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ANALYSIS OF COMPLEX TWO-PHASE INSTABILITIES IN A VERTICAL THERMOSYPHON REBOILER OPERATING AT SUB-ATMOSPHERIC PRESSURES

Abdelmadjid Alane* and Peter J. Heggs
*Author for correspondence
School of Chemical Engineering and Analytical Science,
The University of Manchester,
PO Box 88, Sackville Street, Manchester
M60 1QD
United Kingdom,
E-mail: A.Alane@postgrad.manchester.ac.uk

ABSTRACT

One of the characteristics of multiphase flows with which the operation of process units have to contend is that they often manifest instabilities that have no equivalence in single-phase flow (Bouré *et al*. 1973). These instabilities result often in the occurrence of undesirable large pressure, flow and/or volume fraction oscillations, which, at best, upset the expected behaviour of the multiphase flow system, resulting in a logical decrease in the reliability and life of the components and, at worst, can lead to serious flow stoppage or structural failure. Although two-phase instabilities have been studied extensively, large gaps of unexplained behaviour still remain due to the complex nature of flow, pressure drop and heat transfer mechanisms and the interactions that occur between the three. There is still substantial work ongoing in the field as these instabilities may be detrimental in the smooth operation, control, mechanical integrity and safety of heat exchangers in a multitude of their industrial applications.

This paper sheds light on the experimental studies of transient behaviour at reduced pressures conducted on the thermosyphon research facility at the University of Manchester in the Morton Laboratory. These studies were initiated because literature does not contain many references to this mode of operation and existing design techniques do no adequately cover operation in sub-atmospheric pressures. Thus, the studies meant to establish the operating limits of a full scale replica of an industrial sized natural circulation thermosyphon reboiler comprising 50 vertically-mounted 25 mm OD tubes of 3 m length. Water is used as the process fluid and condensing steam is the heating source. A constant fluid level is maintained at the top of the tube-sheet using an overflow line. The behaviour in the flow-induced unstable region, the heat-induced unstable region and the stable region have been investigated. This work attempts to identify the lower and upper thresholds of instability at various reduced process pressures. For the conditions investigated, explicit thresholds are determined for the transitions between the stable region and the two unstable regions. Instability is defined based on the magnitude of oscillations observed in continuously monitored flows around the recirculation loop. The experiments revealed that the region of stable operation is very dependent on process pressure and progressively becomes smaller as the vacuum becomes lower. The use of throttling in the heat-induced unstable region to return to stable operation tends to be over a narrow region, outside of which the sole way to regain stability is to lower the heat load. In the region of flow-induced instability, throttling of the fluid at the inlet is useless and actually makes the situation worse. These instabilities are alleviated by increasing the heat load or flooding the reboiler.

Keywords: thermosyphon reboiler research facility, boiling, vacuum, two-phase instabilities, flow-induced instabilities, heat-induced instabilities.

INTRODUCTION

Since the pioneering work by Ledinegg (1938) on flow excursions in heated channels, the subject of instabilities in multiphase systems has gained keen interest among researchers [1]. The incomplete knowledge of multiphase flow results in many difficulties in the prediction of multiphase flow, although the fundamental mechanisms which cause unstable behaviour are fairly well understood. Two-phase flow instabilities may result in operational and safety problems. Not only can these instabilities hinder the performance of the system, but sustained oscillations can produce forced mechanical vibrations of components, premature burnout and control problems with a destructive potential [2-3]. Multiphase flow instability was investigated in the past for the purpose of design and safety assessment of nuclear power plant such as water-cooled and water-moderated nuclear reactors and steam generators. While the nuclear industry contributes to understanding these instabilities for safety and operability reasons, their occurrence is frequently encountered in conventional process units such as heat exchangers, cryogenic equipment, boilers, evaporators and various chemical process units [2-4]. Two-phase flow instability is of particular importance to the operation of a vertical thermosyphon reboiler under vacuum.

