Proceedings of the ASME 2010 3rd Joint US-European Fluids Engineering Summer Meeting and
8th International Conference on Nanochannels, Microchannels, and Minichannels
FEDSM-ICNMM2010
August 1-5, 2010, Montreal, Canada

FEDSM-ICNMM2010-30487

RESEARCH ON TWO-PHASE FLOW INSTABILITY IN EVAPORATOR OF REFRIGERATION SYSTEM

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ABSTRACT:

As one kind of fluid machinery related to the two-phase flow, the refrigeration system encounters more problems of instability. It is essential to ensure the stability of the refrigeration systems for the operation and efficiency. This paper presents the experimental investigation on the static and dynamic instability in an evaporator of refrigeration system. The static instability experiments showed that the oscillatory period and swing of the mixture-vapor transition point by observation with a camera through the transparent quartz glass tube at the outlet of the evaporator. The pressure drop versus mass flow rate curves of refrigerant two phase flow in the evaporator were obtained with a negative slope region in addition to two positive slope regions, thus making the flow rate a multi-valued function of the pressure drop. For dynamic instabilities in the evaporation process, three types of oscillations (density wave type, pressure drop type and thermal type) were observed at different mass flow rates and heat fluxes, which can be represented in the pressure drop versus mass flow rate curves. For the dynamic instabilities, density wave oscillations happen when the heat flux is high with the constant mass flow rate. Thermal oscillations happen when the heat flux is correspondingly low with constant mass flow rate. Though the refrigeration system do not have special tank, the accumulator and receiver provide enough compressible volume to induce the pressure drop oscillations. The representation and characteristic of each oscillation type were also analyzed in the paper.

INTRODUCTION

As one of the fluid machinery related to the two-phase flow, refrigeration systems are widely applied in production and manufacture. The instability of the refrigeration system is the phenomena of oscillations of all parameters such as the refrigerant flow rate, refrigerant pressures and temperatures at different points, which was first found in some fix capacity refrigeration systems[1-6]. The increasing employing of variable capacity compressor and electronic expansion valve (EEV) have provided the improvement opportunity and application background for the improvement of system performance [7-10]. However, due to the excessive difference between different operational states, premature control and lingering adjustment of the system parameter, the variable capacity technology also brings oscillations in practical application[9]. The instability will lead lower safety, lower life-span and higher energy consumption in refrigeration system[1-3], so the stability is the necessary condition for a successful and high-efficiency refrigeration system.

Through early experimental observations, Zahn[1] in 1964, Wedekind and Stoecker[2] in 1966 found the oscillatory motion of mixture-vapor transition point and the motion was considered as an oscillatory nature, even for steady flow condition. The prevalent classification for the cause of instability can be explained with a) the influence of the inherent characteristics of two-phase flow instability and b) the influence of the system control characteristics on system stability. The former emphasizes particularly on the rule and characteristics of two-phase refrigerant flow without intention to eliminate the inherent instability while the latter tries to explain and solve the instability problem to keep the macroscopic stability. It is obvious that research on two-phase flow instability provides the basis for research on system stability.

There are usually two main research aspects on the instability of refrigeration system: static research and dynamic research. Static research for system is to study the instability of the system with evaporator and expansion valve (EV) control loop when the system is on the steady condition.

Dynamic researches focus on the dynamic oscillations when the system parameters suddenly changed. Due to the differences on the range of heat flux and working temperature, the classification of dynamic oscillations is summarily depicted as following: Ledinegg instability, flow pattern transition instability, density-wave oscillations, thermal oscillations, and pressure drop oscillations [11, 12].

As the most common fluid, the amount of published experimental research on water two-phase flow instabilities is overwhelming. However, the researches on water two-phase flow instabilities have some differences compared with refrigeration system:

1) Some of the water systems are open circulation and the evaporating pressure is governable as a fixed value with a surge tank or some compressible containers, the similar containers in refrigeration systems do not have such functions;

2) The heat flux of evaporators tube in water systems is often much higher than those in refrigeration systems. The working condition in refrigeration system is also different compared with water system, such as throttling device and quality at the inlet and exit.

These differences may cause the absence of certain types of oscillations. They are also obstructions in application of water two-phase flow instabilities theories and results in refrigeration system.

