal Shellside Thermosiphon Reboilers. Chemical Engineering Progress 83, 64-70.

Zhang, Z., Bieberle, M., Barthel, F., Szalinski, L., Hampel, U., 2013. Investigation of upward cocurrent gas–liquid pipe flow using ultrafast X-ray tomography and wire-mesh sensor. Flow Measurement and Instrumentation 32, 111-118.