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Brief Communication

Experimental investigation on the thermo-hydrodynamics of oscillatory meniscus in a capillary tube using FC-72 as working fluid

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Introduction

A pulsating heat pipe (PHP) is a promising heat transfer device for applications such as electronic cooling. The general design of the PHP is based on an evaporator on the one end and a condenser on the other end of the device. This creates a temperature difference inducing mechanical non-equilibrium which leads to a flow pattern inside the tube. It has been reported (Shafii et al., 2001) that the amount of sensible heat transported in a PHP is higher than the amount of latent heat transfer. However, due to its complicated operating mechanism, the flow phenomenon and the associated heat transfer properties of the PHP have not been fully understood (Angeli and Gavriilidis, 2008; Karimi, 2004).

The influence of the multiple changing variables within a PHP makes the device rather hard to understand. A reduction of the whole PHP to a single unit cell (i.e. vapor bubble and liquid slug) makes the investigation of the individual parameters on the oscillatory behavior much easier. The publications in the field of pulsating heat pipes increased significantly over the last few years (Holley and Faghri, 2005; Khandekar, 2010; Kandlikar, 2002; Groll and Khandekar, 2003; Karthikeyana et al., 2014; Ma et al., 2006). However the fundamental understanding of the thermodynamic processes governing Taylor bubbles or meniscus oscillations remains rather unclear. The effects based on the interaction between the different "cells" of a full PHP have a significant influence on the oscillation pattern. However, to gain a good understanding of the physics behind a pulsating heat pipe, the reduction of the PHP into one unit cell is a promising approach. Compared to the profuse studies on the performance of an entire PHP, studies focused on the single unit cell of a PHP are relatively scarce in literature.

Some pioneering works in the field of single meniscus oscillation have been conducted by Das et al. (2010, 2011) and Rao et al. (2013, 2012). Das et al. (2010) designed an experimental setup where a single liquid slug and a vapor bubble were observed. The experiment consisted of a transparent condenser section and a copper tube as the evaporator. N-pentane was used as the working fluid. Since the setup was not fully transparent the complete meniscus displacement into the evaporator was not reported. The experimental results were used to validate an analytical model for a simple PHP configuration. In a consecutive publication (Das et al., 2011) Methanol was added as working fluid and the effect of evaporator and condenser temperature on the oscillation pattern was documented, using the same setup as in Das et al. (2010).

A recent paper published by Rao et al. (2013) deals with the fundamental understanding of an oscillating meniscus in a capillary tube. The conceptual design was based on a single capillary tube consisting of one evaporator and one condenser section. The experiment contained one unit cell (i.e. one vapor bubble and one liquid slug) and FC-72 was the working fluid. A camera and a pressure transmitter were synchronized to couple the fluid motion with the vapor pressure. This experiment showed the typical characteristics of a PHP unit cell. The difference in comparison to the design of Das et al. (2010) was the orientation of the setup (i.e. vertical)