Researches on the refrigerant two-phase flow instabilities are much less. And the preceding researches focused on the thermal character of refrigerant with several types of tube, but the system setup is same as the water system[13-19]. R-11 and R-113 were used as test fluid in these investigations. Among these results, only Veziroglu et al.[13] investigated the stability boundaries of sustained density-wave oscillations in an electrically heated single channel, up-flow system with R-11 as the test fluid. It is conceivable that the subcooling degree, mass flow rate and heat flux are important for the refrigeration system from the preceding researches and more detailed work still need to be carried out.

Although the experiment investigations are comparatively less, the dynamic oscillations are still considered to be one of the most important causes for instabilities of refrigeration system in many researches. As for the refrigerant two-phase flow in the evaporator of refrigeration systems, Zahn[1], Wedekind and Beck[5], Barnhart and Peters[20] considered that the occurrence of slug flow at the inlet of evaporator caused the oscillation based on their experimental and academic analysis. Actually the slug flow should be a kind of oscillation of thermal or the result of density-wave oscillation; at the same time, Wedekind and Stoecker[2] believed that it was related to the density-wave oscillation; Gruhle and Isermann[21] proposed a probability that it may be influenced by the strong nonlinear character of the heat transfer coefficient. In fact, the change of heat transfer coefficient maybe the compositive result of density-wave oscillation and other oscillations as pressure drop types. However, there is not a general explanation and experimental proof in refrigeration system accepted by all researchers.

This paper proposed some experimental results on two phase flow oscillations in a refrigeration system with a horizontal electric heated evaporator, using R-22 as the test fluid. The static instability experiments also showed that the oscillatory period and swing of the mixture-vapor transition point by observation with a camera through the transparent quartz glass tube at the outlet of the evaporator. The pressure drop versus mass flow rate curves of the evaporator were obtained and three modes of dynamic oscillations were observed in the dynamic experiments: density wave oscillations, pressure drop oscillations and thermal oscillations.

EXPERIMENT SYSTEM

As shown in Fig.1, the experimental refrigeration system consisted of four main components of compressor, water-cooled condenser, evaporator and EEV and other assistant components. The setup is designed so that it is possible to generate the several different types of oscillation.

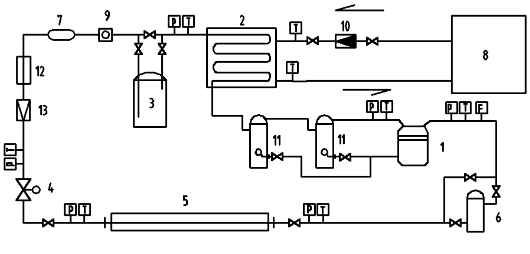


Fig.1 EXPERIMENTAL SYSTEM

1.Compressor 2.Condenser 3. Receiver 4.EEV

5. Horizontal tube electrothermal evaporator 6. Accumulator 7. Filter drier

8. Constant temperature water circulator 9.Sight glass 10. Water flow meters

11. Oil separator 12. Subcooler 13. Mass flow meters

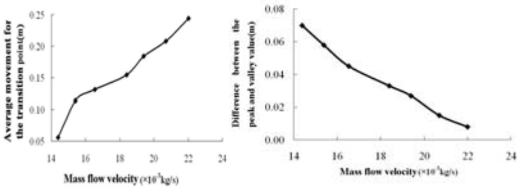
Variable frequency compressor is used to regulate the mass flow rate of refrigerant by changing the power frequency. The constant temperature water circulator provides the cooling water for condensing and the water temperature can be regulated to generate oscillations. The two-phase flow formed in EEV is vaporized in horizontal tube electrothermal evaporator whose heat flux is determined by a voltage regulator. The mass flow rate of water and refrigerant is measured with the water and refrigerant mass flow meter respectively. The precision for mass flow meters is listed in Tab.1. The pressure sensors used in the experiment system are MPM480 of Micro Sensor Co. Ltd with the precision of $\pm 0.25\%$ of full scale. All temperature measurements on evaporator are made by copper-constantan thermocouples with 0.5mm diameter. Six copper-constantan thermocouples are fixed evenly on the outer surface of the test tube and other six copper-constantan thermocouples are inserted into the tube to measure the inside temperature. The signals of thermocouples, pressure sensors and mass flow meters are obtained from data acquisition system to be processed and memorized in computer.

