International Journal of Heat and Mass Transfer 51 (2008) 6199–6207

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

New alcohol solutions for heat pipes: Marangoni effect and heat transfer enhancement

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ARTICLE INFO

Article history:
Received 11 June 2007
Available online 12 June 2008

Keywords:
Heat transfer
Marangoni effect
Alcohol solutions

ABSTRACT

Binary mixtures with a non-linear dependence of the surface tension with temperature were investigated as potential working fluids for wicked heat pipes to take advantage of Marangoni effect. Model experiments were carried out using quartz cuvette and glass tubes filled with different solutions and subject to thermal gradient: a mass flow directed towards hot zones along vapor–liquid interface was observed, while surface temperature profiles were recorded with an IR camera. Experiments on thermal performance of commercial heat pipes finally showed that using suitable binary mixtures better performances can be achieved in comparison with heat pipes filled with water.

1. Introduction

Heat pipes are extremely efficient heat transfer devices that utilize a phase change in the working fluid inside to quickly transport large amount of heat from one side to the other. They offer many advantages in electronics cooling, air conditioning, power generation, chemical engineering and spacecraft cooling [1,2]. Because of their low weight, maintenance-free, reliability and increased heat dissipation, heat pipes are widely used for miniaturized electronic devices and high-tech equipment like notebook PCs.

The requirements of high efficiency and compact size in such electronic devices strongly affect their thermal management that is critical and directly influences cost, reliability, and performances.

Everyday, heat pipes designers have to cope in heat pipe production with serious constraints strictly depending on the kind of applications for which the heat pipe has been selected, like the temperature gradient along the pipe and its heat transfer limits (i.e. boiling limit and capillary limit). Results of axial temperature measurement indicate that axial vapor temperature distribution in heat pipes is extremely small, and this small temperature gradient in the vapor region of heat pipes has given them the reputation of being "isothermal devices".

However, heat pipes designers find sometimes a noticeable and significant temperature drop from the heat source to the heat sink region [3]. This temperature drop could result from the combined resistance of the liquid-wick combination and the wall resistance of the heat pipe or container, and it can result in overall temperature gradients that are substantial, particularly in situations where the effective thermal conductivity of the liquid-wick combination is low. More in general, the presence of a temperature gradient along the pipe could be simply due to its design and specific applications.

The existence of a temperature gradient along the heat pipe induces a surface tension gradient at vapor–liquid interface that moves the liquid toward regions of higher surface tension.

Surface tension of pure liquids is normally decreasing with increasing temperature, indeed, the liquid is moved along the interface toward the cooler zone, which is the condenser zone. This effect, known as Marangoni effect, could influence negatively the heat transfer capability.

In fact, one of the parameters used to define the effectiveness of a heat pipe is represented by its maximum heat load value, and in order to ensure a large heat load without reaching the boiling limit at the evaporator, the most important factor is the wetting of the heated wall by the working fluid: the development of Marangoni flow previously described, counteracting the capillary forces, can play an important role in evaporator priming because it can cause the reduction of the condensate return's amount.

This effect has been observed in axially grooved gas-loaded variable-conductance heat pipe [4], where large surface tension gradients related to temperature gradients in the gas blocked zone induce a surface flow toward condenser, and it is accompanied by a subsurface flow in the groove of equal magnitude but opposite direction (recirculation). In [4], the authors developed a theoretical model with all pressure drops included and highlighted how the pressure drop that drives this subsurface flow results in a capacity degradation as it subtracts directly from the available capillary pressure that drives the condensate return in the active region of the heat pipe.

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doi:10.1016/j.ijheatmasstransfer.2008.01.040

Nomenclature

d	distance from the condenser end	V	velocity
g	gravity acceleration	ρ	density
P	power	σ	surface tension
T	temperature	μ	dynamic viscosity
t	time		

Surface tension is a key factor also for other heat transfer limitations, like boiling and capillary limits, because it influences the dynamics associated with bubble's detachment. As regards the influence on the boiling limit, all heat pipes have a boiling limit, which is directly related to bubble formation in the liquid, and several works present in literature investigated the dynamics of bubbles in several working fluids (pure liquid and binary mixtures) and its role on boiling phenomena on ground as well as in microgravity environment [5–9]. When the number and size of vapor bubbles generated at the wall and/or the fin-wick interface are small, these bubbles may migrate from the solid surface to the liquid–vapor interface and vent into the vapor groove without destroying the capillary menisci.

However, as the heat flux is increased further, bubbles may coalesce, form a vapor blanket at the wall and/or the fin-wick interface, and eliminate the capillary force that circulates the liquid condensate. Vapor bubbles that are coalesced at the evaporator section may block the liquid return from the condenser section and the boiling limit can be reached.

In this context, the negative surface tension gradient with temperature associated with ordinary working fluids, that is, the classic Marangoni effect, will reduce the critical temperature difference when the operating temperature at the evaporator section is increased. All working fluids used in existing heat transfer devices, including LHP's, CPL's and heat pipes, have a negative gradient of surface tension against temperature that induce a Marangoni flow around vapor bubbles, pressing the bubbles onto the heating surface and resulting in an unfavourable situation for boiling performance, because of avoiding bubbles venting in vapor groove as described above.

On the other hand, as regards the influence of surface tension on the capillary limit, the absolute available capillary pumping head,

$$\Delta P = \frac{2\sigma}{r}\cos(\vartheta) \tag{1}$$

in which σ is the surface tension, r is the interface radius of curvature and θ is the contact angle between the working fluid and the wall or the wick surface, it decreases when the evaporator temperature increases just because of the decreasing of surface tension with increasing temperature, and the operation becomes unstable.

Finally, a micro-scale approach reveals that the dynamics associated with fluid motion and heat transport at the evaporating meniscus may detrimentally affect the driving capillary potential by degrading the wettability of the working fluid.

