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Araştırma / Research

ANALYSIS OF THE TWO PHASE FLOW PRESSURE DROP TYPE OSCILLATIONS IN A WATER BOILING HORIZONTAL STRAIGHT TUBE

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ABSTRACT

Two phase flows occur in many industrial applications such as refrigeration systems, turbo machinery, and power plant heat exchangers. Prediction of flow parameters is very crucial in design of two-phase flow equipment. Oscillations incurred by instabilities in two-phase flow systems cause mechanical vibrations, boiling crisis, high transient temperatures, control problems and even burnout at wall surface. This study is focused on determining steady state characteristic curves for certain inlet temperature and exit restriction conditions at different mass flow rates and compares variation of pressure drop type dynamic two phase flow instabilities in horizontal tube system. This work aims to predict low frequency pressure drop type oscillations in an in-tube boiling system. Results provide further understanding of mechanism of pressure-drop-type instabilities in a horizontal boiling tube system. They can also be utilized as guidance for design and control strategy of systems to avoid serious oscillation problems.

Keywords: Two phase flow instabilities, pressure drop type instabilities, density wave type instabilities, stability boundary, inlet sub-cooling

SU KAYNAMALI YATAY DÜZ BORUDA İKİ FAZLI AKIŞ BASINÇ DÜŞÜMÜ OSİLASYONLARININ ANALİZİ

ÖZ

İki fazlı akışlar, soğutma sistemleri, turbo makineler ve enerji santrallerindeki ısı eşanjörleri gibi birçok endüstriyel uygulamada ortaya çıkar. İki fazlı akış ekipmanlarının tasarımında akış parametrelerinin tahmini çok önemlidir. İki fazlı akış sistemlerinde kararsızlıklardan kaynaklanan salınımlar mekanik titreşimlere, kaynama krizine, yüksek geçiş sıcaklıklarına, kontrol problemlerine ve hatta cidarda ani sıcaklık yükselmesine neden olur. Bu çalışma, belirli giriş sıcaklığı ve çıkış kısıtlaması şartlarında değişik debilerde kararlı hal karakteristik eğrilerini belirleme üzerine odaklanmıştır ve yatay borulu sistemdeki basınç düşümü tipi iki fazlı akış dinamik kararsızlıklarının değişimlerini karşılaştırmaktadır. Bu çalışma, borulu kaynama sisteminde düşük frekanslı salınımları öngörmeyi amaçlamaktadır. Sonuçlar, yatay kaynamalı boru sisteminde basınç düşümü tipi kararsızlık mekanizmasının daha iyi anlaşılmasını sağlar. Ayrıca, ciddi salınım problemlerinden kaçınmak için sistemlerin tasarım ve kontrol stratejileri için kılavuz olarak da kullanılabilirler.

Anahtar Kelimeler: İki fazlı akım istikrarsızlıkları, basınç düşüşü tipi istikrarsızlıklar, yoğunluk dalga tipi istikrarsızlıklar, stabilite sınırı, giriş aşırı soğutma

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1. INTRODUCTION

In designing a system using existing procedures; both data source and limitations should be considered. Most common experimental problems on a forced-flow system with an electrically heated single round tube involve acquiring heat transfer and sometimes pressure-drop data. The flaw in this procedure is that it fails in capturing the pressure-drop against flow rate instabilities, which can occur with sub-cooled boiling in channels [1, 2]. This instability may lead to degraded heat transfer or even a physical burnout. Usually the deterioration is a result of flow insufficiency in the tube which occurs where the minimum for pressure-drop versus flow-rate curve is reached. Similar flow instabilities have recently been reported for micro channel arrays [3]. Babelli and Ishii [4] took a closer look at this instability for heated test sections of different orientations and identifies the conditions which lead to it. It tends to appear where significant vapor generation takes place [2]. This is due to enhanced wall friction when sub-cooled boiling is present, and by additional pressure drop due to the acceleration of the flow by increasing voids. The key to predicting the onset of this flow instability is to predict the curve for pressure drop versus flow rate. Some crucial conclusions can be made for the safe operation of these systems by knowing the characteristics of boundaries and oscillations. Moreover, some parameters such as duct geometry, operating and boundary conditions may affect development of instabilities [5]. In Table 1, classification of flow instabilities was shown.

Table 1. Classification of flow instabilities as elaborated by Boure et al. [6]