Many applications in distillation are now using sub-atmospheric pressure operation to lower the system temperatures and so lower the corrosion rates in corrosive environments, obtain higher thermodynamic efficiency and reduced energy consumption, prevent thermal degradation, use cheaper materials of construction and achieve safe operation. It is well known that the system becomes more susceptible to instabilities at reduced pressures [4]. Two-phase instabilities are undesirable as they result in oscillating flow in the loop, which then cause operational difficulties. Bouré *et al.* 1973 classified these instabilities in static and dynamic categories. Chexal and Bergles. 1972 conducted studies to define the stability characteristics of a single-channel natural circulation loop, using both water and Freon-113 as process fluids, at approximately atmospheric pressures [5]. The existing data for thermosyphon loops at atmospheric pressures are unlikely to be extrapolated reliably to sub-atmospheric pressures because of the changes in physical properties, in particular the vapour specific volume [4]. The work presented in this paper is prompted by the lack of instability datasets at reduced pressures and will shed light on the conducted experimental studies of transient behaviour of a full-scale vertical thermosyphon loop operating under vacuum.

NOMENCLATURE

$\tilde{c}_p$	[kJ/kgK]	Specific heat capacity
h	[kJ/kg]	Specific enthalpy
p	[bar]	Pressure
$\dot{Q}$	[kW]	Heat load
$\dot{M}$	[kg/s]	Mass flow
T	[^{o}C]	Temperature
$\dot{V}$	[m^3/s]	Volumetric flow
x	[-]	Vapour mass quality

Special characters

τ	[s]	Period of oscillation
ρ	[kg/m^3]	Density

Supercripts

i	Conditions at inlet
sat	Saturation conditions

Subscripts

0	Reboiler shell side
c	Condensate
e	Excess
f	Fluid properties
g	Gas properties
o	Conditions at outlet
p	Process conditions
s	Steam
tube	Conditions inside tube

THE RESEARCH FACILITY

A full-scale thermosyphon reboiler research facility has been constructed in the Morton Laboratory at the University of Manchester for the purpose of studying the operating characteristics and the instabilities associated with a boiling system at reduced pressures. A schematic of the research facility is given in Figure 1. The equipment is a full scale replica of an industrial sized natural circulation thermosyphon reboiler comprising 50 vertically-mounted 25 mm OD stainless steel tubes of 3 m length. Water is used as the process fluid and condensing steam is the heating source. Though a constant fluid level is maintained at the top of the tube-sheet using an overflow line, this level can be adjusted by displacing the U-leg section. A detailed description of the facility is given by Alane and Heggs. 2006 [6].