An investigation of thermocapillary effects on heated menisci formed by volatile liquids in capillary pumped heat transfer devices [10] showed the importance of the evaporation process from porous or grooved media integral to the operation of capillary pumped heat transport devices such as heat pipes and capillary pumped loops. The thermal conditions at which the destabilizing influences of thermocapillary stresses near the contact line of a heated and evaporating meniscus cause the meniscus to become unstable were investigated. Pratt and Hallinan [11,12] demonstrated that interfacial thermocapillary stresses arising from liquid–vapor interfacial temperature gradients can noticeably degrade the ability of the liquid to wet the pore. Pratt and Khim's investigation [13], on the other hand, revealed that such interfacial thermocapillary stresses arising from liquid–vapor interfacial temperature gradients, can be counteracted by introducing naturally occurring concentration gradients associated with distillation in binary fluid mixtures.

In general, in order to face all these thermofluid dynamic aspects listed above, heat pipe designers must take into account the physical properties of the selected working fluid. For this reason, several efforts have been realized in researching new working fluids that could enhance heat transfer mechanism inside heat pipes, overcoming all the drawbacks previously listed which are strictly connected to the surface tension properties of the working fluid. As far as the idea of the employment of mixtures for a working fluid in heat pipes is concerned, several researchers already paid their attention considering the benefit of non-condensable gas effect caused by the vapor of more volatile component in mixtures.

Tien [14], Tien and Rohani [15] investigated the degrees of separation and operational characteristics of a two-components heat pipe filled with different water/ethanol solutions. He performed a theoretical framework to predict performances obtained by this kind of heat pipe, showing that its separation's degree depends on several factors like initial composition and heat pipe geometry, that this separation of mixture in two pure components does not occur each time.

Brommer [16] analyzed the application of two-component heat pipes characterized by water/methanol binary mixture. His research demonstrated that to improve the start up behaviour of heat pipes in which the working fluid is initially frozen, the freezing point can be lowered by addition of a suitable liquid, like methanol in water for low temperature range. Kadoguchi et al. [17] continued the analysis of two-component heat pipes as their basic idea was that a heat pipe with binary mixture working fluid is a more advantageous heat transfer device than a gas-loaded variable-conductance heat pipe for controlling the temperature of electric device.

For this reason, they investigated heat transfer characteristics of a closed two-phase thermosyphon, a gravity-assisted wickless heat pipe filled with water/ethanol solution. Although these previous studies did not take into account possible Marangoni effect due to the preferential evaporation of more volatile component, the benefit of the Marangoni effect in heat pipes was first focused by Kuramae.

Kuramae and Suzuki [18], Kuramae [19,20] proposed the use of alcohol solution but his approach was totally different compared with the ones of Brommer or Fukano. He focused his attention in the rewetting problem of the evaporator in wickless heat pipes filled with ethanol/water mixture, so that the evaporation of the more volatile component (ethanol) in the evaporator area could induce a solutal Marangoni flow for the evaporator liquid-supply into wickless heat pipes.

On the same path, Zhang [21] promoted the use of innovative working fluids for heat pipe systems like very dilute alcohol solutions (aqueous solution whose alcohol concentration is in the range between 0.0005 and 0.008 moles per liter), which, according to previous works [22,23], exhibit a non-linear dependence of the surface tension with temperature and a positive gradient with increasing temperature in a suitable range of temperatures and concentrations.

For these solutions, at a fixed temperature, the surface tension is a decreasing function of the concentration, but for a given concentration, the surface tension, as a function of the temperature, goes through a minimum and there is a range of temperature above which the surface tension is an increasing function of temperature. Therefore, it is expected to observe surface flows directed from the cold region to the hot side, for temperatures higher than that of the minimum of the surface tension and to improve heat pipes performances taking advantage of this Marangoni flow particular for the aqueous solutions of our interest and induced by temperature gradients. However, these solutions offer another important advantage not taken into account by Chao and Zhang.

Normally, high-carbon alcohol and water systems are the so-called "negative" binary mixtures, in which a more volatile component (in this case water) has a higher surface tension.

In some low concentration regions, however, these aqueous solutions behave like "positive" binary mixtures [24].

In fact, as shown in Fig. 1, which was prepared and provided by courtesy of Prof. Ohta (Kyushu University, Japan), in dilute compositions, alcohol is the more volatile component and the Marangoni flow due to the concentration gradient, coupled with the thermo-capillary flow previously described, is considered to induce rather strong liquid inflow from the cold to the hot region as described in Fig. 2.

This flow represents an additional force which moves the working fluid toward the hot region: in this way, the liquid pressure drop is reduced, the capillary limit and the boiling limit are increased, and consequently, the dry-out limit is increased too.

The great advantage of these solutions is then represented by the possibility to develop a surface tension gradient driven flow, induced by both temperature and alcohol concentration gradient in certain operative conditions: this flow should enhance the capillary pressure head expected with ordinary working fluids.

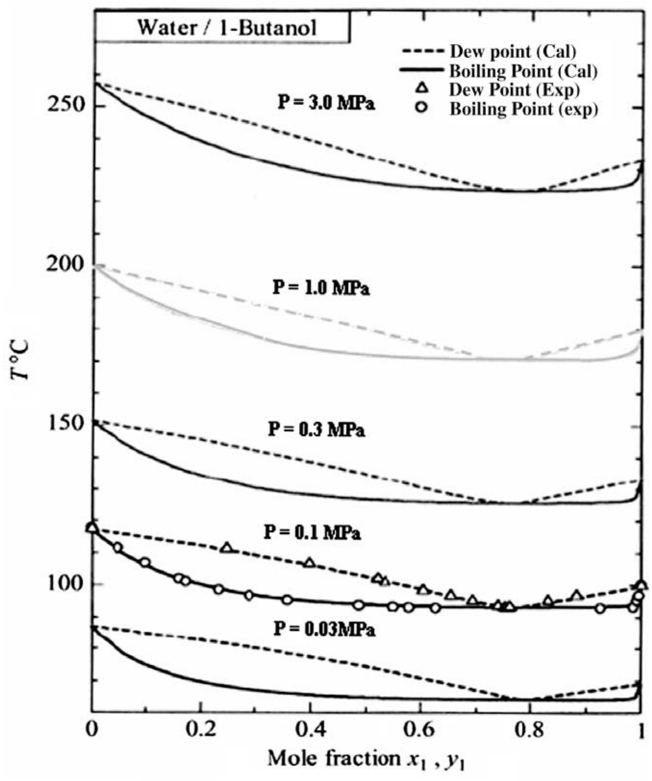

Fig. 1. Phase diagram for 1-butanol aqueous solution at various pressures.