Class		Type	Mechanism	Characteristics
1. Static instabilities	1.1. Fundamental (or pure) static instabilities	1. Flow excursion or Ledinegg instability	In the negative slope region, the inclination of internal characteristic curve is greater than that of external	Flow undergoes sudden, large amplitude excursion to a new, stable operating condition
		2. Boiling crisis	Ineffective removal of heat from heated Surface	Wall temperature excursion and flow oscillation
	1.2. Fundamental relaxation instability	1. Flow pattern transition instability	Bubbly flow has less void but higher ΔP than that of annular flow	Cyclic flow pattern transitions and flow rate variations
	1.3. Compound relaxation instability	1. Bumping, geysering, or chugging	Periodic adjustment of metastable condition, usually due to lack of nucleation sites	Period process of super-heat and violent evaporation with possible expulsion and refilling
2. Dynamic instabilities	2.1. Fundamental (or pure) dynamic instabilities	1. Acoustic oscillations	Resonance of pressure waves	High frequencies (10-100 Hz) related to time required for pressure wave propagation in system
		2. Density wave oscillations	Delay and feedback effects in relationship between flow rate, density, and pressure drop	Low frequencies (I Hz) related to transit time of a continuity wave
	2.2. Compound dynamic instabilities	1. Thermal oscillations	Interaction of variable heat transfer coefficient with flow dynamics	Occurs in film boiling
		2. BWR (Boiling Water Reactor) instability	Interaction of void re-activity coupling with flow dynamics and heat transfer	Strong only for a small fuel time constant and under low pressures
		3. Parallel channel instability	Interaction among small number of parallel channels	Various modes of flow redistribution
	2.3. Compound dynamic instability as secondary phenomena	1. Pressure drop oscillations	Flow excursion initiates dynamic interaction be-tween channel and compressible volume	Very low frequency periodic process (0.1 Hz)

Two phase flow instabilities may cause mechanical vibrations and some difficulties in controlling the system. Furthermore, they may affect normal operation, influence system safety negatively and restrain operating parameters. Studies on two phase flow instabilities can be classified with reference to tube flow orientation and alignment, most of which have concentrated on vertical systems, either with a single or parallel channel arrangement [7-10].

Franga and Lahey [11] used drift flux techniques for the analysis of two phase flow in a horizontal test section 1,385 m in length. Ding et al. [12] has experimentally investigated two phase flow instabilities on a 1,060 m length horizontal in-tube boiling system. They obtained steady state internal characteristics of the system under different system parameters, such as system pressure, inlet temperature, heat input and exit restriction. Widmann et al. [13] investigated the effect of inlet sub-cooling and has shown that dynamic instabilities, such as pressure drop type oscillations (PDOs), thermal and density wave type oscillations, boundaries of which have been determined, occurred. The effect of augmented surfaces on two phase flow instabilities were studied in a 1,060 m long horizontal test section [14, 15]. Likewise, Lin et al. [16] and Ruder et al. [17] have studied on horizontal tube systems.

This study is focused on experimentally determining the steady-state characteristics and investigating PDOs, which is a compound dynamic instability occurs as a secondary phenomenon [6], in a single horizontal channel-boiling flow system. Using a 3.5 m long Cr-Ni heater tube with an inner diameter (D_i) of 12.7 mm and outer diameter (D_o) of 17 mm; effects of inlet sub-cooling, mass flow rate and heat input on dynamic instabilities were investigated and compared with studies used shorter tubes.

2. DESCRIPTION OF THE EXPERIMENTAL SYSTEM AND PROCEDURE

This study is carried out on a test setup, details of which is available in Karagoz et al. [18], designed to enable generation of three main types of two phase flow instabilities; pressure drop type, density wave type and thermal oscillations. Inlet temperature of working fluid has an important effect on two phase flow characteristics, therefore, working fluid is passed through a heat exchanger to ensure desired inlet temperature, which is measured with a dipped thermocouple at the inlet of the test tube. The sub-cooler heat exchanger is mainly a shell and tube heat exchanger, in which working fluid passes through the tube side, while cooling water passes through the shell side.

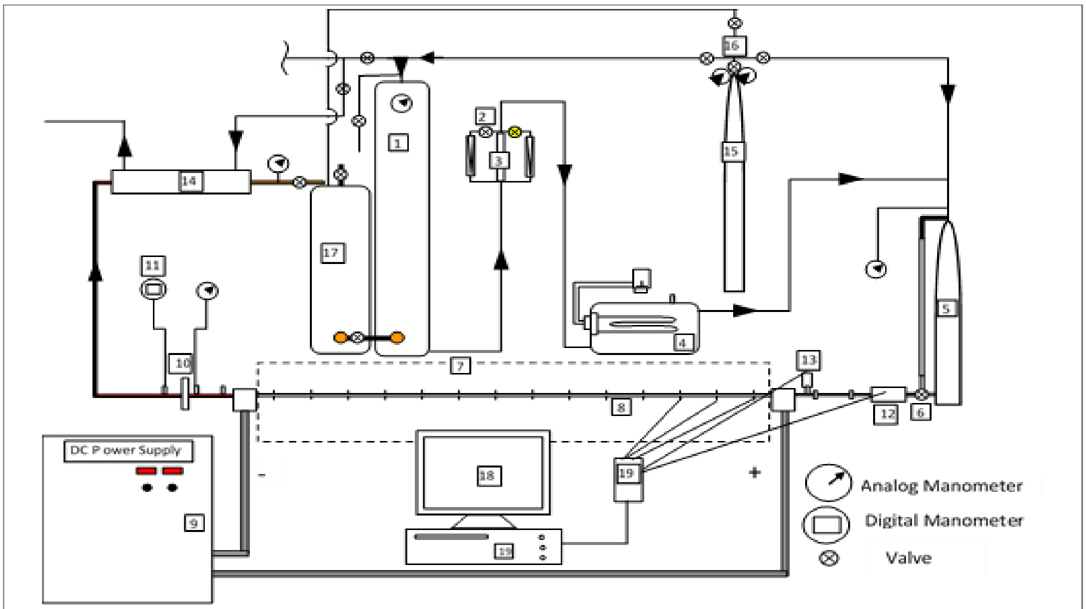
A transparent glass tube is installed at the side of the surge tank in order to observe the change in working fluid volume and the level of the compressible volume in the surge tank. During experiments, the surge tank, acting as a capacitance, is partly filled with nitrogen gas to provide necessary compressibility to the system. A differential pressure transducer, a bourdon-type digital manometer and a pressure transducer are used to measure inlet flow oscillations, the inlet pressure, and oscillations in pressure of working fluid, respectively. And thermocouples were distributed as seen in Fig. 1.