In the experiment, a camera is used to obtain the photographic record of the transition point at the outlet of evaporator through the transparent quartz glass tube as a function of time. The transparent quartz glass tube is set just at the outlet of evaporator and the inner diameter of quartz glass tube is same as the one of evaporator copper tube.

EXPERIMENTAL RESULTS AND ANALYSIS

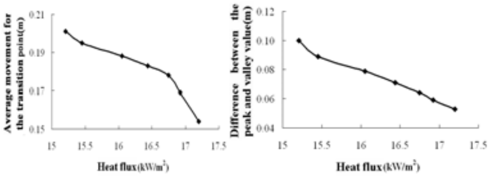
The movement of the transition point at the outlet

When the state for the outlet of evaporator is two-phase, the oscillations will lead to the pulse two-phase flow out of the outlet. With the quartz glass tube, it is convenient to get the picture of transition point between the two-phase flow and superheated flow to research on the movement rules. Fig.2 shows the movement rules of transition point for density wave outlet oscillations with the heat input of 1000W. The density wave outlet oscillations are comparatively steady compared to the other two types of oscillations. Therefore the rules for density wave outlet oscillations are clearer. The average movement of transition point increases when the mass flow velocity increases. And the difference between the peak and valley value for movement decreases when the mass flow velocity increases. On the other hand, the average movement of transition point and the difference between the peak and valley value for movement are inversely proportional to the heat flux.



(a) The average movement versus the mass flow velocity

(b) The difference between the peak and valley value versus the mass flow velocity



(c) The average movement versus the mass flow velocity

(d) The difference between the peak and valley value versus the mass flow velocity

Fig.2 THE MOVEMENT RULES OF TRANSITION POINT FOR DENSITY WAVE OUTLET OSCILLATIONS

Steady state characteristics

Steady state characteristics are displayed with curves of the pressure drop versus mass flow rate of the refrigerant in the evaporator. The pressure drop is defined as the difference between the pressure at the inlet and the outlet of evaporator. These curves are also called the channel demand pressure-drop versus flow rate curves or the internal characteristic curves. A figure of steady state characteristics of the evaporator in the experiment system is shown in Fig.3. It can be observed that the characteristic curve had a negative slope region in addition to two positive slope regions, thus making the flow rate a multi-valued function of the pressure drop.

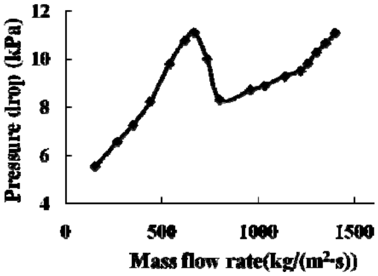


Fig.3 STEADY STATE CHARACTERISTICS CURVE

Steady state characteristics of different heat input on the evaporator

The heat input of evaporator in experiments ranged from 500W to 1500W. The curves of 500W, 800W, 1000W, 1200W and 1500W with the constant evaporating pressure of 0.7 Mpa are shown in Fig.4. It is obvious that the negative slope appears with larger mass flow rate when the heat input gets greater.

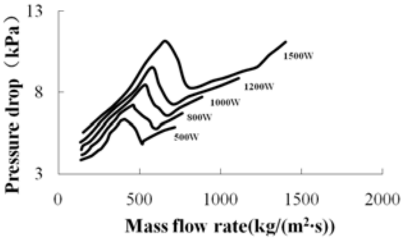


Fig.4 THE STEADY STATE CHARACTERISTIC CURVES OF DIFFERENT HEAT INPUT

Density wave oscillations

As known, the density wave oscillations is the results of fluid waves of alternately higher and lower density mixtures travel across the pipe. The periods of the density wave instability are proportional to the transit time of a fluid particle through the system. The oscillations are due to multiple regenerative feedbacks between the flow rate, vapor generation rate and pressure drop[11].