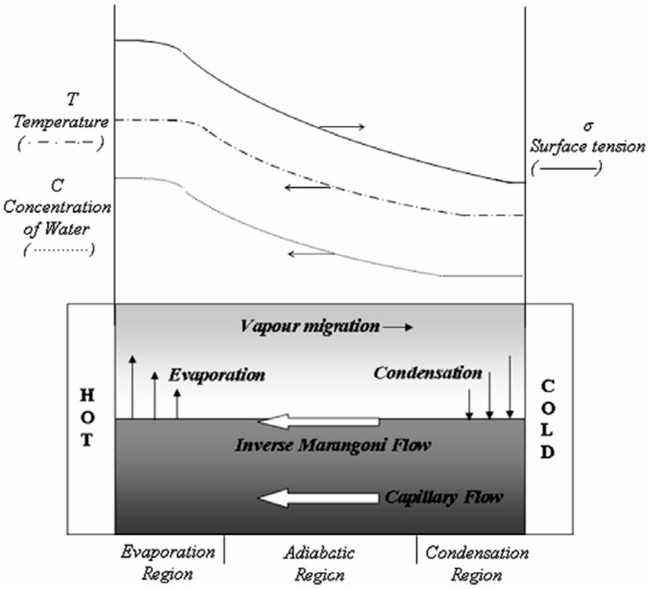

Fig. 2. Surface tension gradient driven flow directed from cold to hot side.

On a micro-scale, it will favour the bubble's detachment from heated surface compared with the ordinary Marangoni flow that keeps them pressed on the heated wall, characterizing boiling phenomena in which bubbles are considerably smaller than in the case of water as previously showed by Abe [25]. Finally, this flow could also be used to avoid wettability degradation inducing a positive concentration and temperature gradient along an evaporating meniscus, but these are not the subjects of our investigation.

The target of the present authors has been to highlight the importance that surface tension driven flows can have in heat transfer mechanism of heat pipes, not only in microgravity environment but also in terrestrial conditions [26]. Scope of this work is to investigate the surface tension of long-chain alcohol solutions and relative surface tension driven flows induced by temperature gradient, showing the advantages of their employment inside heat pipes for commercial applications [27–29].

2. Experiments

2.1. Surface tension measurements

The aim of the work presented in this section was to verify the existence in some alcohol solutions of a "positive" surface tension gradient with increasing temperature as reported in the literature. In order to achieve this goal, Dataphysics OCA 15 tensiometer has been used. The experimental system for the measurements of the surface tension is shown in Fig. 3.

It is characterized by an electronic injection system with a vertical controllable syringe that allows injecting a liquid pendant drop in air or an air-bubble in an external liquid matrix.

In the present work, in order to measure surface tensions of aqueous solutions at different temperatures and fixed alcohol concentration, an air-bubble of prescribed volume was formed into the liquid matrix so that alcohol concentration inside the solution could be preserved compared with the Pendant Drop Method.

The principle remains practically the same: the determination of the profile of a drop of one fluid suspended in another fluid, and instead of using liquid-drop in air, it has been preferred air-bubble in liquid. To this aim an optical glass cuvette (with inner

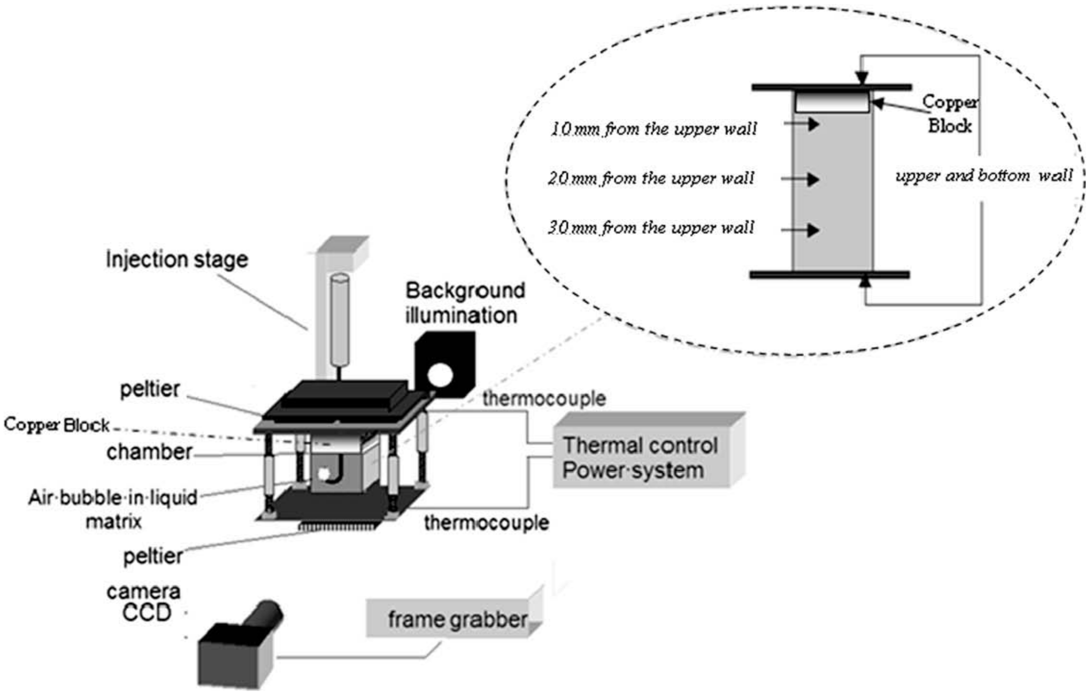

Fig. 3. Setup for experimental surface tension measurements and close-up of locations where temperature was investigated inside cuvette.

dimensions: 9.5 mm × 9.5 mm × 43.5 mm) was filled with the experimental fluids (i.e. the selected water/alcohol solutions). The bubble was injected in the fluid through a syringe with a curved needle, free to translate along the vertical axis into a copper block with an inner hole (diameter: 0.5 mm). The lower wall of this block is almost coincident with the squared cross-section of the cell. Only a small gap (0.5 mm) is left between the copper block and the side walls of the cuvette, to allow volume accommodation when the syringe is translated and when the bubble is injected. In this way, the fluid is enclosed between the lower wall of the cell and the lower surface of this block.

