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Evaporating flow experimental tests in small square open channels

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ABSTRACT

The evaluation of the liquid evaporating flow rate in heat pipe arteries (i.e. transfer heat flux) can be improved if the flow behavior inside these channels of very small sizes is better studied. In this paper, experimental tests performed in small square section open channel (4 mm side), in horizontal configuration, aiming at visualizing and analyzing the steady evaporating flow are presented. The channel size is not as small as the usual size used for heat pipe, and the characteristic length (width of the groove) is then larger than the water capillary length (about 2.7 mm), thus gravity force being predominant on capillary force. For this reason, although present results will not add specific and newer details about the liquid flow in the arteries (microchannels) of the heat pipes, they in any case extend the already available experimental data concerning the performance evaluation in small open ducts. In the initial cold conditions of the tests, before heating, no driving force acts and liquid fills the channel at a certain level without flowing in it. When evaporation starts, the liquid begins to flow both by driving capillary and gravity pressure axial gradient inside the channel. Then, according to the established steady evaporation rate, the liquid differently flows and fills the channel sections. The apparatus and the visualization devices used in these tests allow to take pictures of the gas-liquid interface (meniscus) at several positions along the channel for different steady evaporating rate (supplied heat flux). Images are processed using an appropriate software, "ImageJ", and the interfacial meniscus radius and liquid height along the channel are measured. The values of these two parameters allow the estimation of the liquid filling rate (fluid saturation), the capillary and gravity pressure gradients and the mean axial liquid speed in the channel. So, although gravity effects are present in these experiences, the above measured values and the maximum sustainable heat flux, are compared to the predictions of the analytical and numerical solutions performed in the study of R.H. Nilson, S.W. Tchikanda et al., in the case of no driven gravity pressure gradient ($G^* = 0$).

1. Introduction

The need to manage high waste heat fluxes for space applications and for electronic components identifies heat pipe devices as appropriate systems for the purpose [1–3]. Heat pipes are sealed tubes which transport heat from a heat source to a heat sink using the latent heat of vaporization of a liquid heat carrier (the working fluid). The heat is released by condensation at the heat sink and then the condensed liquid is transported back to the evaporator zone by capillary forces. The capillary action can be exerted by proper wicks arranged on the tube internal surfaces or by axial or circumferential grooves (arteries) obtained into the tube [4–6]. This system has no mechanical parts and is, in particular, suited for the 0-g space environment, since the relatively small capillary forces are not affected by the gravitational field of the Earth. An important objective in the heat pipe design and its manufacturing is the increasing of the transferable heat flux from the evaporator heat source to the condenser heat sink. To be able to do that the optimization of several parameters must be considered in the design of the device as the geometry of the capillary structure. Concerning this aspect and referring to heat pipes with axial grooves as capillary structure, microgrooves having triangular, trapezoidal, sinusoidal, and rectangular cross sections have been created by micromachining, saw cutting, and electrical discharge machining. More recently, special attention has been payed to rectangular channels instead than triangular cross sections. The reason is that the rectangular shape section having a size of few microns in width and a depth up to a millimeter or more can be fabricated using a new manufacturing technologies as the LIGA

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process based on electro-deposition of metals into lithographically patterned molds [7,8], while a deep triangular cross section cannot be realized in this way. Several experimental results and related analytical and numerical studies have been carried out to improve and extend the knowledge on the hydrodynamic characteristic of laminar developing and fully developed flows in noncircular small size ducts. Specifically, heat transfer device, heat sinks and other systems in many engineering applications are often miniaturized. So, these components are obtained with mini and microchannels having different cross sectional shapes. Consequently, the goal of these studies was initially to evidence eventual microscale phenomena and then to develop models (or extracted correlations and approximate analytical solutions) useful to predict the pressure drop (or the friction factor) in these microchannels. The efforts of the researches in this field were to always improve, simplify and generalize the previous and existing models [9–20]. Tchikanda et al. [21] derived analytical expressions for the mean velocity of a liquid flowing in an open rectangular microchannel. Jacolot et al. [22] presented a study about the flow behavior inside four different grooves typically used in heat pipes. They developed an experimental bench in order to visualize the liquid-vapor interface inside these channels. Subsequent experimentation, which was associated with image processing programs, allowed the measurement of liquid height and meniscus radius evolution in one of these heat pipe grooves along its axis. These measurements allowed the evaluation of mean friction factor of the laminar flow inside this kind of axial artery. The work of Jacolot et al. [22] was particularly useful for the present activity allowing the authors to draw the main indications to set up the experimental device and to carry out and analyze the first cold series of tests performed into a small square section open channel in which it was evidenced the influence of the capillary pressure on the pressure drop evaluation [23]. The experimental data of this previous series were processed according the Jacolot et al. considerations and the Faghri [24] hypothesis, and the results (friction factor values) were compared with the numerical correlations of Shah [9,10] and the analytical/numerical expression of Tchikanda model [21]. Following this kind of studies the activity continued and a second series of experimental tests in hot conditions has been performed (with the same small square section open channel and visualization devices used in the first cold series) with the aim of analyzing the structure and the flowing conditions when the fluid is hot and evaporation occurs at the gas liquid interface. Then, using the same software “ImageJ” it was possible to process the images and to measure the interfacial meniscus radius and the liquid height (from the bottom of the groove) along the channel. The values of these two parameters allowed the estimation of the liquid saturation (that is the liquid area fraction), the mean liquid speed, the capillary pressure along the channel, and more the maximum sustainable heat flux. The experimental results were analyzed and processed accordinly the analytical and numerical solutions performed by R.H. Nilson, S.W. Tchikanda et al. [25]. Others works were done to model the bulk axial flow including details of the thin film region immediately adjacent to the fluid/solid contact where most of the evaporation occurs [26–29]. This nanoscale region has microscale implications because the apparent contact angle is dependent upon the local evaporation rate adjacent to the meniscus contact line [27–32].

