OVERVIEW OF HEAT PIPE STUDIES DURING THE PERIOD 2010–2015

Stéphane Lips,1,* Valérie Sartre,1 Frédéric Lefèvre,1 Sameer Khandekar,2 & Jocelyn Bonjour1

1University Lyon, CNRS, INSA-Lyon, CETHIL UMR5008, F-69621, Villeurbanne, France
2Department of Mechanical Engineering, Indian Institute of Technology Kanpur, Kanpur 208016, India

*Address all correspondence to: Stéphane Lips, E-mail: stephane.lips@insa-lyon.fr

Despite numerous studies conducted on heat pipes over the last 50 years, the development of predictive tools for the design of heat pipes remains challenging, even for conventional technologies. As a result, heat pipes are still the subject of more than 250 scientific articles each year. The present review aims to identify and understand the current scientific approaches followed by scientists in heat pipe science. Different types of heat pipes are reviewed in order to identify the main phenomena involved in these systems. A brief overview of the heat pipe history is given and different applications are presented. A global review of recent studies on heat pipes is then presented. Advances are identified in terms of heat pipe characterization, scientific issues linked to the working fluid, understanding phase-change heat transfer in thin liquid films, and system modeling. Examples of recent studies are detailed to highlight strategies that can be followed to answer current issues. This global review highlights the main advances in heat pipe science over the last five years and draws perspectives on forthcoming scientific results.

KEY WORDS: heat pipes, experimental studies, theoretical studies

1. INTRODUCTION

Heat pipes are widely used in many industrial applications. They enable the transfer of high-heat fluxes with low-temperature gradients by using the latent heat of vaporization of a working fluid. The diversity of different kinds of heat pipes reflects the diversity of the conditions in which they are used. However, whatever type of heat pipe is used, its normal behavior is bounded by several operating limits that depend on various phenomena. Heat pipes are the subject of thousands of scientific articles published in more than 100 international journals. Two long-term established series of international conferences are dedicated to heat pipes every 2–3 years and they are a subject of interest at all general conferences dedicated to heat transfer. However, despite the numerous studies that have been undertaken on heat pipes for the past 50 years, the development of predictive tools for their design is still challenging, even for conventional technologies. This has resulted in real limitations in extending the use of heat pipes in the industry since each new heat pipe has to be carefully designed for each specific application. By reviewing recent research studies published on heat pipes, the authors aim to understand the scientific key issues that have led to this situation and the strategies that can be implemented to progress toward a better understanding of the different types of heat pipes.

Riffat and Ma (2007) proposed a review of developments in heat pipe technology and applications between 2000 and 2005. They noted different kinds of advances during the period. New kinds of wick structures for conventional and flat heat pipes were proposed and new working fluids were incorporated. They highlighted the development of new types of loop heat pipes (LHPs) and capillary pumped loops (CPLs) that were expected to be widely used in industrial applications. They also noted studies on flexible heat pipes as well as micro-heat pipes. New applications were studied, such as solar collector systems and heat pipe integrated turbines. Traditional topics, such as high-
temperature heat pipes and space applications, were also reported. For air conditioning systems, the coupling between phase-change materials and heat pipes was investigated. Finally, Riffat and Ma (2007) reported the development of new models and mathematical methods for the design of various kinds of heat pipes.

Since 2005, the research field on heat pipes has changed substantially. Figure 1 presents a word cloud created from the titles of articles published on heat pipes between 2012 and 2014 (about 800 papers). In this word cloud, the size of the words is proportional to the square root of the number of occurrences of each word. It is a convenient tool used that demonstrates a general overview in a given field (McNaught and Lam, 2010). Besides the words directly related to heat pipes themselves and their main components, it appears that experimental works are dominant compared to simulations, numerical analyses, and modeling. On the other hand, analytical approaches are very rare. Papers are often interested in heat pipe performance, and the diversity of the applications is shown by the paper titles (electronic cooling, light-emitting diodes, air conditioning, solar collector, cryogenic applications, vehicles, thermoelectric generators, energy storage, etc.). One can note the importance of the working fluid (water, ethanol, mixture) and materials (metal, copper, silicon, aluminium, glass, ceramic, copper oxide) used in heat pipes since they explicitly appear in many paper titles. The link between heat pipe science and material science is highlighted by the important occurrence of the words nanofluid(s) and carbon nanotubes, and also by the words material, sintered wick, and process of fabrication. Progress in manufacturing also promotes the development of micro-heat pipes as well as light-weight heat pipes.