The higher part of the copper solid and the bottom wall are heated/cooled by Peltier elements, in combination with a power supply and a water circulating system, so that the temperatures of the surfaces are constant and controlled (with an accuracy of 0.1 °C in the range 20–100 °C) during the experiments.

The liquid temperature at various points inside the cell was measured by K-type sheathed thermocouples whose diameter was 0.3 mm. The points of interest for temperature measurements were the higher part of the copper solid, the bottom wall, and three locations inside the cuvette as shown in Fig. 3:

Surface tension measurements have been performed first at room temperature (20 °C) and then at higher temperatures (i.e. 40–60–80 °C) by heating up the Peltier elements increasing the electric power. Once achieved the selected temperature as recorded by all thermocouples, the bubble was formed and the surface tension was measured on the basis of the shape detected with a parallel light background illumination. The bubble shape was captured with a digital video camera (zoom: 6×; matrix: 752 × 582 "square pixels"; field of view: from 1.31 mm × 1.05 mm up to 8.77 mm × 6.75 mm; frame rate: up to 25 images/s; optical distortion: less than 0.05%). The contrast between "white and black" pixels in the captured image allows one to detect the "experimental shape" of the bubble, while a reference unit (such as the needle's diameter that appears in the captured image) defines the bubble volume. At the same time, a software computes the shape of the bubble solving the Young–Laplace equation: the surface tension is finally evaluated once the bubble' size and shape are known.

Each session of experiments related to surface tension measurement for a fixed temperature was repeated three times. Nearly 10 acquisitions have been done for each selected temperature (20–40–60–80 °C) and the final value of surface tension was an average value of all the experimental data obtained; for each temperature, the maximum deviation was equal to nearly ±0.5 mN/m.

The cuvette was practically sealed so that the amount of alcohol in solution was preserved at each selected temperature: however, in order to be sure about the concentration of alcohol in solution, for each session of experiments, the cuvette was emptied and then filled again with the solution of interest: a good reproducibility of the results was confirmed.

2.2. Flow visualization in glass cuvette

In order to study the behaviour of alcoholic solutions in presence of surface tension driven flows, a number of experiments have been carried out using two kinds of preliminary configurations:

1. cuvette filled with a thin layer of liquid and subject to thermal gradient;
2. glass tubes partially filled with water or with alcohol solutions and heated at one side.

The first experimental configuration involves a rectangular quartz cuvette (ext.: 12,5 mm × 12,5 mm × 45 mm; int.: 10 mm × 10 mm × 39 mm) shown in Fig. 4.

The cuvette was inserted into two copper blocks heated by two Pertier elements. The liquids investigated are bi-distilled water and 1-heptanol aqueous solution (0.1 wt%) prepared with bi-distilled water: the liquid layer thickness was almost 1 mm.

The target of the experiments performed using this configuration was to observe the velocity field in a free surface of thin liquid layer subject to a horizontal thermal gradient. The hotter end was fixed at 60 °C while the colder end at 40 °C. These values have been

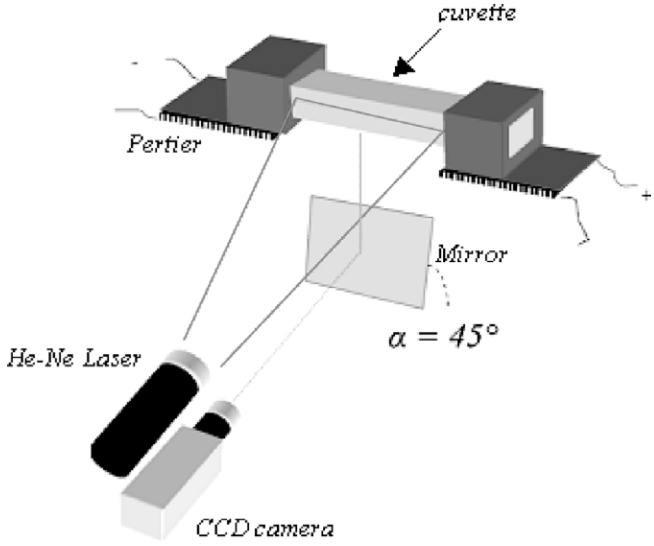

Fig. 4. Experimental configuration to investigate alcohol solutions subject to a thermal gradient.

chosen in order to confirm the existence of a surface tension driven flow directed toward the hotter end instead of the colder one. These temperatures have been fixed after realizing that for the 1-heptanol solution investigated (0.1 wt%), the minimum temperature at which the surface tension gradient starts to have a positive slope is near 40 °C (see Fig. 5 in result and discussion).

A laser sheet (He–Ne), whose thickness was almost 0.5 mm, was used to illuminate tracer particles of glass powder (diameter 10 μm, density 450 kg/m^3) present at liquid–vapor interface, while a CCD camera recorded the tracers movements at interface observing it from below through a mirror positioned below the experimental setup with an inclination of 45°, as shown in Fig. 4.

Small video clips were recorded and then analyzed, monitoring the history of tracers inside the images, so that through the measurement of the distance covered in a fixed interval time it was possible to extract the velocities of tracers.

