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Heat transfer measurement and flow regime visualization of two-phase pulsating flow in an evaporator

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ABSTRACT

Heat transfer and flow regime of two-phase R134a pulsating flow in an evaporator have been studied experimentally in this work. Heat transfer coefficient was measured and liquid-vapor two-phase flow regimes was observed under different mass flux, inlet vapor quality and pulsating period. Results show that heat transfer can be enhanced by pulsating flow in short periods (<16 s) with a maximum enhancement of 28% compared with the continuous flow; a deterioration of heat transfer is also observed for flow under long pulsating periods for some conditions, which could be as much as 30%. The effect of mass flux and inlet vapor quality is complex and coupled with pulsation period, which might result from the difference of flow developing between different pulsating periods. The instantaneous flow regime is recorded by a high speed camera and statistically analyzed to explore the mechanism of pulsating flow on heat transfer performance. The statistical analysis of flow regime from the recorded video shows that the flow regime of pulsating flow at on-time remains the same as that of continuous flow with the same instant mass flux, and the flow regime at off-time is mostly stratified, stratified wavy flow depending on the pulsating period. The transition of stratified-wavy flow regime to intermittent, annular flow regime of pulsating flow is the main contribution to the enhancement of heat transfer while dry-out during off-time plays an important role in heat transfer deterioration.

1. Introduction

Pulsating flow (pulsed flow), characterized as periodic variation of one or some flow parameters, exists in numerous systems, such as arterial circulation, combustion engine, reciprocating compressor system and so on. It could be a natural response to the system operation, which is the case for most situations; however, it also might be generated due to the flow instability, for example, the flow pulsation could encounter in evaporators at the liquid and liquid-vapor two-phase coexist region induced by density wave or pressure-drop oscillation, which could mislead the control system and result in a well-known phenomena called hunting in some AC&R systems [1–5]. Such flow pulsation/oscillation is also very common in microchannel heat exchanger and results in fluids maldistribution [6–9]. It is very important to understand the flow dynamic and thermal behavior of pulsating flow for system performance improvement and control strategy development.

The thermal behavior of pulsating flow is very complex and how it affects heat transfer coefficient is not clear. For single phase convection, the pulsation could reduce the time-averaged thickness of the boundary layer and hence the thermal resistance, which could enhance heat transfer coefficient. For the flow boiling, on one hand, pulsations could induce a better bulk mixing, increase wall wetting and alter flow regimes; also the local pressure variation due to pulsation might lead to a local vacavitation effect and change the nucleation. On the other hand, it might suppress the nucleate boiling by a decreased wall superheat. All above factors add the complexity to understand the effect of pulsating flow on heat transfer performance, which might also explain why different conclusions are drawn under different conditions when it comes to the question whether pulsating flow could enhance heat transfer performance. A summary of prior research on pulsating flow has been listed in Table 1. There has been a lot of work done on single phase pulsating flow both experimentally and theoretically, and the conclusion from experimental work varies, even conflicts with each other due to different approaches to set up the pulsation and different conditions to run the experiment in different work. Theoretical analysis could examine a wider range of conditions and more precisely set the pulsating parameters (such as amplitude, frequency). Most results from theoretical work point out that the enhancement by pulsating flow exists a maximum value under

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Table 1
Prior research on pulsating flow.