After leaving the test section working fluid arrives to a recovery section comprised of a condenser, a storage tank, a nitrogen tank and a regulator. Working fluid leaves the test section almost wholly in vapor phase and is condensed in the condenser, thereafter accumulated in a storage tank where it is pumped into the main tank through a flow control valve by pressurizing the storage tank with nitrogen gas. Experimental parameters are given in Table 2.

Table 2. Figures of Experimental parameters

System pressure	7.5 bar
Mass flow rate	25-140 g/s
Exit restriction diameter ratio	0.45 and 0.25
Inlet sub-cooling	15°C, 25°C, 30°C, 35°C and 40°C
Heat input	0 kW, 15 kW, 21 kW, 24 kW and 28 kW
Test Tube	Cr-Ni cylindrical tube (316L Stainless Steel) D_o=17.00 mm D_i=12.7 mm

For each experiment, all mechanical components and instrumentation are checked for flawless operation. The inlet temperature is maintained within ±0.5°C. Pressure is measured at several locations using different gauges as shown in [15]. The total error rate for flow measurements is ±0.05%. The full scale accuracies of the differential pressure transducer, pressure gauges and pressure transducer are ±0.05%, ±0.1% and ±0.1%, respectively. The cylindrical test tube is electrically heated uniformly, and the heat input, with an overall uncertainty of ±0.2%, is calculated as the product of measured current supplied by the DC power supply and the voltage drop across the heated section.



Fluid Supply Section	Test Section	Fluid Outlet Section
1- Main tank	5- Surge tank	14- Condenser
2- Flow control valve	6- Fluid inlet control valve	15- Nitrogen tank
3- Flowmeters (two pcs)	7- Test chamber	16- Regulator
4- Heater	8- Test tube	17- Storage tank
	9- DC power supply	18- Computer
	10- Orifice	19- Data Acquisition Card
	11- Digital manometer	
	12- Turbine type flowmeter (flow transducer)	
	13- Pressure transducer	

7 – Test Chamber (details)

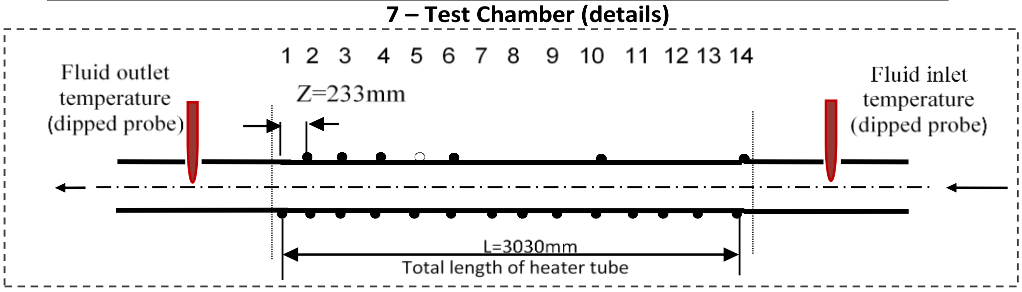


Figure. 1. Schematic view of the experimental set-up and distribution and locations of thermocouples

3. RESULTS AND DISCUSSION

Temperature measurements during the experiments were made using T-type copper-constantan thermocouples with a diameter of 0.25 mm. An analog/digital Advantec Data Acquisition card was used to read and evaluate the signals from the thermoelements and pressure/flow transducers. The total error rate of readings from this control card, which has a sampling capability of 100 samples per second, varies between ±0.10°C and ±0.50°C depending on the selected data acquisition card.

A pressure transducer was employed to measure the inlet pressure at the inlet of the test tube and the oscillations to occur at the inlet pressure. The 4-20mA analog signals from this pressure transducer were processed with the data acquisition card. A DC power supply is used to electrically feed the transducer. The total error rate from the pressure transducer is ±0.1%.

A turbine-type flow meter was employed to measure the flow oscillations in the system. The flow meter was mounted between the surge tank and the test tube in the test system. The total error rate in the data readings from the flow meter is ±0.05%.

Experiments were repeated at least three more times for each configuration in order to ensure the repetitiveness of the experiments and accuracy of the test results. The results obtained from repeated experiments have been consistent and in a great concordance with each other.

3.1. Steady State Characteristics

Two-phase steady state characteristic curves which denote the pressure drop versus mass flow rate for five different inlet temperatures are shown in comparison with the single phase curve in Fig. 2. The pressure drop is defined as the difference between the pressure in the surge tank and at the exit of the test tube [14]. These curves resemble an inverted "S" shape for all investigated inlet temperatures. The right-hand side portion of the curve, corresponding to higher mass flow rates, denotes the single phase region, where the curve slope is positive and flow is stable.