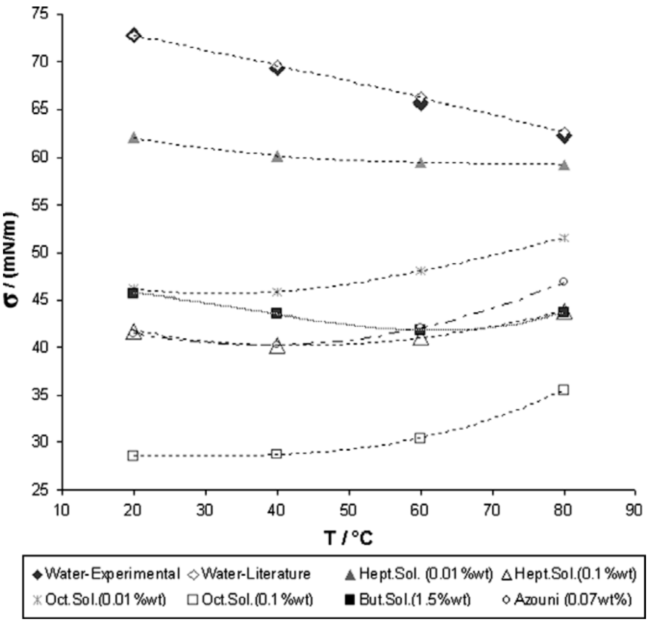

Fig. 5. Surface tension measurements for water and alcohol solutions.

2.3. Model experiments in glass tubes

The goal of this experimental session was to analyze the heat transfer characteristics associated with the particular Marangoni flow expected for the 1-heptanol aqueous solution and to compare the results with pure water, using a preliminary configuration.

The second experimental system includes two Pyrex glass tubes (inner diameter: 10 mm, thickness: 1 mm, length: 165 mm) filled with bi-distilled water and 1-heptanol aqueous solution (0.1 wt%) prepared with bi-distilled water. Each pipe was filled under vacuum with almost 3.5 cc of preliminarily degassed liquids using the so-called "vacuum and backfilling procedure".

In order to establish a temperature gradient along the glass tubes, one end was heated up with a resistance heater (connected to a power supply) along the outer surface for a length of 35 mm. The system was investigated in horizontal configuration without additional cooling units (the only mechanism for heat transfer at the cold sides of the pipes was radiation and natural convection).

The diagnostic system includes an infrared thermal camera and a K-type sheathed thermocouple with diameter of 0.3 mm, to measure the temperature of the tube surface at the evaporator section: in particular, the thermocouple was positioned on the upper surface of the glass tube, at 17.5 mm from the end of the tube, in order to detect the temperature in the middle of the evaporator section.

The surface temperature distribution has been measured by means of an infrared thermal camera (Flir Thermacam SC3000) operating in the long wave spectral band (8–9 μm). The instrument is based on an advanced Stirling cooled GaAs Quantum Well Infrared Photodetector (QWIP) sensor, providing resolution of 320 × 240 pixels, with a sensitivity of less than 20 mK at 30 °C and accuracy of ±1% for measurements up to +150 °C. The image capturing frequency is 50 Hz. All outputs can be stored as analog videos or in digital format with frequency of 50 Hz as 14-bit radiometric IR digital images.

The thermal camera measures the radiant energy emitted by an object in the (infrared) window in which the sensor of the thermal camera is sensitive. An internal software allows one to detect the temperature distribution based on automatic corrections related to the atmospheric transmission, optics transmission and surface emissivity. The thermal camera has a standard 20° lens with a field of view at minimum focal distance (30 cm) of 20–15°; two additional close-up lens can be mounted to enlarge the field of view: with the first close-up lens the field of view is 34 mm × 25 mm at 10 cm distance to the object; with the additional microscope lens the field of view is 10 mm × 7.5 mm at a distance of 3 cm.

2.4. Heat transfer experiments in grooved heat pipes

The performance tests of conventional heat pipes filled with different working fluids have been finally carried out with a different experimental set up.

Four axially grooved copper heat pipes (see Table 1), were delivered by Fujikura Ltd.: two of them, with 250 mm length and diam-

Table 1
Specifications of heat pipes tested

Length	250 mm
Diameter	4 mm/8 mm
Material	Copper (C-1020)
Working fluids	Bi-distilled water 1-hept. sol. (0.1 wt%)
Capillary structure	Grooved
Groove width and depth	0.11 mm (4 mm heat pipes) 0.13 mm (8 mm heat pipes)
Number of grooves	40
Amount of liquid	0.4 cc/1.7 cc

eters of 4 mm and 8 mm respectively, were filled with bi-distilled water while the other two ones, with the same characteristics, were filled with 1-heptanol aqueous solution (0.1 wt%) prepared with bi-distilled water, in order to compare these two working fluids in two different types of heat pipes:

A copper block with four cartridge heaters inside was utilized to heat the evaporation region of the heat pipes tested (length 30 mm); the opposite side was cooled with a fan for 70 mm (condensation region). Except the condenser, the system was properly insulated wrapping the pipe into a glass-fiber material to ensure that as much of the input heat as possible was transmitted through the heat pipe from the evaporator to the condenser. Two K-type sheathed thermocouples with diameter of 0.25 mm were positioned in the middle of the evaporator and condenser regions: in particular, one thermocouple was positioned on the upper surface of the pipe, at 15 mm from the evaporation end, while the other thermocouple was positioned on the upper surface of the pipe at 35 mm from the condensation end, so that both thermocouples could detect the temperatures in the middle of the evaporator and condenser respectively. The precision and the uncertainty of these sheathed thermocouples are 0.1 K and 0.5 K, respectively. The experimental set up was mounted with the heat pipe horizontal with respect to the earth's gravity. Experiments with the heat pipes were carried out in air at atmospheric pressure.

The experimental procedure was organized as follows. A given electrical power is supplied to the four cartridge heaters, while the fan cools the condensation side of the heat pipe. The temperature profiles are recorded in real time until a steady state is achieved: the heat transfer performances in this condition are characterized by the thermal resistance of the heat pipe, defined as the ratio between the difference of the evaporator and condenser steady state temperatures and the power input.