Authors	Working media	Conditions	Approach	Summary of conclusion
Martinelli (1943) [10]		Low frequency, vertical flow	Experiment	No effect
Wang et al. (2014) [11]	Water	Vertical narrow channel Period 10–30 s	Experiment	No effect
Mehta et al. [12]	De-ionized and de-gassed water	Frequency0.05, 1.0, 3.0 Hz Square mini-channel	Experiment	Negligible effect
Baird et al. [13]	Water	A steam jacketed copper tube Frequency 0–70 Hz	Experiment	41% enhancement on the overall heat transfer coefficient
Shuai et al. [14]	Aqueous solution of glycerol (60 wt%)	A co-axial cylindrical tube heat exchanger Frequency < 2 Hz	Experiment	300% enhancement
Sailor et al.[15]	Air	A brass heat transfer surface, Frequency 20–60 Hz	Experiment	Exceeding 50% enhancement
Zohir [16]	Water	Parallel flow and counter flow heat exchanger Frequency 0–40 Hz	Experiment	Enhancement of 20% in parallel flow and 90% in counter flow
Patel et al. [17]	Air	A pipe with pulsator at different location Frequency 1–3.33 Hz	Experiment	Maximum enhancement of 17.7 and 44.4% at pulsation frequency of 3.33 Hz
Karamercan et al. [18]	Water	Steam-water double pipe heat exchanger with steam in the shell side Frequency 0.4–11 Hz	Experiment	An increase of ??, the maximum enhancement is at transition regime (No details)
Jun et al. [19]	Water	Single pipe heat exchanger	Experiment	Enhance heat transfer by 10%
Pendyala et al. [20]	Water	A vertical tube frequency 0.133–0.5 Hz	Experiment	An increase of 60% of Nusselt number in laminar flow but no effect in turbulent flow
Kharvani et al. [21]	Water	Spiral-coil tube, Re of 6200–16,300, pulsation frequency from 0 to 20 Hz	Experiment	An enhancement of 26%
Wantha [22]	Air	Finned heat exchanger frequency 10–50 Hz amplitude 13.33%–15.33%	Experiment	Enhance heat transfer by 20%
Al-Haddad et al. [23]	Air	A rigid circular pipe frequency 5–60 Hz	Experiment	Developed an empirical correlation and enhancement depending on a critical dimensionless number
Moschandreou et al. [24]			Theoretical model	Found a positive peak in the effect of pulsation where heat transfer could be enhanced maximally
Benavides [25]	Water	Straight channel Strouhal number 0–14	Theoretical model	The heat transfer was not changed for straight channels with fully development profiles of velocity while it changed where velocity profile was not developed
Jafari et al. [26]	Incompressible newtonian	A corrugated channel Strouhal number 0.05–1 Amplitude 0–0.25	Lattice Boltzmann Method (LBM)	The enhancement highly dependent on pulsation velocity parameters, an optimized velocity exists
Yin et al. [27]		A round tube at a triangular pressure waveform	Analytical solution	Triangular waveform can enhanced heat transfer coefficient when the oscillating frequency decreased or the amplitude increased
Wang et al. [28]	Air	A channel with delta winglets under laminar pulsating flow	Numerical simulation	An increase of 25% of overall *j*-factor
Bohdal et al. [29]	R404A two phase	Flow boiling in a refrigerator with frequency of 0.029–0.07	Experiment	A reduction in size of the active surface of heat transfer by decreasing the boiling region
Chen et al. [30]	R134a two phase	Flow boiling in a narrow annular duct, oscillation of a triangular wave with amplitude from 10% to 30% cycle time from 20 to 120 s	Experiment	Slightly effect on the time averaged heat transfer coefficient
Roh et al. [31]	R410A two phase	Heat pump system with a control valve installed in parallel with the expansion valve	Experiment	COP was improved by 4% at a cycle time 200 s
Yuan et al. [32]	Water two phase	A gear pump generated pulsating flow with amplitude from 0.1 to 0.3 and period from 10 to 30 s	Experiment	Heat transfer was enhanced when intermittent flow boiling appears
Kærn et al. [33]	R134a two phase	Round tube, flow boiling with water as the heating source, period of 1–9 s	Experiment	Heat transfer coefficient improved by 3.2% at low cycle time (1–2 s), reduced by 8% at higher heat flux and cycle time 8 s
Wang et al. [34,35]	R134a two phase	Generated by a solenoid valve with two parallel identical round tube plane-fin heat exchanger with air as the heating source, period of 2 s–24 s	Experiment	Enhancement of 123%

the optimized condition, which includes one or some of the optimized key parameters, such as pulsating amplitude, frequency, flow regimes (developing/developed), vertical/horizontal flow and so on, and the enhancement ratio strongly depends on the velocity profile (Benavides [25], Jafari et al. [26]). Most work on flow boiling of pulsation is by experiment, again, conclusion from different group could be very different due to the variation of experimental conditions. Some have a focus on the coefficient of system performance (COP) (Roh et al. [31], Ilic et al. [36]), which has more factors involved other than only heat transfer coefficient. Kærn et al. [33] measured local time-averaged heat transfer coefficient during pulsation at a period range of 1–9 s, and found that a heat transfer enhancement of 10% for pulsating flow at a lower pulsating period, and a heat transfer reduction of 20% at a higher pulsating period.

In this work, effects of pulsating on flow heat transfer of R134a flow boiling has been studied under a wide range of conditions with different parameters of heat flux, mass flux, pulsation period and vapor quality. Pulsating flow regime has been observed within a transparent tube and how the pulsating flow could affect the heat transfer coefficient has also been statistically analyzed.