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Experimental investigations on thermo-hydrodynamics of continuous Taylor bubble flow through minichannel

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ABSTRACT

Pulsating Heat Pipe (PHP) has received significant attention in the field of electronics cooling due to its simplicity, manufacturing ease and versatility. PHP involves intricate internal gas–liquid two-phase thermo-hydrodynamics. The present paper is an effort to understand this complex hydrodynamics under adiabatic and diabatic conditions. Experimental investigations are reported for air–water two-phase flow through 2.12 mm horizontal circular minichannel. The influence of individual gas and liquid inlet flow rates on Taylor bubble velocity, void fraction, liquid holdup and lengths of the liquid slug and Taylor bubble, frictional pressure drop and heat transfer in continuous Taylor bubble train flow (CTB) is analysed. The findings of the present investigation could be helpful to develop mathematical model for PHP for future research.

1. Introduction

Miniaturized systems in next generation computers and power electronics involve generation of very high heat fluxes at their top clock speed. For instance, newly designed Intel computer chip generates 100 W/cm^2 of localised heat flux with the total power exceeding 300 W [1]. It becomes very important to dissipate these high heat fluxes in order to limit the maximum operating temperature of chip (@ 85 °C) as well as to maintain uniform temperatures in the electronic parts. Heat pipes have potential to dissipate such high heat fluxes. Pulsating Heat Pipe (PHP) is a gas–liquid two-phase heat transfer system able to dissipate heat without any additional power input. The ideal flow pattern in the PHP is the capillary slug flow or Taylor bubble flow driven by pressure difference between evaporator and condenser. With increase in heat flux, the oscillatory slug flow is first converted to directional slug flow which further shapes into directional annular flow at high heat flux [2].

These thermally induced flow patterns are very complex due to their dependence on many important parameters such as thermal gradient, thermo-physical properties of the working fluid and filling ratio. In addition to this, hydrodynamics of Taylor bubble flow, i.e., bubble shape, size and velocity, liquid film thickness surrounding the Taylor bubble, frictional pressure drop, oscillating frequency and evaporation at the interface significantly affects the local heat transfer. Hence, mathematical model for the PHP as a whole system is quite involved.

Mehta and Khandekar [3] suggested a coupled approach for PHP analysis by splitting the complete PHP model development in steps. The first step towards the development of PHP model is to study the hydrodynamics of continuous Taylor bubble train flow (CTB) under adiabatic condition. It can be extended for non-boiling diabatic and Pulsating Taylor Bubble flow (PTB) without phase change. Moreover, the sensible heat transfer in PHPs becomes primary mechanism of heat transfer in the trapped liquid slug between Taylor bubbles [4]. The Taylor bubble velocity of CTB may be qualitatively compared to the effect of intensity of pulsation on Taylor bubbles, i.e., PTB and liquid slugs. Void fraction and liquid holdups can be viewed as the effect of charge ratio under varying heat flux conditions. The fundamental understanding of these parameters will help in developing suitable mathematical model for PHP and in turn towards commercialization of PHP. The primary motive of the present research paper is to understand the complex thermo-hydrodynamics of Taylor bubble flow without phase change (non-boiling) and pulsation frequency. The following issues are addressed in the present work.

1. Hydrodynamics of CTB through circular minichannel under adiabatic condition to evaluate the effect of inlet flow parameters on Taylor bubble velocity, void fraction, liquid hold-up, lengths of the liquid slug and Taylor bubble and frictional pressure drop.

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2. Estimation of the influence of hydrodynamics on heat transfer rate for non-boiling diabatic CTB.

2. Experimental setup

The experimental setup developed to carry out adiabatic and diabatic investigations on non-boiling gas–liquid two-phase flow is shown in Fig. 1. It consists of gas–liquid flow circuits, visualization section, pressure drop measurement and heating section. The Heating section is designed to calculate the local convective heat transfer coefficient. The transparent section is used to supply predetermined Taylor bubble and liquid slug length for CTB to the heating section through flow control unit.

The working fluids used are air and water. Reversed Osmosis (RO) water is stored in a 500 l capacity nonporous light weighted cylindrical polyethylene tank. RO water passes through 10 micron Lixus make sediments filter to remove large dirt, sand, silt, scale and rust particles. Water flow rate is controlled using Alicat Scientific make LC series digital liquid flow controller of 100 CCM (Cubic Centimeter per Minute). It has ±2% accuracy, ±2% full-scale repeatability and less than 100 ms control response time. Air is supplied to the test section using a single stage, single cylinder, air cooled, PE 10/1 series reciprocating compressor. The compressed air goes to separate air storage tank. The storage tank is protected using a pressure relief valve at the top and one solenoid valve at the bottom. A drain valve is provided below the air storage tank to remove all the contaminants including oil present in the air. Dry air from the storage tank flows to the test section through a filter regulator (FRC1 series). Alicat Scientific make MC series digital gas mass flow controller of 100 SCCM (Standard Cubic Centimeter per Minute) is used to accurately measure and control the mass flow rate of gas. It is calibrated for 30 on board gases and operates via laminar differential pressure measurement. It has ±0.4% accuracy and ±0.2% full-scale repeatability.