Once the heat pipe has reached steady state, the electric power is increased and a new steady state is investigated. This procedure has been followed several times until dry-out is reached as shown in Figs. 7 and 9.

The temperature profiles at the evaporator and condenser regions were recorded on a memory card through the use of a PC-linked data acquisition system with a sampling frequency of 0.2 Hz, and extracted as EXCEL files that could be managed with a Personal Computer.

3. Results and discussion

3.1. Surface tension measurements

The experimental results for the surface tension measurements are summarized in Fig. 5:

The investigated fluids are bi-distilled water and dilute aqueous solutions of long-chain alcohols (1-butanol, 1-heptanol, 1-octanol). For the 1-heptanol solutions and the 1-octanol solutions the results refer to two values of the concentrations (0.01 wt% and 0.1 wt%): the solution of water and 1-butanol has a concentration equal to 1.5 wt%. The graph compares the experimental surface tension profiles with the results obtained by Azouni et al. [23] related to a 1-heptanol solution whose concentration was equal to 0.07 wt%.

It has been decided first of all to measure the surface tension of water and compare the results with the ones reported in the literature in order to have the confirmation of the reliability of the tensiometer.

The agreement of the measured surface tension for water with the reference data provided by NIST (National Institute of Standards and Technology) [30] was fairly satisfactory. The standard deviation from the NIST data was 0.04% and the maximum deviation was 0.11%, which appeared at the highest temperature of the present measurements, 80 °C. From this comparison, we could confirm a good reliability of the present surface tension data obtained with the tensiometer.

For all the investigated alcohol solutions, when the alcohol concentration is very low, the surface tension decreases when the temperature increases; increasing the alcohol content, it is possible to find suitable concentrations such that a positive surface tension gradient with the temperature is found when the temperature exceeds a certain value. Typically, the temperature corresponding to the minimum of the surface tension is an increasing function of the number of carbon atoms.

These results have suggested the employment of alcohol solutions in preliminary configurations of interest with the objective of visualizing the expected surface tension gradient driven flow directed towards evaporator region, in correspondence of a certain temperature gradient as indicated by the surface tension measurement results.

3.2. Flow visualization in glass cuvette

In order to investigate the dynamics associated with surface tension driven flows in alcoholic binary mixtures, experiments have been performed analyzing the thin liquid layer inside the quartz cuvette. Once a horizontal thermal gradient was applied (hot side at 60 °C, cold side at 40 °C), in the case of bi-distilled water it has been observed an interface flow directed from the cold to the hot side; the liquid was transported towards the hot zone, and after impacting on the cuvette cross-section wall, it came back towards the cold zone for continuity all along the side walls.

Analyzing the images related to the experiments performed, it could be observed how the liquid–vapor interface was then characterized by a central flow directed from cold to the hot side, and two tight, side wall-flows directed from the hot to the cold side.

The flow described above is mainly driven by buoyancy effects in air which occupies the greatest part of the internal volume of the cuvette, giving rise to a counter-clockwise circulation cell; a motion in the liquid phase is thus generated by the tangential stresses at the liquid–air interface, directed from the cold to the hot region and characterized by relatively small surface velocities, equal to nearly 1 mm/s.

The theoretical model for this problem, involving a two-phase flow with a liquid–vapor interface, is based on the solution of the continuity, Navier–Stokes and energy equations for a viscous incompressible liquid; the boundary conditions at the liquid–vapor interface are the continuity of the mass flux and the surface balance equation of tangential momentum:

$$\mu \frac{\partial V_t}{\partial n} = \frac{\partial \sigma}{\partial t} \tag{2}$$

where t and n denote tangential and normal directions and σ is the surface tension, while the continuity of the heat flux at the liquid–vapor interface represents the boundary condition for the interface temperature.

The experimental values previously described represent, in particular, the average interface velocities, measured considering the tracers moving in the central region of the liquid–gas interface.

It is important to highlight that the cuvette experiments do not reflect real model experiments for heat pipes. The internal volume inside the cuvette is in fact partially filled with liquid (water or 1-heptanol solution) covered by air, that is a non-condensable gas, and typical evaporation and condensation process in heat pipes does not occur in this situation.

In the case of the water-1-heptanol solution, the flow was in the same direction as in the pure water case, but it was characterized by higher velocities, equal to nearly 15 mm/s.

The buoyancy effect previously described and present in the air above the liquid–vapor interface is still present, so the flow is directed in the same direction observed in the case of bi-distilled water; however, higher surface velocities occur due to the surface tension gradient induced by the surface temperature gradient (Marangoni effect). The molecules of the surface liquid layer are moved from the low surface tension region to the high one and drag by viscosity the underlying liquid: but unlike the bi-distilled water case, the liquid which impacts the cuvette cross-section is then transported back through lower layers under liquid–vapor interface instead of side wall-flows along the interface.

This result confirms that for the 1-heptanol solution investigated (0.1 wt%), the surface tension gradient in that temperature range has a positive slope, and it induces a surface tension driven flow directed toward the hotter end instead of the colder one.

3.3. Model experiments in glass tubes

The experimental results of the tests with glass tubes in the horizontal configuration are shown in Fig. 6 that presents the temperature profiles obtained along both tubes. These profiles have been extracted from thermal images using a proper function of thermal camera. In this case the electrical power is 5 W. The pipe filled with water is compared with the pipe filled with a solution of water and 1-heptanol (concentration: 0.1 wt%). In horizontal configuration, the average surface temperature distributions for pipes filled with pure water and with the binary mixture are different. In the water-filled pipe, the temperature of the evaporator section is higher and the temperature of the condenser section is lower than in the corresponding case of the pipe filled with the alcohol solution. Therefore, the temperature gradient along the pipe filled with alcohol solution is smaller than the one measured in the case of water. The reason of such a different temperature distribution could be linked to the development inside alcoholic solution of the surface tension gradient driven flow previously observed in the cuvette, which allows the pipe filled with alcohol solution to be a sort of heat pipe whose capillary action is replaced by Marangoni effect.

