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Effect of inlet pressure and temperature on density wave oscillations in a horizontal channel

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HIGHLIGHTS

- Period of Density Wave Oscillations increases with inlet pressure.
- Period of Density Wave Oscillations increases with inlet temperature.
- Flow regime in the pipe might control the period of the oscillations.

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ABSTRACT

The period of Density Wave Oscillations (DWOs) in an uniformly heated horizontal test section is experimentally investigated. The test section consists of a 5 mm I.D. pipe where R134a is used as working fluid. The experiment is performed for a range of inlet pressures P_i [500–1200 kPa], inlet sub-cooling [10 and 20 K], maintaining constant heat fluxes q'' [38 kW/m^2] and mass flux G [300 kg/m^{2}s]. The effect of the system parameters on the period of the DWOs is studied. It is observed that the period of the DWOs increases as inlet pressure and inlet sub-cooling temperature increase. Furthermore it is observed changes in the period which might be connected to the changes in the flow regime distribution inside the pipe.

1. Introduction

Two phase flow instabilities (Boure et al., 1973; Tadrist, 2007; Kakac and Bon, 2008; Manavela Chiapero et al., 2012) can be observed in different industrial areas such as refrigeration systems (Liang et al., 2011), LNG regasification (Baek et al., 2011), boiling water reactors (Durga Prasad et al., 2007), steam generators (Kim et al., 2009), and gas-lift wells (Hu, 2004). 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. For this reason it is important to understand the effect on the instability of system parameters such as flow rate, pressure, inlet temperature, thermal power and exit quality. In addition the characterisation of the oscillations in term of frequency and amplitude during the oscillations is relevant for design and operation of the equipment. A particular case of two phase flow instabilities is the density wave oscillation (DWO). A simplified description of DWOs is based on the delays induced by the transient distribution of pressure drops along the pipe. This is originated by the difference in density between the sub-cooled liquid entering the channel and the two-phase mixture exiting. A sudden pressure drop perturbation necessarily leads to a flow rate perturbation, which causes an enthalpy perturbation propagating throughout the pipe modifying the lengths of the single-phase and two-phase regions. In this case, the approach describes the oscillations as the product of enthalpy perturbations travelling with mixture flow velocity, and fluid waves of higher and lower density mixture travelling across the system. The travelling density waves affect the pressure drop in such a way that self-sustained oscillations are stabilised. The period of oscillations should be of the order of twice the mixture transit time. A different description of the mechanisms of DWOs is based on the different speeds of propagation of perturbations between the single-phase region (speed of sound) and the two-phase region (kinematic velocity) (Rizwan-Uddin, 1994). The oscillations seem to be more likely related to mixture velocity variations rather than to mixture density variations in particular at high inlet subcoolings. In this case the period of oscillations can be equal to even three or four times the mixture transient time. It is also important to mention the occurrence of higher-mode oscillations at high subcoolings and low power levels characterised by short periods of a fractions of the transient

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Table 1
Experimental studies of two phase flow instabilities in horizontal pipes.

Reference	Fluid	P_i (kPa)	T_{sub} (K)	I.D. (mm)	L (m)
Andoh (1964)	Water	700	90	4.58	3
Maulbetsch and Griffith (1965)	Water	100–600	50–120	1.19–6.35	1.5
Stenning and Veziroglu (1965)	R11	300–1000	14	3.75	0.95
Yuncu (1990)	R11	700	40	5	0.8
Ding et al. (1995)	R11	760	20–50	10.9	1.06
Comakli et al. (2002)	R11	350	16–28	11.2	3.5
Yilmaz et al. (2002)	R11	350	16–28	11.2	3.5
Cao and Kakaç (2009)	R11	300–600	50–100	7.5	0.605
Liang et al. (2011)	R22	500–800	50	8	3
Fan and Hassan, 2013	FC-72	10–45	43	0.889	0.150
Dorao et al. (2014)	R134a	500–1200	10–20	5	2

time (Yadigaroglu and Bergles, 1972). Nevertheless this relation is difficult to be confirmed experimentally as the definition and measurement procedure of the channeltransient time are not easy to define (Manera et al., 2005; Kruijf et al., 2002).