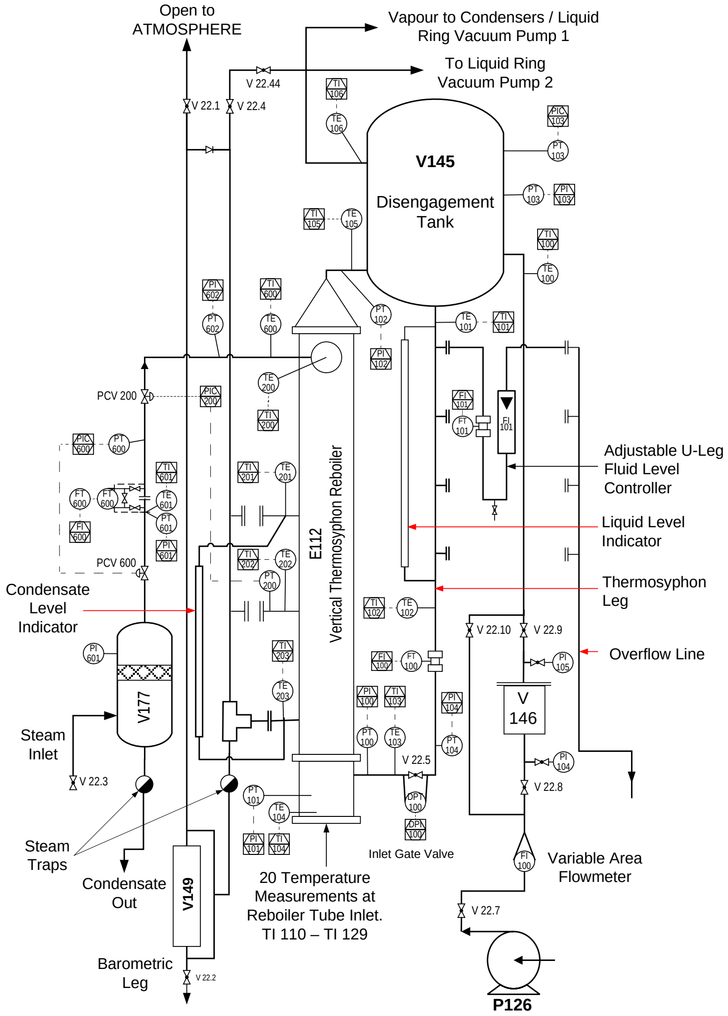

Figure 1 Schematic of the Subatmospheric Thermosyphon Loop

The liquid level inside the reboiler tubes is monitored using a magnetic level indicator. The unit is well instrumented and bi-directional flow, fluctuations in flow and periods of oscillation can be captured in the natural recirculation loop by means of an electromagnetic flowmeter (FI 100). The electromagnetic flowmeter is an Endress+Hauser PROline Promag 50. Provisions were made to measure pressures and temperatures using DRUCK and Bourdon Haenni pressure transmitters and constantan-copper T-type thermocouples. The thermocouples have an outside diameter of 1.50 mm, which gives them a small heat capacity and thus a quick response to temperature changes. 20 thermocouples were inserted in the 50-tube bundle of the reboiler. All sensors were calibrated in-situ. The analogue signals from the measuring devices are conditioned in the control panels using analogue-to-digital converter cards, which are then digitised using Emerson 8CH, TI blocks for the thermocouples and Emerson AI, 8CH, 4-20 mA for the pressure transmitters and electromagnetic flowmeters. The resultant digital signals are then sent through data cables to the computers where they are characterised and converted into numerical readings using the DeltaV® control software. The DeltaV® control system is also used as a data logger, whereby the data are continuously recorded and logged into an Excel spreadsheet. Readings are taken at regular time steps, which are selected to the requirement of the user. The glass rotameters were not insulated in order that readings of flow and visual observations of vapour intrusion through the condensate line can be made. Colour videos of the flow phenomena observed in the glass rotameters were made with a 1.3 Mega Pixel SAMSUNG digital camera.

EXPERIMENTAL STRATEGY

The fluid in the loop was first brought to the desired level for the experiment. The levels used in this work correspond to a) the outlet nozzle when the reboiler was operated under flooded conditions and b) a level adjacent to top tubesheet of the reboiler (see Figure 1). This was completed with valve V 22.7 set open and pump P 126 switched on. Once the required fluid level is obtained, V 22.7 is adjusted to obtain a feed value sufficient to compensate for the process fluid lost to evaporation and any excess fluid is disengaged from the loop through the overflow U-leg (Figure 1). The liquid ring vacuum pump is then switched on and the pressure in rig is set to the desired value by regulating the amount of gas recycle [6]. Before starting the steam feed to the reboiler, vacuum is pulled in the shell side to degas the confined volume and ensure that the entire heat transfer area is free from air blanketing. As the cooling water was flowing through both condensers, the data logger in DeltaV® is set to record the experimental data at 4 s intervals and steam was then brought to the reboiler by activating the two control valves (PCV 600 and PCV 200). The output to the control valves was set manually using the DeltaV® control system. Following the set up of the steam flow to the reboiler, the rig was allowed to reach steady state conditions before the experimental data were collected. The process is said to reach steady state when the trends of the process variables (temperature, pressure and flow) displayed on the DeltaV® data logger were seen not to change with time. The time required to reach steady state depended on the initial degree of subcooling of the process fluid and the heat load. The initial start-up would require between 20 – 60 min but this was completed within 2 – 5 min of a change of heat load when the equipment was warm. Situations of steady state were reached only when the thermosyphon reboiler facility was operated in the stable region. Manual data were collected from the process over a time period which is noted. The heat load to the reboiler was altered by adjusting the steam control valves as required. The reboiler shell side pressure changed accordingly. Data were collected at different heat loads over the range of 14 - 891 kW at various process pressures (0.131 – 1.04 bar) (see Table 1). The heat loads were varied incrementally over the specified range to identify the zones of stable and unstable operation in the rig. Subcooling decreased during the course of each run. The relatively slow sampling rate (0.25 Hz) allowed the data to be written constantly to the hard disk of the operating computer, which generates large data files. A log was maintained for the entire tests conducted on the research facility. This was utilised to highlight all process changes and note the time when they occurred. The information was used in conjunction with the numerical data from the rig to analyse the results.