Effectively, as explained in the Introduction paragraph, several authors investigated alcohol solution like ethanol–water for the interest in developing wickless heat pipe in which the capillary force could be replaced by the Marangoni force induced by a concentration gradient present in solution.

In this case, the Marangoni force in 1-heptanol solution is induced by concentration and temperature gradients.

The continuous process through which the working fluid evaporates, travels across the pipe towards the opposite and colder edge, condenses and is pushed back towards the evaporator allows to consider the pipe filled with alcohol solution, compared with the one filled with water, like a heat pipe capable of transferring heat from one side to the other. The phenomena described induce to conclude that the heat transfer mechanism is therefore enhanced in the case of the 1-heptanol solution compared with that of water.

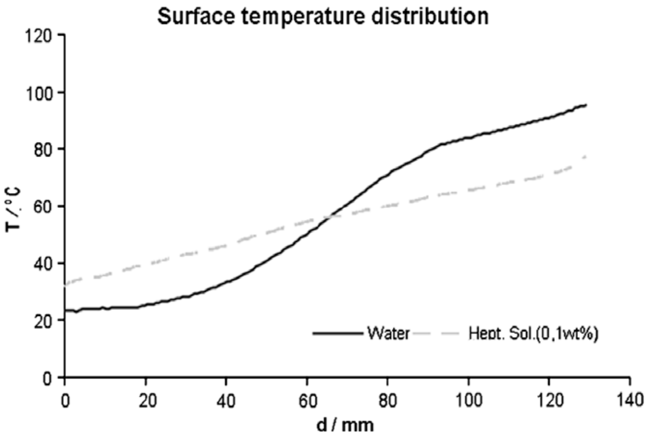

Fig. 6. Temperature profiles along glass tubes: horizontal configuration.

3.4. Heat transfer experiments in grooved heat pipes

3.4.1. Heat pipes: 4 mm

Several heat transfer performance evaluations have been carried out with grooved heat pipes in order to compare the function of conventional working fluid, water, and a proposed working fluid in the present study, 1-heptanol aqueous solution. The results obtained in the horizontal configuration are shown in the Fig. 7; in this figure it is presented the temperature history measured in the evaporation and condensation regions of both heat pipes, and recorded during all the duration of the experiment:

The Fig. 8 presents the thermal resistance profiles calculated for both heat pipes.

It is quite evident that the heat pipe filled with 1-heptanol solution (0.1 wt%) exhibits:

- A higher dry-out limit (it is nearly doubled compared with water case).
- A lower thermal resistance.

These advantages can be explained considering that in this kind of configuration, like in microgravity environment, surface tension effects play an important role, and the development of the Marangoni flow in 1-heptanol solution helps to keep the evaporator zone primed compared with the case of water.

It is interesting to highlight that when power input is quite low, i.e. equal to 4 W, thermal resistance measured in the heat pipe filled with water is smaller than the one measured in the case of the heat pipe filled with 1-heptanol solution. Analyzing the absolute temperature values, it has been observed that in heat pipe filled with alcoholic solution, evaporator vs. condenser temperatures were nearly 44.6 °C against 40.0 °C. Even if a minimum in surface tension measurement has been observed at 40.0 °C, it is

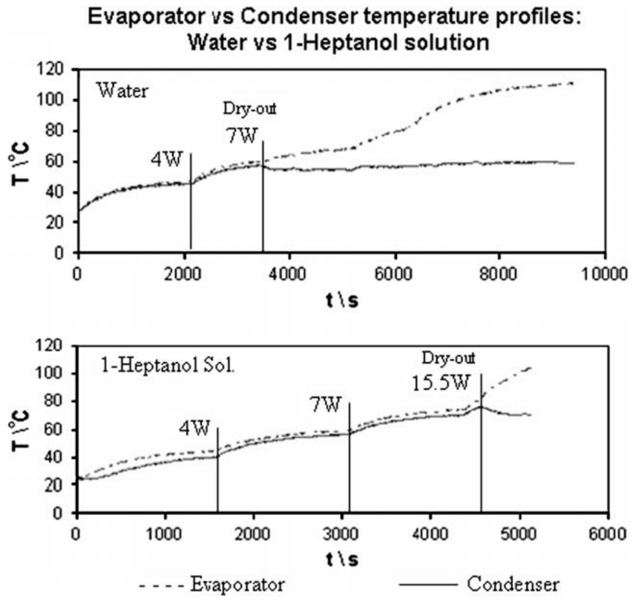

Fig. 7. Temperature history for 4 mm grooved heat pipe: water vs 1-heptanol solution.

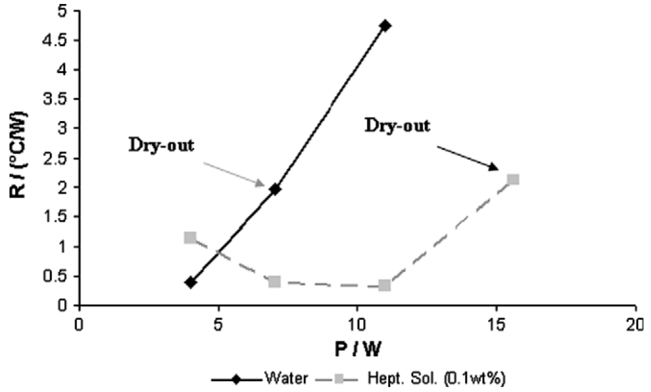

Fig. 8. Thermal resistance for 4 mm grooved heat pipes.

important to underline that additional measurements should be performed in order to evaluate in detail the temperature at which the alcoholic solution exhibits effectively the minimum.

Both temperature values could be smaller than the one which represented the minimum in the surface tension profile; consequently, there could be the development of Marangoni flow in 1-heptanol solution (absent in case of water as previously explained) from hot to cold side, that degrades heat transport capability as expected and as experimentally observed.