In the stable region, flow rate decreases as pressure drop decreases. Near the minimum point of the curve, the first bubble is observed, and the flow enters the two phase region where the slope is negative. While operating in this region, pressure drop increases as the flow rate decreases. Then, the system operates in a single phase vapor region where pressure drop starts to decrease with decreasing flow rate. With higher heat input, fluid incoming with a certain mass flux can absorb more energy, hence reach saturation faster. The two-phase region therefore stretches to occupy more space in the heater tube, and consequently, a higher pressure drop occurs for same mass flux as shown in Fig. 3.

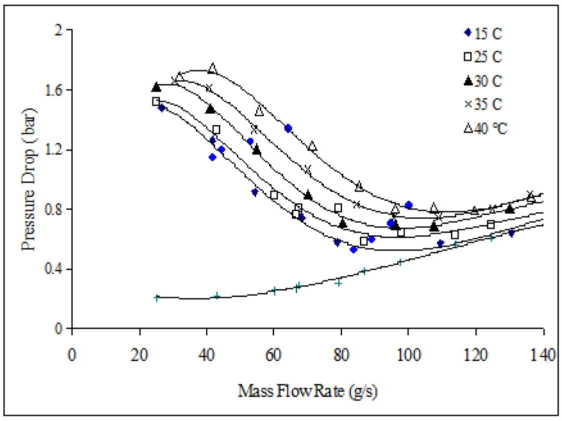


Figure 2. Steady state characteristic curves for different inlet temperatures

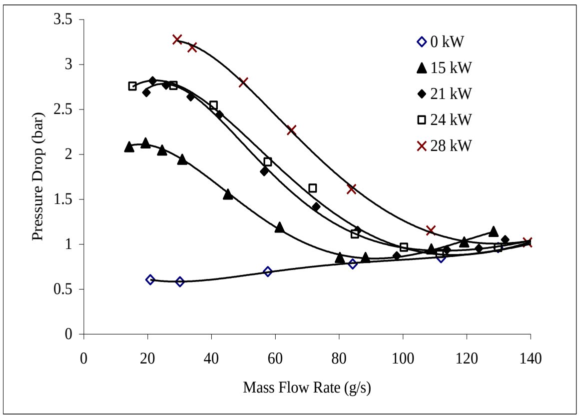


Figure 3. Steady state characteristic curves for different heat inputs

An exit restriction installed at the end of test section simulates a long tube situation, and raises the pressure in the test section since it lets the fluid find a narrower way to escape. A larger diameter of the orifice plate (shorter tubes) will impose less resistance to the two phase region in the test section, and therefore flatten the characteristic curves. Increase of exit restriction also has a similar effect on the boiling process as that of system pressure. Fluid subject to higher pressure will have its boiling temperature increased and latent heat reduced, hence a shorter process from liquid to vapor. This phenomenon can be seen in Fig. 4. The curve with $\beta=0.25$ has its lowest point corresponding to a lower mass flux compared to the one with $\beta=0.45$.

3.2. Stability Boundaries

In the experiments, three different modes of oscillations; pressure drop type, density wave type and thermal oscillations, were observed at different mass flow rates. Keeping the heat input, system pressure and exit restriction constant, these oscillations appeared for all inlet temperatures. The boundaries for the beginning of oscillations are shown by dashed lines in Fig. 5. Oscillations are first observed on the right-hand side of the steady state characteristic curve, near the lowest point, where the slope is positive.

These are PDOs superimposed with density wave type oscillations. The boundaries of PDOs move towards lower flow rates as inlet temperature decreases, which denotes that unstable region is inversely correlated to inlet temperature. PDOs end near amid the negative slope region. The boundaries of PDOs are a function of inlet temperature and mass flow rate. A tube burnout may occur if the mass flow rate is decreased further.

PDOs begin near the minimum point of steady state characteristic curves. Typical flow diagram and acquired experimental data for PDOs for inlet temperatures of 35°C, 25°C and 15°C are shown in Fig. 6 and Figs. 7-9 respectively. As it is apparent in the figures, PDOs are associated with large amplitudes of the fluctuations of bottom and top wall temperature, inlet pressure and mass flow rate. When the amplitudes of inlet pressure are maximum, the amplitudes of mass flow rate become maximum.

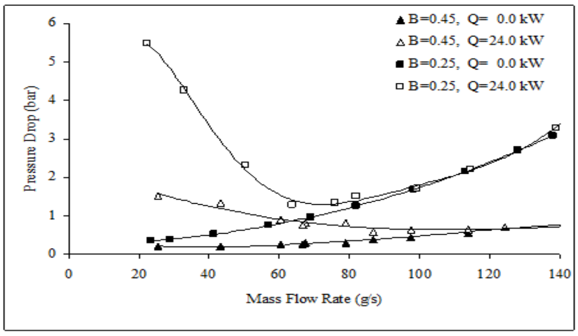


Figure 4. Steady state characteristic curves for different heat inputs and ß values