Table 1 Thermosyphon reboiler operating conditions

Test fluid	Water
Process pressure / bar	0.131 – 1.036
Steam pressure in reboiler shell	0.323 – 2.547
Heat load / kW	14 – 891
Recirculation in loop / l/min	-182 – 382

RESULTS AND DISCUSSION

The heat load from the condensing steam is calculated from the difference between the enthalpy of the superheated steam entering the shell of the reboiler and the combined enthalpies of the steam and condensate exiting the shell side as follows:

$$\begin{aligned}\dot{Q}_0 &= \dot{M}_c\left[\frac{\dot{M}_s}{\dot{M}_c}\tilde{c}_{pg}\left(T_0^i - T_0^{sat}\{p_0\}\right) + h_{fg}\{p_0\}\right] \\ &= \dot{M}_s\left[\tilde{c}_{pg}\left(T_0^i - T_0^{sat}\{p_0\}\right) + (1 - x_o)h_{fg}\{p_0\}\right]\end{aligned} \qquad (1)$$

where $\dot{M}_c = \dot{V}_c\rho_c$

As the heat load to the reboiler was increased, three modes of operation were observed. At low heat loads, a large magnitude, low frequency oscillation in the recirculation in the loop was obtained at a quasi-constant heat load regardless of the process pressure. These are termed flow-induced instabilities. When the heat load was increased, the oscillations decayed in magnitude to disappear eventually as the threshold of instability is exceeded and stable operation was obtained. As the heat load was increased further, the vapour mass quality at the outlet header of the reboiler was of sufficient magnitude to cause the two-phase pressure drop to oscillate, which in turn caused the pressure at the inlet and recirculation in the loop to oscillate. The pressure oscillation reinforces the flow oscillation which caused it in the first place [4]. The resultant oscillations are remarkably inconsistent with larger magnitude occurring at higher frequency. These are termed heat-induced instabilities.

The first instability category that occurs at low heat loads is associated with high subcooling lengths. Under these conditions, Pickering *et al.* 1994 suggested that the instabilities are either chugging or flow-induced instabilities. Chugging occurs as the fluid in the tubes fails to boil at its saturation temperature due to insufficient nucleation sites [4-7]. Instead, the fluid allows for substantial superheat to develop prior to boiling (see Table 2). Under these conditions, it is suspected that a vapour phase is obtained as a result of surface evaporation, which does not require the formation of bubbles, and the occurrence of periodic large exit bubbles. As the liquid becomes superheated, a nucleation site is activated at the top of the tubes at the end of the subcooled zone [5]. The fluid boils violently and, in doing so, the vapour bubble grows rapidly in both directions and pushes the fluid at the top and bottom of the heated tubes, which is eventually expelled from the heated channel [5]. The vapour formed from surface evaporation adds up to the two-phase pressure drop obtained at the outlet nozzle, which exerts an additional force on the fluid at the inlet.