Additional explanation for higher thermal resistance at low power input may be based on possible difference between the dew point and bubble point of the phase diagram of water/1-heptanol. Since the mixture at 0.1 wt% is a non-azeotropic composition, it is likely that small temperature difference between the evaporation region and the condensation region may be established.

Although the phase diagram for water/1-heptanol is not available, one of the present authors (YA) experimentally noticed that the temperature difference between the dew point and the bubble point at 0.1 wt% concentration was less than 0.2–0.3 K. We can, therefore, conclude that higher thermal resistance at low power input should not be caused by non-azeotropic characteristics.

On the contrary, when power input is higher, i.e. equal to 7 W, evaporator vs. condenser temperatures were nearly 59.0 °C against 56.3 °C, and it is expected the development of a Marangoni flow directed towards hotter side instead of colder one. For this reason, the enhanced recirculation of liquid inside the pipe, as it has been observed in glass tubes, reduces the temperature gradient along the pipe and, consequently, its thermal resistance.

3.4.2. Heat pipes: 8 mm

The results of the experiments with 8 mm grooved heat pipes with external diameter of 8 mm are shown in Fig. 9. These tests have been carried out using the same experimental set up of the 4 mm diameter heat pipes.

Fig. 9 shows the results obtained for the heat pipe filled with water, at different power inputs, and the corresponding results obtained at the same conditions for the heat pipe filled with the 1-heptanol solution; in this Figure as well as in Fig. 7, it is presented the temperature history measured in the evaporation and condensation regions of the heat pipe, and recorded during all the duration of the experiment:

Fig. 10 presents the thermal resistance profiles measured in both heat pipes.

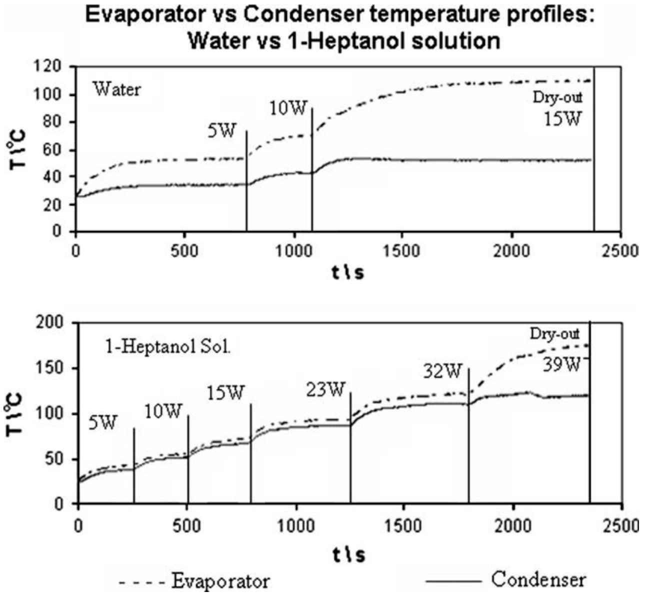

Fig. 9. Temperature history for 8 mm grooved heat pipe: water vs 1-heptanol solution.

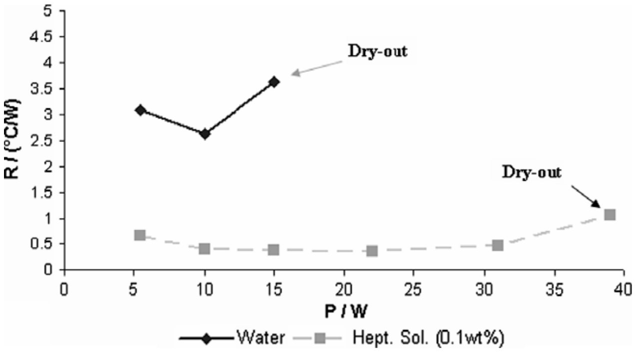

Fig. 10. Thermal resistance for 8 mm grooved heat pipes.

The results confirm that the heat pipe filled with alcohol solution has a smaller thermal resistance and a higher dry-out limit than the heat pipe filled with water. The anomalous high values of thermal resistance measured in case of water are probably due to wettability of water and copper surface. Though heat pipes should have manufactured so that a good wettability between working fluid and wick surface was maintained, the wettability with water may be under more appreciable influence of impurity, surface properties of copper et al. comparing with alcoholic aqueous solutions. The authors believed this is very important advantage of alcoholic aqueous solutions.

Finally, if we compare the results obtained in 4 mm and 8 mm heat pipes, a higher dry-out limit is expected with 1-heptanol solution as the larger is the pipe's diameter, the smaller is the related pressure drop in vapor phase: on the contrary, the Marangoni flow is always the same, therefore, more efficient is its action in improving heat transfer performances of the grooved heat pipe.

4. Conclusions

The experimental and numerical results presented in this paper show that suitable alcoholic solution working fluids can be identified to improve heat pipe transfer performances. The surface tension measurements experimentally reconfirmed that long-chain alcohol solutions exhibit a non-linear surface tension profile as reported in previous papers: the surface tension increases with increasing temperature from a certain value of temperature. By this particular temperature dependence of the surface tension, the Marangoni flow caused by temperature gradient and concentration gradient, provides an additional mechanism for liquid return from the condenser to the evaporator, other than forces like capillary and gravitational ones. Numerical and experimental results demonstrated the development of such additional flow in a certain temperature range and for a certain concentration of alcohol in water. Model experiments in glass tubes show that this particular surface tension behaviour, induced also by the evaporation at liquid–vapor interface, is associated with a heat transfer enhancement.

The results of heat transfer experiments in grooved heat pipes confirm that heat pipes filled with long-chain alcohol solutions at suitable concentrations showed higher dry-out limit and lower thermal resistance (and probably more uniform thermal performances) than heat pipes filled with water. This was found both in heat pipes models (Pyrex tubes) and in conventional copper grooved heat pipes. The authors want to highlight that these results have been obtained throughout an extensive test-campaign on commercial heat pipes, and the higher performances measured with alcohol solutions have been always observed, showing a good reproducibility of the results summarized into this article.

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