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Experimental study of the heat transfer coefficient deterioration during Density Wave Oscillations

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HIGHLIGHTS

- Study of heat transfer deterioration during Density Wave Oscillations.
- Density Wave Oscillations can deteriorate the heat transfer coefficient.
- The impact is more severe for low pressure, mass flux and inlet temperature.

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ABSTRACT

The effect of the Density Wave Oscillations (DWO) on the heat transfer is studied experimentally. A horizontal test section of 5 mm I.D. with R134a as working fluid was used for the experiments. The time averaged boiling heat transfer was found to be different under DWO conditions than under steady-state flow. Four different cases were studied considering different inlet pressure, temperature and mass flow rate. It was observed that the occurrence of the DWO can result in a premature dry-out and that the impact of the DWO on the heat transfer depends on the particular conditions. However for the studied cases the impact on the heat transfer was not severe.

1. Introduction

Two phase flow instabilities (Boure et al., 1973; Tadrist, 2007; Kakac and Bon, 2008; Liang et al., 2010; Manavela Chiapero et al., 2012) can be observed in different industrial areas such as refrigeration systems, boiling water reactors, and steam generators. The induced oscillations of the flow rate and system pressure are undesirable as they can cause mechanical vibrations, thermal fatigue, transient burn-out of the heat transfer surface, degradation of the heat transfer performance and problems of system control. However these effects have been seldom quantified. The two phase flow instabilities have been extensively studied during the past decade. However only a fraction has been focused on horizontal heated pipes and studying the aspects of the oscillations (Stenning and Veziroglu, 1965; Yuncu, 1990; Ding et al., 1995; Comakli et al., 2002; Yilmaz et al., 2002; Cao and Kakaç, 2009; Liang et al., 2011; Fan and Hassan, 2013; Dorao et al., 2014). In addition, only a limited number of studies have been focused on the effect of the two phase flow oscillations on the critical heat flux (CHF) and heat transfer coefficient (HTC), see Table 1.

Chang et al. (1996) investigated the impact of a flow excursion on the critical heat flux (CHF) and proposed a flow excursion CHF correlation. Umekawa et al. (1996) performed CHF experiments under oscillatory flow conditions, by using different test sections in order to investigate the effect of the tube wall heat capacity. In these experiments the oscillatory flow was imposed by a mechanical oscillator, and the oscillation periods were chosen to resemble DWO in a steam generator. The CHF was defined as the heat flux when the outer tube wall temperature exceeded predefined values specific to the tube thickness. It was observed that the CHF decreases until reaching a minimum value when increasing the normalized amplitude of oscillation ($\Delta G/G_0$), where ΔG is the flow oscillation amplitude and G_0 the mean flow. This work has also observed that large heat capacity tube shows less heat transfer degradation than the thin walled. More thermal capacity translates into a much less dynamic wall temperature, giving less feedback

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Table 1
Experimental studies of the impact of the oscillatory flows on the CHF and HTC.

References	Fluid	D (mm)	L (mm)	G (kg/m^2 s)	Note
Chang et al. (1996)	Water	1–10.8	12–860	1300 –27 000	CHF
Umekawa et al. (1996)	Water	3.0, 4.0, 5.8	900	100–700	CHF
Kim et al. (1999)	Water	5.0, 6.6, 9.8	500/600	40–400	CHF
Kennedy et al. (2000)	water	1.168/1.448	160	800–4500	HTC
Brutin and Tadrist (2006)	n-Pentane	0.889	200	800–4500	HTC
Barber et al. (2011)	n-Pentane	0.771	70	3.52	HTC
Fan and Hassan (2013), Fan (2013)	FC-72	0.889	130	160–870	CHF/HTC