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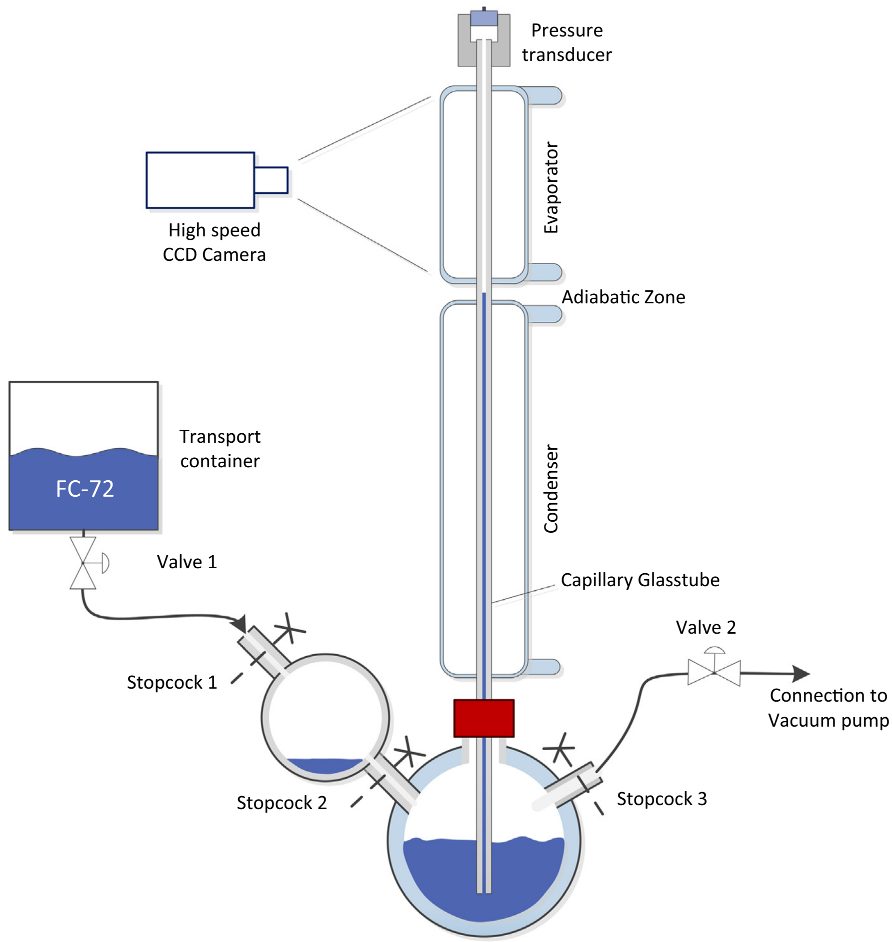

Fig. 1. Schematic figure of the experimental test rig.

and the transparency of the evaporator section as well as the different working fluid. In a further study by Rao et al. (2012), the experimental data concerning the pressure oscillation was compared to an analytical model. It showed good agreement with the model and a typical double peak pressure structure was observed. The authors attributed this oscillatory structure to the presence of thin liquid film inside the evaporator.

The objective of the present work is to gain a better understanding of the physical mechanism behind single meniscus oscillation in a capillary tube. An experimental investigation using FC-72 as the working fluid is conducted. The visual synchronization between meniscus displacement and pressure data is conducted to understand the underlying physics of single meniscus oscillation. The thermodynamic parameters such as reservoir, condenser and evaporator temperature have been investigated. Finally the effect of geometry such as evaporator and condenser lengths on the pressure amplitude is also analyzed.

Experimental description and procedure

Fig. 1 shows the schematic of the experimental facility used for the oscillatory meniscus in a capillary tube.

The inner diameter of the capillary glass tube is 2.0 mm (corresponding to a Bond number of 1.7) while the outer diameter is 6 mm. A low value of Bond number ensures that surface tension force dominates gravity force. The outer diameter of the tube is important for its structural stability and the connector solutions to the pressure transducer as well as to the reservoir. The layout of the experimental test rig consists of a pressure transducer, which is attached to one end of the capillary tube. A short transparent evaporator and a condenser section whose length is twice that of the evaporator is part of the design. The spherical reservoir at the other end of the capillary tube is filled with the working fluid (i.e. FC-72). The reservoir temperature and thus its pressure can be controlled. The temperature inside evaporator, condenser and the reservoir sections are controlled through thermostatic baths. The temperature of evaporator and condenser are measured through thermocouples fixed to the inner walls of the heat exchangers. Vacuum connectors have been used to connect the reservoir as well as the pressure transmitter with the capillary tube. The implementation of single bore stopcocks helped to reduce the leakage rate of the system ($Q_L = 8.3 \cdot 10^{-6} \frac{\text{kPa}}{l\ sec}$). The reservoir is designed to be sufficiently large to reduce the influence of pressure variations due to meniscus oscillation (which is about 0.16 kPa). Moreover a second smaller spherical reservoir is added to simplify the filling process. The oscillation of the meniscus inside the capillary tube is recorded by using a high speed CCD camera (1000 fps).

The pressure transducer is synchronized to the high-speed camera such that the snapshots of the meniscus displacement are recorded simultaneously in correspondence to the pressure data measured by the transducer. The accuracy of the pressure measurement is ±0.15 kPa. After filling the device and turning on evaporator and condenser the meniscus moves into the adiabatic zone. This is the starting condition from where a pressure impulse has to be applied. The pressure impulse is created through a rapid