In the experiments, the pure density wave oscillations begin from the smallest mass flow rate to the boundaries of pressure drop oscillations. In the Fig. 5 and Fig. 6, the recordings of density wave oscillation of 1500W are shown with the curves of mass flow rates and evaporating temperature. The periods and amplitudes of oscillations can be calculated from the figure. For the heat input of 1500W, the period of density wave oscillations is about 4s; the amplitude for evaporating temperature is 0.6 ^{o}C; the amplitude for mass flow rate is about 60 kg/ (m^2·s)). When the heat input decreases, the period decreases and the amplitude increases.

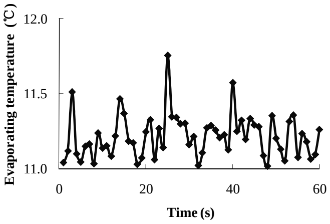


Fig.5 THE EVAPORATING TEMPERATURE CURVE FOR DENSITY WAVE OSCILLATIONS (HEAT INPUT: 1500W)

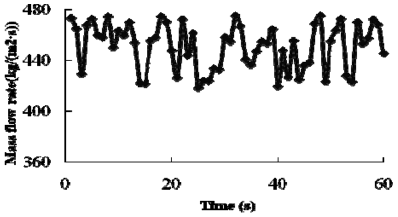


Fig.6 THE MASS FLOW RATE CURVE FOR DENSITY WAVE OSCILLATIONS (HEAT INPUT: 1500W)

Pressure drop oscillations

Pressure drop oscillations start at the negative slope of the steady state characteristic curves. Internal characteristics with negative slopes, and external characteristics steeper than the internal characteristics as well as the existence of a compressible volume (e.g. surge tank) in the flow circuit are the conditions necessary for the occurrence of the pressure drop type oscillations. Typical recordings of pressure drop oscillations are shown in Fig.7 and Fig.8 with the heat input of 1500W. For the heat input of 1500W, the period of pressure drop oscillations is about 10s; the amplitude for evaporating temperature is 1 ^{o}C; the amplitude for mass flow rate is about 150 kg/ (m^2·s)).

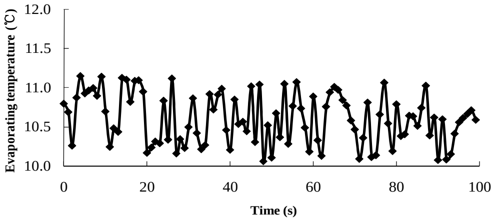


Fig.7 THE EVAPORATING TEMPERATURE CURVE FOR PRESSURE DROP OSCILLATIONS (HEAT INPUT: 1500W)

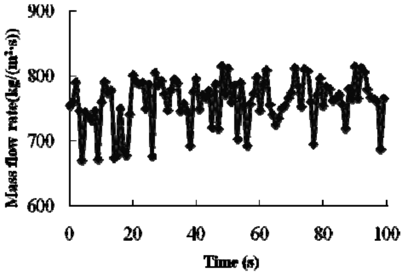


Fig.8 THE MASS FLOW RATE CURVE FOR PRESSURE DROP OSCILLATIONS (HEAT INPUT: 1500W)

Thermal oscillations

For thermal oscillations (In some literature, this type is considered to be a kind of thermal oscillations), the flux oscillation is aroused by the generation and growth of bubble, sometimes accompanied with the density wave oscillation. The typical character of oscillations concerning the thermal is long period and great swing. The inducement of these oscillations mostly fell on the high subcooling degree and low quality. Typical recordings of pressure drop oscillations are shown in Fig.9 and Fig.10 with the heat input of 1500W. For the heat input of 1500W, the period of pressure drop oscillations is about 60s; the amplitude for evaporating temperature is 3 ^{o}C; the amplitude for mass flow rate is about 900-1000 kg/ (m^2·s)). The density wave oscillations are obviously simultaneous when the thermal oscillations appear.