This word cloud (Fig. 1) also gives a brief summary of the subject of the studies: effect of gravity forces and inclination angles are studied, as well as magnetic and electric fields. The start-up procedure is the topic of several articles and the transient response of heat pipes is studied. The word cloud even gives clues about some experimental devices used to characterize heat pipes, such as neutron radiography.

The diversity of the words present in the titles is also a reflection of the diversity of the journals in which the papers were published. The 800 papers dedicated to heat pipes between 2012 and 2014 were published in more than 200 different international journals. Figure 2 presents the distribution of the papers in the main journals. Despite the great number of journals publishing articles on heat pipes, about 40% of the papers were published in only 10 journals and almost all of them were dedicated to research on heat transfer. However, one can see that heat pipes are also of interest in the scientific and research communities developing solar and renewable energy, industrial, and electronic cooling applications.

The word cloud and the typology of the international journals publishing studies on heat pipes enables us to highlight the main key words describing the current research on heat pipes; however, it does not give information on the content of the articles. The aim of the present paper is to summarize the research dedicated to heat pipes during the

FIG. 1: Word cloud of the titles of heat pipe articles published between 2012 and 2014 (200 top used words in about 800 papers)
Overview of Heat Pipe Studies during the Period 2010–2015

2. BRIEF OVERVIEW OF HEAT PIPE TECHNOLOGIES, HISTORY, AND APPLICATIONS

2.1 Various Heat Pipe Technologies

A heat pipe is a system that is able to transfer high heat fluxes from a heat source to a heat sink with low thermal resistance using the liquid–vapor phase change (Reay et al., 2014). It consists of a cavity filled by a fluid at saturation. The liquid evaporates at contact with the heat source and condenses close to the heat sink. The way the vapor and liquid flow to the condenser and evaporator, respectively, depends on the type of heat pipe. The main types of heat pipes are summarized in Fig. 3. A distinction can be made between conventional heat pipes, LHPs, and oscillating heat pipes.

The family of conventional heat pipes comprises thermosyphons and cylindrical, flat plate, and rotating heat pipes. The liquid and vapor flows are countercurrent within the heat pipe body. The liquid flows from the condenser to the evaporator owing to gravity, capillary, and centrifugal forces, or a combination of these forces. In capillary heat pipes, the capillary structure (grooves, meshes, or porous medium) has to be continuous from the condenser to the evaporator.

The generic term loop heat pipe refers to LHPs themselves, but also to CPLs and two-phase loop thermosyphons (also called closed-loop thermosyphons). In these systems, the liquid and vapor flow in separate lines. For LHPs and CPLs, the sum of the frictional and gravitational pressure drops are compensated by the capillary forces in the capillary structure placed at the evaporator only. A CPL differs from a LHP by the placement of the reservoir, which has great importance on the overall system behavior. In closed-loop thermosyphons, the gravitational forces compensate for the frictional pressure drop.

Oscillating heat pipes, also called pulsating heat pipes (PHPs), are made of a single meandering tube placed between the heat source and the heat sink. Its diameter, close to the fluid capillary length, distributes the fluid within the tube into liquid plugs and vapor slugs. The violent vaporization of multiple liquid slugs in the evaporator, associated

FIG. 2: Distribution of recent papers (2012–2014) on heat pipes in various international journals
with the condensation of multiple vapor plugs at the condenser, generates self-sustained oscillations of the fluid. This leads to efficient heat transfer from the heat source to the heat sink, both by latent and sensible heat. These systems are cheap and easy to manufacture; however, their behavior is difficult to predict and they are currently sparsely used in the industry.