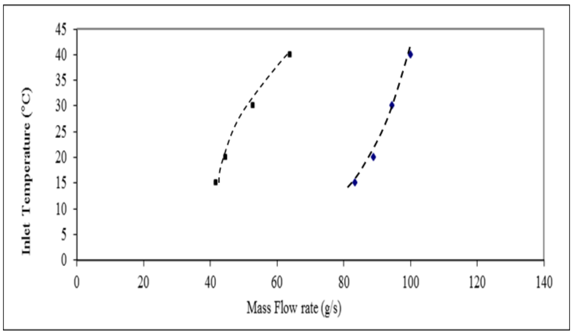


Figure 5. Boundaries of pressure drop type oscillations

3.3. Mechanism of Pressure Drop Type Oscillations

The mechanisms for PDOs can be explained by lags in propagation time and feedback phenomena that are present in any two-phase flow system. The momentary disturbance, which is proportional to the propagation wave speed, takes some time to reach other points along the system. These delayed disturbances along the system are then echoed back to the initial point of the disturbance creating a new disturbance, and so on. With reference to Fig. 6, the following steady-state correlations are considered;

$$(P_{main\text{-}tank} - P_{surge\text{-}tank}) = K_1 (m_1)^2 \tag{1}$$

$$(P_{surge\text{-}tank} - P_{exit}) = \varphi m_2 \tag{2}$$

whereas K_1 is an experimentally determined constant for the inlet restriction, φ is a dimensionless void fraction, (m_1) and (m_2) are the mass velocities into and out of the surge tank (compressible volume) respectively.

Equation (1) represents the pressure-drop across the inlet restriction and is a statement of the momentum equation across the restriction. Equation (2) is the pressure-drop between the surge tank, which is downstream of the restriction, and the exit section of the system, and it is the system curve shown in Fig. 6. While operating on the negative slope portion, a slight increase in surge tank pressure causes more fluid to enter than that leaves.

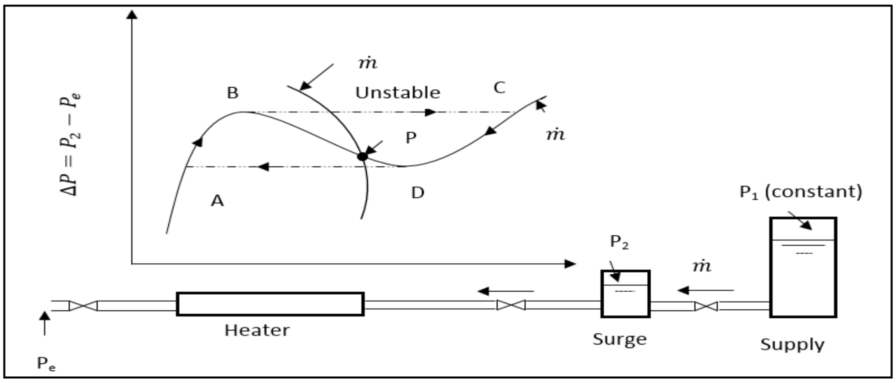


Figure 6. Schematic flow diagram and limit cycle of pressure-drop type oscillations

The surge tank pressure increases due to accumulation of fluid. The operating point moves up until it reaches the peak (point B). Any higher pressure can only be sustained by a higher mass flow rate as suggested by the system curve. This point is found to be in the single-phase liquid region (point C) at which the amount of fluid leaving the surge tank is more than that entering it. Therefore, the surge tank pressure decreases till the operating point reaches the curve minima at D. Any lower pressure can now be obtained only if the mass flow rate is reduced to the value at point A. Hence, an excursion to A is observed. Here, the mass leaving the surge tank is less than that entering it. Hence the pressure goes up pushing up the operating point till A is reached, where once again a flow excursion is observed. Thus perturbation at any point on the negative slope region results in a flow oscillation tracing the limit cycle ABCDA. This is essentially the mechanism of pressure-drop oscillations [19].