from the wall to the flow. It is concluded that the heat flux distribution and its dynamics have to be taken into account when evaluating the CHF for tubes with large heat capacity. Kim et al. (1999) performed an experimental study to investigate the difference between a stable and oscillatory flow in forced and natural convection. In particular, the effect of flow oscillations on the CHF for water flow in three vertical round tubes was investigated. The experimental data indicates that the CHF generally decreases as the amplitude or period of flow oscillations increases. It was also found that the CHF can be much lower for natural circulation all though oscillations in the inlet have similar characteristics. Flow oscillation CHF correlation factors were developed for both natural and forced circulation. Kennedy et al. (2000) studied convective boiling in mini-tubes of 1.17 and 1.45 mm diameter using deionised and degassed water. Numerous experiments were performed for the two test sections at a specified heat flux. The focus was on the nucleate boiling and unsteady flow threshold which were obtained experimentally by analyzing pressure loss curves as a function of inlet mass flow rate for several heat fluxes. From these observations the heat flux when flow boiling becomes unsteady was deduced by the authors to be 90% of the heat flux necessary for a full fluid vaporisation. It was concluded that the onset of significant void generally occurs at a slightly higher mass flux, or lower heat flux, than the onset of flow instability. As a result, correlations for the onset of significant void can provide a conservative estimate for safe determination of the range of operational parameters. Brutin and Tadrist (2006) performed an experimental study on destabilisation mechanisms and scaling laws of convective boiling. The loop was composed of an 889 μm hydraulic diameter mini-channel coupled to a hydraulic jack type injection device providing a constant mass flow rate. A buffer tank completely filled with liquid was placed upstream of the test section to reduce mass flow rate fluctuations. A high speed camera was used to observe the flow patterns. Slug formation did always occur in the first half of the mini-channel. Experiments were conducted at several heat fluxes for variable mass flow rates. Barber et al. (2011) investigated flow boiling instabilities of n-Pentane in a single micro-channel of hydraulic diameter 771 μm. The periodic oscillations of the local heat transfer coefficient were correlated. In this case, the instability was attributed to the bubble dynamics and the channel wall thermal properties. In addition, it was observed as an augmentation of the heat transfer coefficient during two-phase periodic flow boiling, but this was accompanied by significant pressure fluctuations.

Fan and Hassan (2012, 2013) studied the flow boiling heat transfer in a horizontal micro-tube with an inlet orifice. Several instabilities were encountered, such as Ledinegg, DWO and PDO, either individually or in combinations. Adding an orifice could not increase the normal CHF in a micro-tube. However, adding a small orifice can avoid or delay the premature CHF since it helps improve flow stability.

In this work the effect of Density Wave Oscillations on the HTC will be studied for 4 studied conditions. The experiments are performed in a horizontal straight tube evaporator of 50 mm I.D. and 2 m long, using refrigerant R134a as working fluid. The paper is organised as follows. Section 2 describes the characteristics of the experimental facility. In Section 3 the experimental results and discussion are presented. Section 4 summarises the main conclusions of this work.

2. Experimental facility

The experiments are performed at the Two Phase Flow Instability facility at the Department of Energy and Process Engineering, NTNU (Manavela Chiapero et al., 2014a,b). The facility is a closed loop consisting of a main tank, a pump, a conditioner, a heated test section, a visualisation glass, an adiabatic test section and a condenser, see Fig. 1. The working fluid (R134a) is circulated by a magnetically coupled gear pump. The pressure in the loop is controlled by the saturation conditions at the main store tank. A pre-heater or conditioner adjusts the inlet temperature of the refrigerant before entering the test section. The pre-heater is a shell and tube heat exchanger with glycol in the shell side. The flow is measured with a Coriolis mass flow meter before the heated test section. Before and after the heated section a manually operated valve and an orifice plate are installed with a value of $K_i=2.63$ and $K_e=2.70$, respectively. The heated section is a stainless steel tube with 5 mm I.D. and 8 mm O.D. and 2035 mm long, Fig. 2. The tube is heated by Joule effect with a rectified sine wave and is insulated to reduce heat loss to the surroundings. In order to have control of the heating profile, the heating is done by 5 independent sections of 40 cm long, Fig. 3. The test section is equipped with 7 pressure taps for differential pressure drop measurements, a number of external (wall temperature) thermocouples, and 2 internal thermocouples. The pressure taps are connected to two pressure transducers by a network of valves which allows for a custom point of measurement. An additional third pressure differential transducer measures the overall test section pressure drop. Ten thermocouples are distributed along the outside bottom wall of the test section while there are seven on top. In particular, positions 6 (at 1117 mm from the inlet) and 10 (at 1917 mm from the inlet) include thermocouples on top, bottom, both sides of the wall plus an in-flow internal thermocouple. All the variables are logged with a National Instruments NI RIO data acquisition system. The temperatures, absolute pressures, pressure differences and mass flow rates were acquired at a frequency of 10 Hz.

2.1. Measurements and accuracy of measurements

For the temperature measurement, type-T thermocouples with 0.5 mm diameter have been used with an accuracy of 0.1 K (in-house calibration). The absolute pressure at the inlet and outlet of the heated section was used for determining the saturation temperature, T_{sat}, of the fluid based on the equilibrium properties calculated with software REFPROP.