Table 1 presents a summary of previous research on two-phase flow oscillations in horizontal pipes. Andoh (1964) performed experiments with distilled water for investigating the effect of inlet temperature, flow rate, inlet subcooling and oscillation frequency at the inception of the flow oscillation. It was observed that the tendency for oscillation increases with subcooling. Maulbetsch and Griffith (1965) studied the effect of an upstream compressible volume as energy storage element on Pressure Drop Oscillations. It was concluded that when the compressible volume is external to the test section, the instability can be eliminated by sufficient throttling between the test section and the compressible volume. However for very long test section ($L/D > 150$) there can be sufficient compressibility due to vapor generation that the throttling did not have any value. Stenning and Veziroglu (1965) identified three distinct modes of flow oscillation which were termed Density Wave Oscillations (DWOs), Pressure Drop Oscillations (PDOs) and Thermal Oscillations (ThOs), classification that is still in use today. Yuncu (1990) studied the stability of an electrically forced-convection single horizontal channel with a gas surge tank placed upstream of the heated channel. DWO and PDO were observed. Stable and unstable boundaries were experimentally determined for a given range of heat flux, mass flow rate, and compressible volume in the surge tank. Ding et al. (1995) performed an experimental investigation of two phase flow instabilities (PDO, DWO and ThO). The dependence of amplitude and period on heat flux, inlet temperature and mass flux was studied. It was observed that DWO amplitude of inlet pressure oscillations did not change significantly with flow rate at same heat input but decreased as the heat input increased. Furthermore DWO oscillation period decreased as flow rate decreased, as heat input increased and as the subcooling increased. Comakli et al. (2002) studied two phase flow instabilities (DWO, PDO and ThO) in a horizontal in-tube flow boiling system. It was observed that the stability limit moves to lower mass flow rates with decreasing inlet temperature. Furthermore it was found that the periods and amplitudes of the PDO and DWO decrease with decreasing mass flow rate, and increase with decreasing inlet temperature. Yilmaz et al. (2002) investigated the effect of inlet subcooling on two-phase flow instabilities in a horizontal pipe system with augmented surfaces. Cao and Kakaç (2009) investigated two phase flow instabilities in a horizontal pipe. The experiments confirmed that a drift flux based numerical model predicted PDO quite well, in contrast to DWO, which could not be predicted because the model did not take the propagation of continuity waves that generates DWO explicitly into account. Liang et al. (2011) studied a R-22 vapor-compression refrigeration cycle. The paper is concerned with an experimental investigation of two-phase flow instabilities in a horizontal straight tube evaporator. The working condition in a refrigeration system is different from a water system, for example due to throttling device and the quality at the inlet and exit. Fan and Hassan (2013) experimentally investigated the effect of inlet orifice in a single microtube on flow instabilities using FC-72 as working fluid. It was observed that the instabilities can trigger a premature critical heat flux, CHF. Adding an inlet restriction can increase the premature CHF. Dorao et al. (2014) studied DWO in a horizontal heated pipe. It was observed that the period of the DWOs increases as the inlet pressure increases while the sub-cooling, heat flux, and mass flux were kept constant.

In spite of the experimental work in the area, there are several fundamental aspects on the nature of the DWOs that remains no well understood. In particular the nonlinear characteristics of the oscillations and the effect of the system parameters have not been completely studied, for example the effect of inlet pressure in the characteristics of the oscillations. Most of the previous research has focused on investigating the limits of the DWO's stability region, and the effect of the system parameters in the limits of stability. This aspect has been particularly relevant for the validation of linear system codes. However with the growing development and use of nonlinear system codes (Papini et al., 2012; Narayanan et al., 1997), more detailed data bases are required for code validation.

This paper studies the effect of inlet pressure in the characteristics of the DWOs (period of the oscillations) for a heat flux ($q'' = 38\ \text{kW/m}^2$), mass flow rate ($G = 300\ \text{kg/m}^2\ \text{s}$), and two inlet temperature subcooling (10 K and 20 K). 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 followed. Section 2 describes the characteristics of the experimental facility. In Section 3 the experimental results and discussion are presented. In Section 4 the main conclusions of this work are discussed.

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, Fig. 1. The working fluid (R134a) is driven by a magnetically couple 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