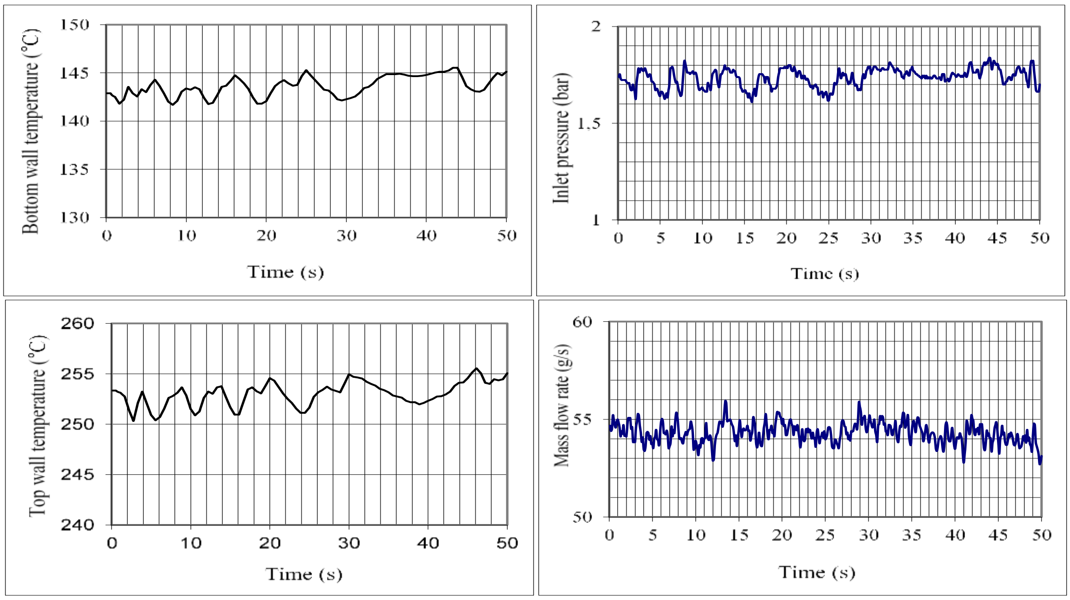


Figure 7. Recordings of pressure drop type oscillations ($\dot{m} = 54\ g/s$, Q=24 kW, Tg=35°C)

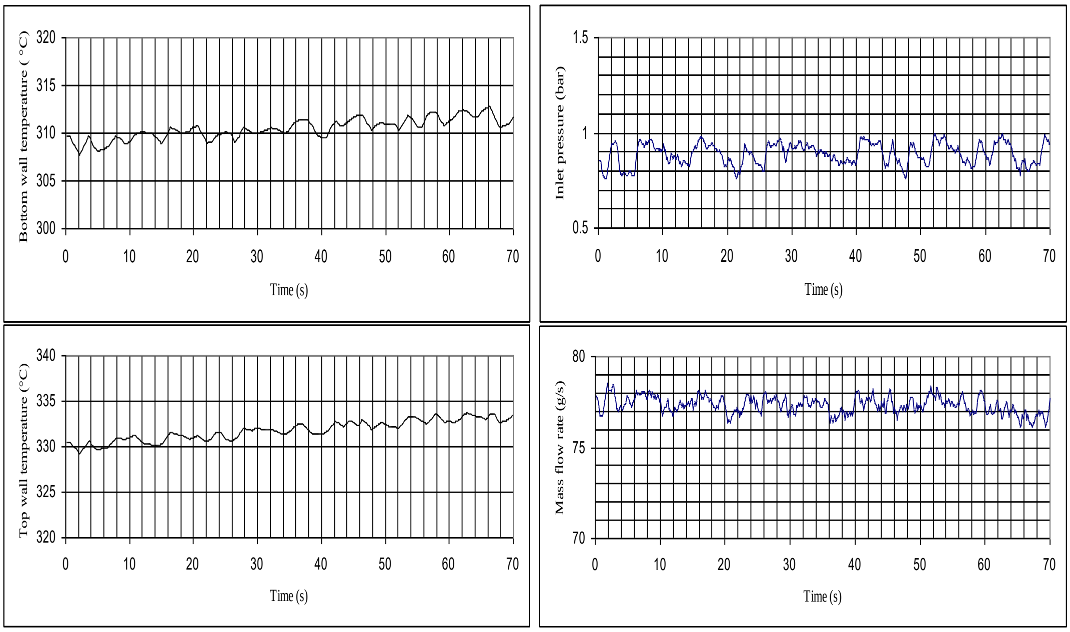


Figure 8. Recordings of pressure drop type oscillations ($\dot{m} = 77\ g/s$, P=24 kW, Tg=25°C)

Figure 10 shows the effect of inlet sub-cooling and mass flow rate on amplitudes of PDOs. Amplitudes of inlet pressure increase with decreasing inlet temperature. Likewise, as the mass flow rate decreases, amplitudes of inlet pressure decrease. As seen in Fig. 11, periods of inlet pressure decrease with decreasing mass flow rate and increasing inlet temperature. Apparently, both bottom and top wall temperatures, top being larger, oscillate with large amplitudes.

Figures 12 and 13 suggest that lower inlet temperature generally increases the amplitudes and periods of oscillations. Liu and Kakaç [19], explained this trend by plotting steady state characteristic curves for different inlet temperatures on same scale, the points of max values were found to be very close to each other, while the points of min values be far apart with the curve at the very bottom representing the lowest inlet temperature.

Therefore, the lower the inlet temperature, the greater the pressure difference between min and max values, vice versa. The PDOs, following limit cycle, tend to produce larger amplitudes when inlet temperature is lower, therefore take longer [20].