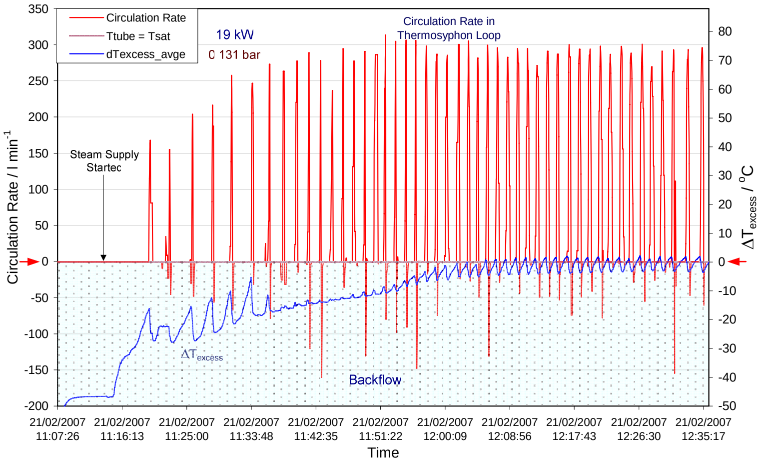

Figure 2 Recirculation and ΔT_e at the flow-induced instability

The subcooled fluid from the cold leg of the reboiler then enters the tubes due to the siphoning effects and the process is repeated resulting in the oscillations observed in Figure 2. In addition, some of the fluid pushed up out of the tubes will fall back as the vapour momentum is insufficient to sustain the flow of the fluid through the converging outlet nozzle and across the pipework to the disengagement tank (see Figure 1). The falling fluid re-enters the tubes. The combination of subcooled fluid entering the heated tubes and the downcomer results in a quiescent period to allow the fluid to attain its nucleation superheat once more before boiling. Figure 2 shows a typical trace of the recirculation signal from the electromagnetic flowmeter at 0.131 bar and 19 kW.

The negative indications from the graph correspond to reversed flow in the entire thermosyphon loop as the two-phase pressure drop at the outlet nozzle and the bubble formation pushes the fluid out through the inlet leg. This observation is unique in that previous publications reported solely on reversed flow in individual heated channels. Chexal and Bergles. 1972 classified this as chugging (static instability), which is characterised by a periodic expulsion of the fluid from the channel. This expulsion may vary from simple changes of inlet and outlet flows to violent ejection of the fluid through both ends of the channel [5], which here results in reversed flow in the loop.

Observation of the trace in the loop indicates that the flow oscillations were continuous, and the flow regime seemed to be unstable in nature as it occurred intermittently. Though, the period of oscillation based on the flow in the loop was found to vary with the process pressure (see Table 2), no clear pattern was established. This can be justified by the strong interactions that exist between the process pressure, the length of the subcooled region, the extent of subcooling and the latent heat of vaporisation. However, the process of identifying the individual effects is complicated in that they are all strong functions of pressure.

The data in Table 2 indicate that the average excess temperature prior to the activation of the loop is confined within 0.88 – 3.75^{o}C irrespective of the process pressure. The profiles of excess temperature followed sudden drops corresponding to the decrease in fluid temperature that occurred every time the fluid started to evaporate and the loop was activated prompting the fluid to flow in the loop. The dips in the profiles result from the subcooled fluid from the cold leg entering the tube bundle driven by the siphoning effects. Because the temperature of the condensing steam on the outer surface of the tubes is quasi-constant, the profile of the process temperature is replicated by the excess temperatures since:

$$\Delta T_e = T_{tube} - T_{sat} \qquad (2)$$

where, $\Delta T_e < 0^{o}$C denotes subcooling. The excess temperature data presented in Table 2 show that the degree of subcooling of the fluid following a flow cycle in the loop decreased with increasing pressure. Based on the average excess temperature, the subcooling disappeared entirely at $p \geq 0.738$ bar. The same data indicates that no flow is obtained in the loop until all the subcooling of the fluid is removed. This observation is true for all the pressures investigated in this wok except at 0.131 bar, whereby the first surge of flow occurred with a degree of subcooling of $\Delta T_e = -17^{o}$C. Though, as the frequency of the intermittent flow became more intense, all the flow occurred solely when the liquid exceeded its saturation temperature ($\Delta T_e \geq 0^{o}$C). This can be justified by the length of the subcooled region at 0.131 bar, which can reach up to 90% of the entire length of the tubes in which the fluid remains below its saturation temperature. As the fluid moved up the tubes the pressure decreased resulting in the fluid to flash at the top section (surface evaporation), which forces the subcooled fluid to enter the hot leg justifying its flow [5].