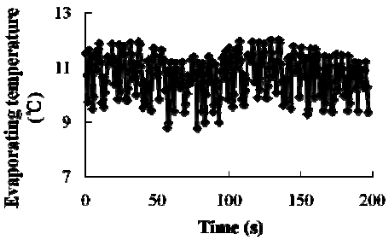


Fig.9 THE EVAPORATING TEMPERATURE CURVE FOR THERMAL OSCILLATIONS (HEAT INPUT: 1500W)

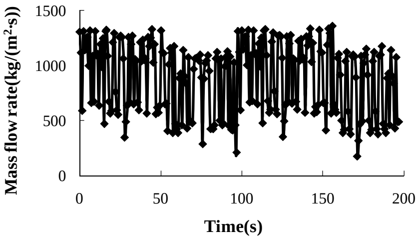


Fig.10 THE MASS FLOW RATE CURVE FOR THERMAL OSCILLATIONS (HEAT INPUT: 1500W)

Stability boundaries

During the experiments, the boundaries of several oscillations are defined with two distinct lines with different mass flow rate. The boundary between density-wave oscillations and pressure drop oscillations means that it is possible to induce pressure drop oscillations at the right side of the boundary; the boundary between pressure drop oscillations and thermal oscillations means that it is possible to induce thermal oscillations at the right side of the boundary; With the same evaporating pressure, these oscillations appear for all heat input in our experiments. The boundaries between density-wave oscillations, pressure drop oscillations and thermal oscillations are shown in Fig.11. In our experiments, as the mass flow rate increases gradually, the density wave oscillations first come out. Then pressure drop oscillations are observed at the middle of steady state characteristics curves, where the slope is negative. And the pressure drop type oscillations come out with superimposed density wave oscillations. When the heat input increases, the boundaries between the pressure drop and density wave oscillations move to the higher mass flow rates, which means the unstable region of density wave oscillations increases as the heat input increases. In the experiments, the end or the onset of the density wave oscillations is not found when reducing the mass flow rate. With the smallest mass flow rate, the density wave oscillations still exist. And with our experimental system, the mass flow rate can not be smaller because there is a minimum value in characteristic curve of compressor.

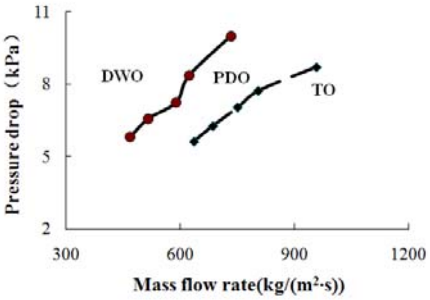


Fig.11 BOUNDARIES OF DIFFERENT OSCILLATIONS

DWO- and density-wave oscillations, PDO - pressure drop oscillations, TO- thermal oscillations, respectively.

It is can be concluded that the density wave oscillations happen when the heat load is high with the constant mass flow rate. Thermal oscillations happen when the heat load is correspondingly low with constant mass flow rate. Though the refrigeration system do not have special tank, the accumulator and receiver provide enough compressible volume to induce the pressure drop oscillations. For the inner tube, it is obvious that the density wave oscillations happen for almost all the mass flow rates in our experiments. Pressure drop oscillations in refrigeration system are also incidental while the state lies on the negative slope of the steady state characteristic curves. Thermal oscillations can be induced while the mass flow rate is so high that the heat load can not evaporates the refrigerant adequately. It may happen with some premature control in refrigeration system.

CONCLUSION

In the paper, the two-phase flow instability in a refrigeration system is studied. The important findings in the study are summarized as follows:

1) The static instability experiments also showed that the oscillatory period and swing of the mixture-vapor transition point by observation with a camera through the transparent quartz glass tube at the outlet of the evaporator. The average movement of transition point and the difference between the peak and valley value for movement are inversely proportional to the heat flux. The average movement of transition point and the difference between the peak and valley value for movement are directly proportional to the mass flow velocity.

2) The pressure drop versus mass flow rate curves of refrigerant two phase flow in the evaporator were obtained with a negative slope region in addition to two positive slope regions, thus making the flow rate a multi-valued function of the pressure drop.

3) For dynamic instabilities in the evaporation process, three types of oscillations (density wave type, pressure drop type and thermal type) were observed at different mass flow rates and heat fluxes, which can be represented in the pressure drop versus mass flow rate curves. For the dynamic instabilities, density wave oscillations happen when the heat flux is high with the constant mass flow rate. Thermal oscillations happen when the heat flux is correspondingly low with constant mass flow rate. Though the refrigeration system do not have special tank, the accumulator and receiver provide enough compressible volume to induce the pressure drop oscillations.

ACKNOWLEDGEMENT

The study was supported by Natural Science Foundation of China (Grant No. 50676099).

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