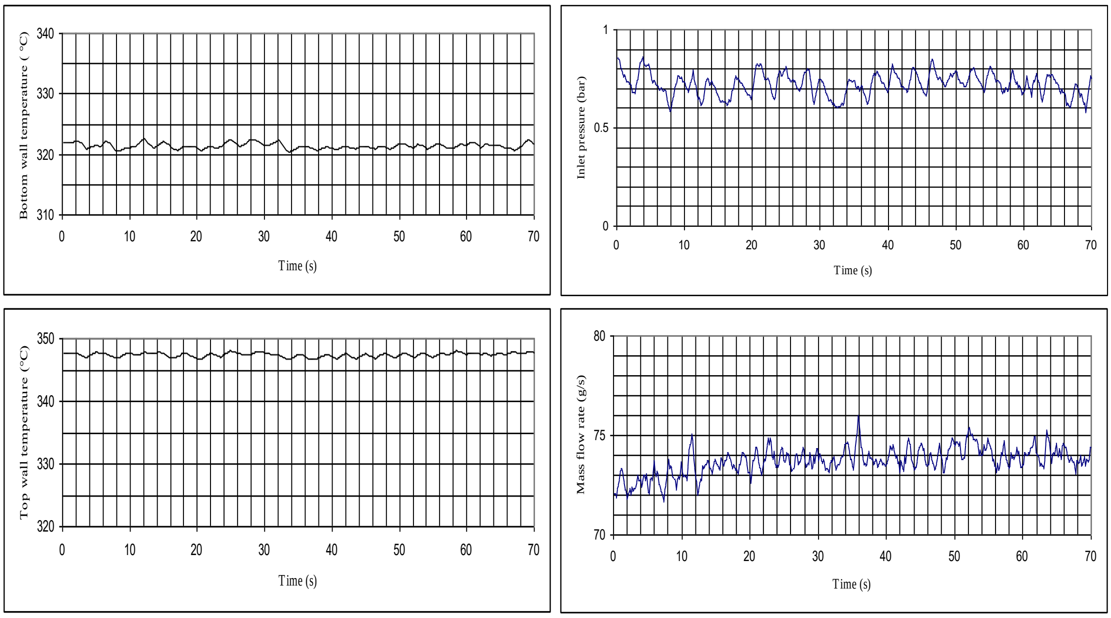


Figure 9. Recordings of pressure drop type oscillations ($\dot{m} = 74\ g/s$, P=24 kW, Tg=15°C)

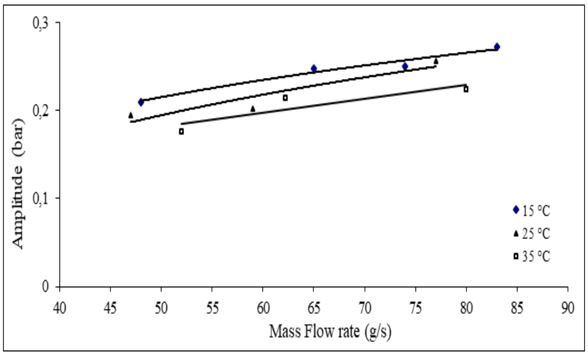


Figure 10. Effect of inlet temperature and *m* on amplitudes of inlet pressure oscillations

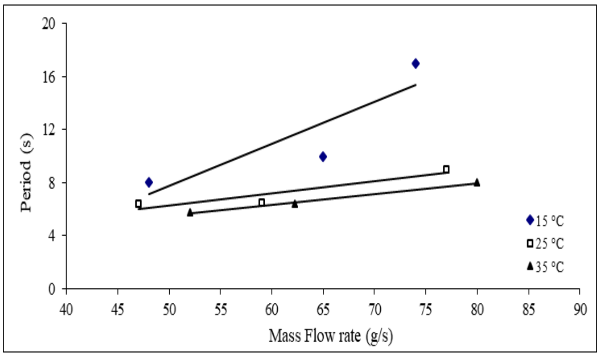


Figure 11. Effect of inlet temperature and *m* on periods of inlet pressure oscillations

Figures 14 and 15 reveal the fact that mass flow has similar effect on both amplitude and period of PDOs. With reduction of mass flow both amplitude and period decrease. The main reason can be concluded that as mass flow is reduced, pressure inside the heater tube increase due to increased vapor generation, as a result of which the compressible volume in the surge thank decrease. At this moment, system becomes “stiffer”, and therefore amplitude and period of oscillations reduce [20].

3.4. Comparison with Other Studies

In this study, we found similar results with Ding [12], Widmann [21] and Kakaç et al. [15], in relation to the steady state characteristic curves. The stability boundary of the PDOs moved towards lower mass flow rate with decreasing inlet temperature and the unstable region increased with increasing inlet temperature.

As seen in Fig. 15, in this study the mass flow rate region of 60 to 75 g/s is stable while Ding [12] and Widmann [13] have shown this region as unstable showing that PDOs occurred as well as density wave type oscillations in this region. Stability boundary obtained in this study moved toward lower mass flow rates, decreasing the unstable region, which means the stable region is larger. This may be attributed to the experimental setup, such as length and diameter of the test tube, exit restriction etc., and different operational conditions, such as heat input, pressure etc. In Table 2 results of this study are compared with those of Ding [12], Widmann [13], Liang et al. [22] and, Kakaç and Cao [23] for the same. Amplitudes and periods of PDOs vary depending on inlet temperature, mass flow rate, heat input and other operation conditions.