Table 2 Characteristics of oscillations at different conditions

$p_{process}$ / bar	$\dot{Q}_0$ / kW	ΔT_e / ^{o}C	τ / s	Recirculation / l/min
0.131	18.81	0.880 – 2.690	80 – 144	-160 – 314
0.239	17.99	1.670 – 3.570	196 – 292	-141 – 310
0.505	16.72	1.620 – 3.500	123 – 197	-75 – 199
0.738	13.71	2.210 – 3.750	79 – 156	-76 – 142
1.036	14.65	2.530 – 3.470	117 – 156	-113 – 278

These results indicate that the fluid necessitated a degree of superheat (see Table 2) for flow to start in an intermittent pattern. This confirms that chugging, whereby the fluid in the heated channel fails to boil at its saturation temperature due to insufficient nucleation sites [4-7], was the dominant boiling mechanism. Thus, the fluid allowed for some superheat to develop which resulted in violent boiling with vapour expelling the fluid at both ends of the tubes. This implies that chugging instability was obtained. Considering the dataset generated from the test series at low heat loads (see Table 2), it can be seen that the magnitude and range of the oscillations decreased with increasing pressure for conditions confined within process pressures [0.131 – 0.738 bar]. The opposite pattern was observed between [0.738 – 1.036 bar]. This observation can be justified by the interactions between the previous parameters. A threshold must exist between 0.738 – 1.036 bar, after which the oscillations start to increase in magnitude once again.

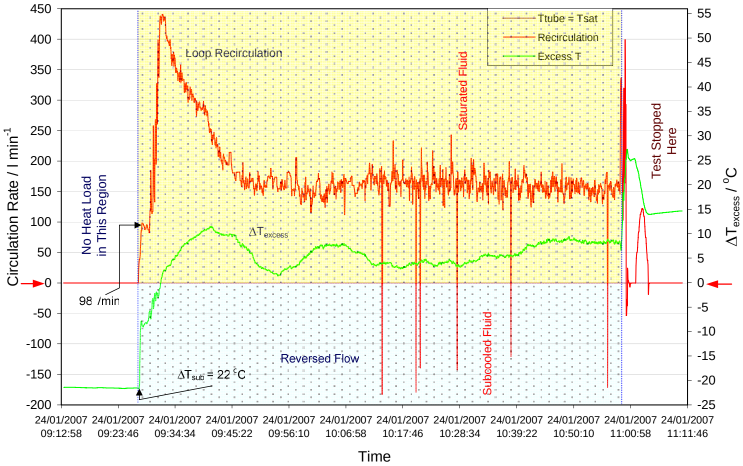

Figure 3 Recirculation and ΔT_e at the density-wave instability at 0.239 bar and 891 kW