Air and water enter into the test section through Y-junction. The test section involves 2.12 mm internal diameter circular glass tube and stainless steel (SS 316) tube. Glass tube is used to visualize the flow patterns of gas–liquid two-phase flow while SS tube is used for diabatic experiments. The internal diameter is measured with the help of Sipcon make SVI-IMG-300 series vision measuring system as shown in Fig. 2. The measurement accuracy of the system is $(3 + L/200)$ micron where L is the length of the sample. The photographic view of heating section is shown in Fig. 3. The total length of the SS tube is 300 mm while the length of the heating section is 250 mm. As shown in Fig. 3(a), total five pair of equidistant (50 mm) Rays make PT-100 type (wire wound, 3-wire construction, class B) Resistance Temperature Detector (RTD) is installed on SS tube wall to measure the wall temperatures. Two RTDs are used to measure the fluid inlet and outlet temperatures. The measurements are made differentially with respect to the entrance temperature of the fluid with a minimum detectable temperature difference of ±0.5 K. RTDs are calibrated and their accuracy is found as ±0.5%. Ni–Cr wire (350 ohm, 0.5 mm OD) is wrapped over SS tube for 250 mm length (approx. 8 turns between RTDs) to heat up the test section and is shown in Fig. 3(b). Other components used for the experiments are Multispan make multifunctional meter to monitor real time wattage input and Simon servo voltage controller to supply constant 230V to the system.

The flow patterns are observed with the help of image recording system. It consists of two halogen light source each 1 kW, high speed camera, tripod stand, memory card and computer. The high-speed CMOS 9.1 megapixels, 3X optical zoom and ultra hi-speed continuous Shutter CASIO make Exilim EX-FS10 series camera is used for flow visualization. The high-speed Movies are captured at the rate of 210, 420 and 1000 frames per second (fps). The image size in terms of recorded pixels for 210 fps is 480×360, for 420 fps is 224×168 and for 1000 fps is 224×64. The camera is set with the help of tripod stand. After capturing the images, the data from memory card is transferred to the personal computer for post processing. ImageJ software is used for the post processing of captured data.

Pressure drop measurement is carried out using HTC make PM-6205 series digital water manometer. It has 11 different measuring units. The present experiments are carried out in kPa unit which has least count of 0.01 kPa. The manometer is equipped with data hold, min–avg–max value with relative time stamp, zero adjust, offset and DIF function and USB computer interface. The accuracy of the manometer is ±0.3% of full scale reading.

2.1. Experimental procedure

The experiments in the present research work are carefully conducted. The test section is first set to perfect horizontal position using spirit level. The electrical instruments are then turned on. Once the scanner system is in function, the RTDs readings (total

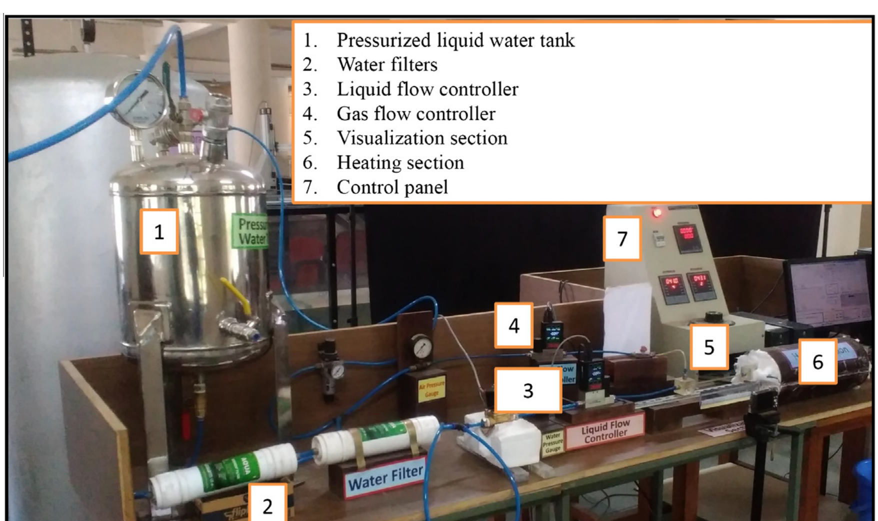

Fig. 1. Photograph of the non-boiling gas–liquid two-phase flow experimental setup.