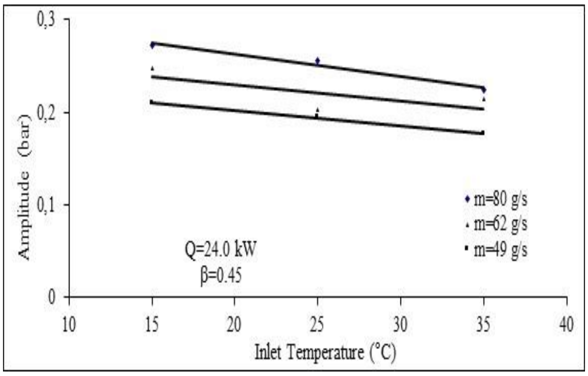


Figure 12. Effect of inlet sub-cooling and *m* on amplitudes of inlet pressure oscillations

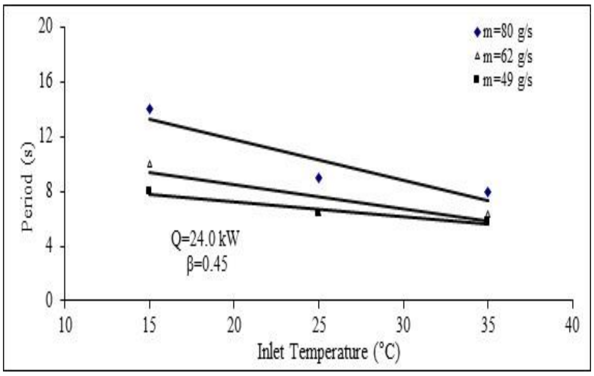


Figure 13. Effect of inlet sub-cooling and *m* on the periods of inlet pressure oscillations

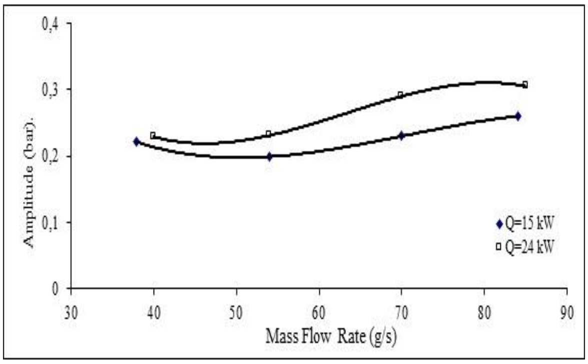


Figure 14. Effect of heat input and *m* on the amplitudes of inlet pressure oscillations

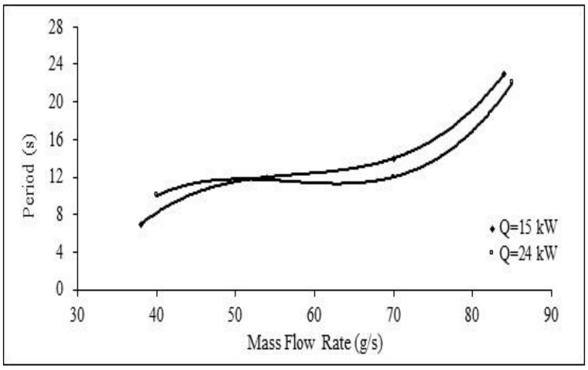


Figure 15. Effect of heat input and *m* on the periods of inlet pressure oscillations

Table 3. Comparison of periods and amplitudes of oscillations with those of other studies

Study	Tube Type	$\dot{Q}$ [W]	T_i [°C]	$\dot{m}$ [g/s]	Pressure Drop Oscillations	
					Amplitude [bar]	Periods [s]
This study	Bare	24000	15 25 35	49 62 80	0.25 0.23 0.21	8.2 7.3 6.7
Widmann et al. [13]	Bare	2500	24 16 10	56.3	1.379 1.456 1.469	11.8 14.2 17.8
Ding [12]	Bare				1.3	15
Kakaç et al. [5]	Bare	2500	20	0.04 [kg/(m^{2}s)]	2.2	16
Kakaç et al. [15]	Bare	400 600 800 1000	23	11,89	0.21 0.52 0.76 0.92	13 18 30 37
Liang et al. [22]	Bare	5000 [W/m^2] 9000 [W/m^2] 11000 [W/m^2] 13000 [W/m^2] 17000 [W/m^2]		110 [kg/(m^{2}s)] 195 [kg/(m^{2}s)] 185 [kg/(m^{2}s)] 170 [kg/(m^{2}s)] 150 [kg/(m^{2}s)]	2.1 1.9 1.7 1.6 1.4	9.5 9.9 10.2 10.5 10.7
Kakaç et al. [23]	Bare	2000 2500	24	717	1.5 2.2	18 16

4. CONCLUSIONS

Two phase flow instabilities occur under certain conditions. It is very important to avoid or control these instabilities in designing and operating systems. Key findings in this study can be summarized as follows:

(1) The pressure-drop type oscillations arise from interactions between flow and compressible volume in the surge tank [20].
(2) The stability boundary moves toward lower mass flow rates as inlet temperature decrease, which means that the system is less stable for higher inlet temperatures [18].
(3) The periods and amplitudes of PDOs vary with mass flow rate, inlet temperature, heat input [7, 8].
(4) At a given inlet sub-cooling or inlet temperature, the amplitudes and periods of the oscillations increase with increasing heat input rate.
(5) The period and amplitude of the oscillations increase with decreasing mass flow rate at the initial operating point on the negative slope.

Instable region shrinks with smaller effective diameters, thus the single phase flow region stretches and improve the stability. However, with smaller effective diameters pressure-drop hence the amplitudes and periods of pressure-drop-type oscillations increase. This phenomenon was also tested and reported by Omeroglu [24].

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