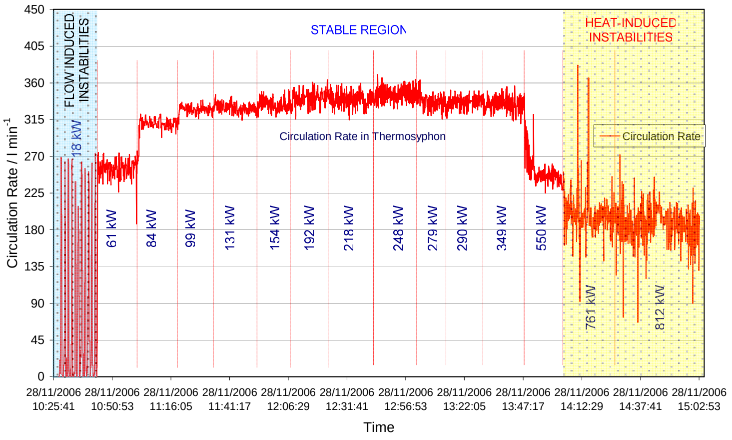

Figure 4 Recirculation at 0.239 bar at different heat loads

Figure 3 is a profile of flow oscillations obtained in the loop at high heat loads. This instability type is a compound instability as it combines more than one mechanism. At this high heat loads, large vapour mass qualities are obtained from the tube bundle (up to 12.13% in this work). Analogous to the flow-induced type, the vapour exerts a pressure pushing the fluid at the top and bottom of the tubes. This forces intermittent flow stoppages in the loop, which generates an oscillating two phase flow. This gives rise to significant variations in the two-phase pressure drop and the perturbation can acquire a 180^{o} out-of-phase pressure fluctuation at the exit, which is transmitted to flow at the inlet. As a result, the two-phase pressure drop across the boiling section of the tubes commences to oscillate, which reinforces the flow oscillations in the tubes. This in turn accentuates the pressure oscillations across the tubes. These oscillations are eventually cascaded to the inlet leg (T, p and $\dot{V}$) as their magnitude becomes large [4]. This type of instability is termed the density-wave instability, which is characterised by flow oscillations of large amplitude [-182 – 382 l/min] and usually regular sinusoidal-like short periods [5], as small as 4 s in the present work (see Figure 3 and Figure 4). Chexal and Bergles. 1972 reported that these periods reflect the time required for a density wave to travel the entire length of the channel [5].

These oscillations occur at high heat loads/fluxes and are dynamic in nature. They are caused by the regenerative feedbacks and interactions between the flow, the rate of vapour generation with its compressible characteristic and the two-phase pressure drop. These oscillations are passed to the inlet leg generating enthalpy disturbances in the sensible heating zone. Once these disturbances reach the boiling zone, they are effectively translated to void fraction disturbances that travel with flow creating an additional dynamic pressure drop in the two phase region [3-4-5]. Density-wave oscillations are clearly the most violent encountered in the present work and represent the upper limit of system operation. These instabilities are very likely to occur in practice since reboilers are usually designed to maximise heat flux [5]. Replicating these observations over the entire pressure range requires a higher steam pressure, which is currently not available in the Morton Laboratory.

A zone of stable operation is enveloped within the area delimited by the described regions of flow-induced and density-wave instabilities. The present analysis highlighted that the zone of stable operation shrinks with reducing pressures as the low heat load stability limit is almost constant while the upper heat load stability limit is found to increase with pressure.

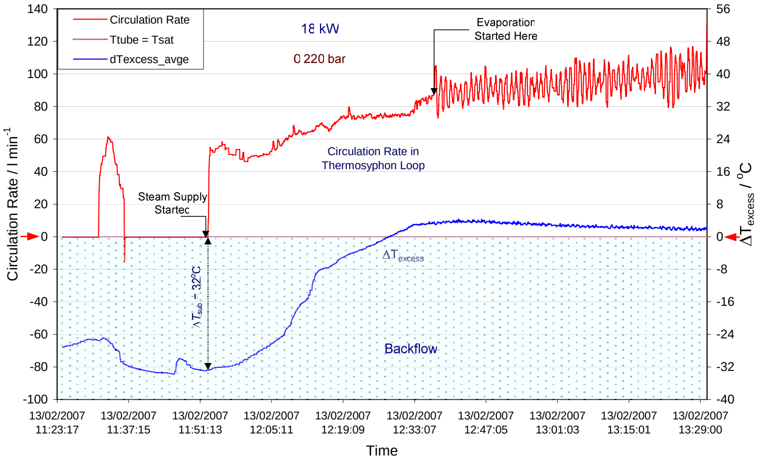

Figure 5 Recirculation and ΔT_e at the flow-induced instability – flooded reboiler at 0.220 bar