2. Apparatus and experiment description

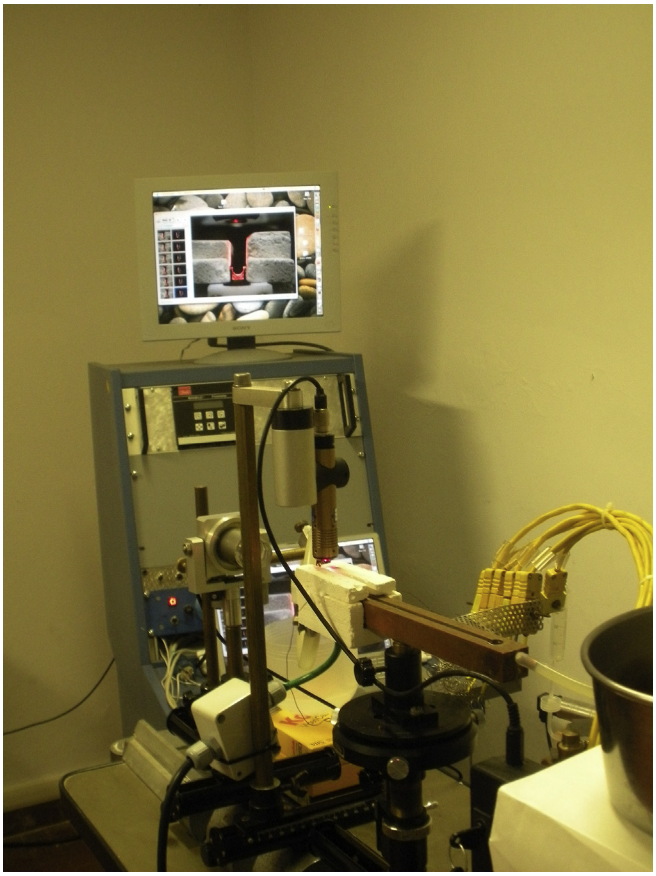
Fig. 1. Sketch of the experimental apparatus.

The experimental apparatus, shown in the picture in Fig. 1, is essentially the same that was previously utilized to carry out a series of cold tests on a small channel to study the influence of the capillary pressure on the liquid pressure drop and to estimate the relative friction factor values [23]. The device is allocated on an optical bench and test section, placed in horizontal position, consists of a single open groove (channel) machined on a copper piece of parallelepiped shape. For the present diabatic experiences the test section and the instrumentation have been implemented as described in the following. As schematically shown in Fig. 2, the groove has a square section of 4 mm in side and is connected to one end to the liquid feeding line (Inlet Flow) through a small injection sump, while the opposite end (Exit) is open to allow the visualization. Fig. 3 shows the layout of seven thermocouples placed on the test section to measure the liquid and the solid (copper) temperature which values are acquired by a computer. The evaporator region of the groove, that is the heated zone, is obtained inserting an electric heater (cartridge type, 6.5 mm in diameter and 30 mm in length) in the exit zone side. The evaporator and the adiabatic zone are considered 50 and 25 mm in length respectively. Both these zones are obviously thermally insulated (of course the upper part of the groove of these two regions are both open, so not insulated, as the other part of the channel). A cavity (cut) is created in the adiabatic zone just to reduce the conduction heat transfer between the evaporating and condensing zone. In these tests the condenser, of course, has not the function to condense the vapor generated by the evaporator because the groove is open and the steam, released to the environment, does not come back in the condenser region. The evaporation of the liquid generates the capillary and gravity forces and while in an actual heat pipe microchannel the capillary force is dominant and the gravity one negligible, in the present small channel these forces are of the same order of magnitude. These two pressure gradients cause the replacement of the liquid which is drawn in the groove from the small pool through the feeding line (Inlet flow). The condenser must either dissipate to the ambient the inevitable conduction heat coming from the