Restricting the flow at the inlet to the loop is widely reported in literature to be efficient in stabilising flow [3-5]. The present work shows that this can be achieved only over a narrow range of heat loads after the heat-induced instability starts (see Figure 4), after which the load needs to be lowered. In the region of flow-induced instability, throttling is impractical and actually makes the situation worse. For the conditions examined, increasing the heat load above the defined limit of stable operation resulted in stable flow. Alternatively, flooding the reboiler was considered by increasing the level of the fluid in the loop. The flooded reboiler creates a closed loop of fluid. As a result, flow starts in the loop before evaporation commences. In this case, flow is initially induced by the buoyancy forces arising from the combined density gradients and the body force that is proportional to density [8]. The body force here is gravitational. It was not possible to determine the time it took for the fluid to start evaporating as there was no provision to visually inspect the phenomena taking place inside the reboiler. However, the pattern of recirculation in the loop, as captured in Figure 5, can provide an indication of when evaporation was triggered. The graph shows that within 8 minutes after the fluid reached its saturation temperature ($\Delta T_e \geq 0^{o}C$), a clear transition in the recirculation pattern was observed as this started to fluctuate. As the fluid becomes superheated, evaporation starts in a process which prompts the evaporating hot fluid to be replaced by a relatively cooler fluid from the cold leg. This reduces the evaporation rate and the resultant recirculation momentarily. This recurring process is at the origin of the fluctuations. The same pattern was observed in all tests conducted under the flooded reboiler conditions. Thus, evaporation is likely to have commenced at the point when distinct fluctuations started occurring in the recirculation around the loop. The data presented in Figure 5 are obtained for a flooded reboiler using the process conditions that triggered flow-induced instabilities when the fluid level was maintained at the top tubesheet. The graph shows that recirculation in the loop at 0.220 bar varied within 73 – 117 l/min when the heat load was maintained at 18 kW. This flow range is significantly narrower than -141 – 310 l/min, which was obtained under similar conditions with the fluid level at the top tubesheet of the reboiler (see Table 2). The occurrence of the fluctuations, however, was more consistent with relatively higher frequencies under the flooded conditions, namely 48 – 76 s compared to the initial 196 – 292 s. The graph in Figure 5 shows that reversed flow is completely suppressed. The obtained data indicate that when the fluid level is above the exit nozzle of the reboiler, it exerts a cooling effect which leads to some condensation to occur. The partial condensation results in a reduced velocity of the two-phase flow leaving the outlet nozzle of the reboiler. This acts as a damping mechanism which lowers the oscillatory two-phase pressure drop and re-stabilises the system. A fluid level above the exit nozzle, however, will act as an exit restriction with a destabilising effect [5]. The results show that the stabilising effects are dominant.

CONCLUSIONS

Two-phase instability experiments have been conducted on an industrial thermosyphon reboiler using water. The obtained results are of paramount interest for start-up of vertical thermosyphon reboilers and determining the range of stable operation.

Flow-induced instabilities or chugging of static nature were found to occur in the thermosyphon with the tubes entirely submerged. These instabilities occurred over the pressures investigated at the same fractional opening of the two control valves regulating the steam pressure and flow with quasi-constant heat loads [14 – 19 kW]. These variations are negligible in light of the overall heat loads utilised on the rig, namely up to ~891 kW. Any increase in the signal output to the flow control valve (increased load) resulted in a continuous and steady flow in the loop regardless of process pressure. This implies that the low threshold for flow-induced instabilities in the present thermosyphon reboiler is independent of pressure. The instabilities produced intermittent reversed flow in the entire loop. These instabilities were effectively alleviated by flooding the reboiler, as the additional static head resulted in a damping mechanism, which re-stabilises flow. Heat-induced instabilities, also termed density-wave instabilities, were triggered at high heat loads. The threshold was a function of process pressure. The density-wave instability generated oscillations of flow that were inconsistent in amplitude and frequency. This is a compound instability with more than one mechanism of importance.

The zone of stable operation is enveloped between the thresholds of flow-induced and density-wave instabilities. The zone of stable operation shrinks dramatically with reducing pressures.

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