Despite the strong differences between the various heat pipe technologies, there are several phenomena shared by these systems. Obviously, liquid–vapor phase-change heat transfer is present in all heat pipes. The phase change occurs at the scale of the capillary structure or at the scale of the thin liquid films present in the system. The capillary forces are indeed almost never negligible. Moreover, because the fluid is always heated through a wall the interactions between the working fluid and the wall, mainly wetting effects, are of great importance. Finally, there is always a

<table>
<thead>
<tr>
<th>Heat Pipe Technology</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional heat pipes</td>
<td><em>a) Thermosyphon</em></td>
</tr>
<tr>
<td>Gravity assisted heat pipes</td>
<td><em>b) Cylindrical heat pipe</em></td>
</tr>
<tr>
<td>Capillary heat pipes</td>
<td><em>c) Flat plate heat pipe / Vapor chamber</em></td>
</tr>
<tr>
<td>Other heat pipes</td>
<td><em>d) Rotating heat pipe</em></td>
</tr>
<tr>
<td>Loop and pulsating heat pipes</td>
<td><em>e) Two-phase loop thermosyphon</em></td>
</tr>
<tr>
<td></td>
<td><em>f) Loop heat pipe</em></td>
</tr>
<tr>
<td></td>
<td><em>g) Capillary pumped loop</em></td>
</tr>
<tr>
<td></td>
<td><em>h) Pulsating heat pipe (PHP)</em></td>
</tr>
</tbody>
</table>

**FIG. 3: Different heat pipe technologies**

*Interfacial Phenomena and Heat Transfer*
coupling between hydrodynamic and thermal phenomena since the working fluid follows a thermodynamic cycle in the systems.

In this paper, research studies on heat pipes are classified according to the type of studies and not the type of systems. The similarities of the phenomena involved in all heat pipes suggest that progress in understanding of one kind of heat pipe generally helps in understanding other kinds.

2.2 History and Applications

In order to have an overview of the research in heat pipe science, a global analysis of the studies published on heat pipes is needed. Figure 4 presents the evolution of the number of articles related to heat pipes indexed on the Web of Science database (Reuters, 2015) between 1975 and 2014. Table 1 summarizes the exact queries used to plot Fig. 4. Several technologies are distinguished by filtering the content on the article title only; therefore, the present analysis does not pretend to be exhaustive but rather aims to give the general trends of research in heat pipes during the last 40 years. The category “others” in Fig. 4 refers to all papers in which the type of heat pipe has not been identified through the title. These often refer to conventional cylindrical heat pipes, but also to studies dedicated to phenomena involved in heat pipes in general.

Heat pipe science began during the 1960s and conventional heat pipes were soon widely used in space applications, for instance, to transfer the heat dissipated by the components to the radiators. To try to reduce the weight of the systems, CPLs and LHPs were invented by the National Aeronautics and Space Administration during the 1960s and by the Russian Federal Space Agency during the 1970s, respectively. However, these technologies were not reliable during this period.

During the 1980s, terrestrial applications of heat pipes were developed, mainly with thermosyphons because of the difficulty overcoming gravitational forces. Thermosyphons have been widely used in industrial applications, as well as in heat exchangers. The development of electric locomotives also motivated the use of heat pipes in mobile applications.

During the 1990s, new types of heat pipes were invented and studied in depth. Micro-heat pipes appeared thanks to progress in micro-technologies, with the aim of reducing the thermal contact resistance between the electronic component and the heat sink by directly integrating the heat pipe into the silicon substrate of the electronic component. At the same time, progress in porous material technologies enabled the implementation of CPLs and LHPs in spacecraft.
TABLE 1: Queries corresponding to Fig. 4

<table>
<thead>
<tr>
<th>Type of Heat Pipe</th>
<th>Query (in the Title)</th>
<th>Total Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>All kinds of heat pipes</td>
<td>Heat pipe(s) or thermosyphon(s) or thermosiphon(s) or vapo(u)r chamber(s) or capillary pumped loop(s)</td>
<td>3634</td>
</tr>
<tr>
<td>Thermosyphon</td>
<td>Thermosyphon(s) or thermosiphon(s)</td>
<td>820</td>
</tr>
<tr>
<td>Rotating heat pipe</td>
<td>Rotating and heat pipe(s)</td>
<td>49</td>
</tr>
<tr>
<td>Micro-heat pipe</td>
<td>Micro-heat pipe(s)</td>
<td>112</td>
</tr>
<tr>
<td>Flat heat pipe</td>
<td>Flat (plate) heat pipe(s)</td>
<td>119</td>
</tr>
<tr>
<td>LHP</td>
<td>Loop heat pipe(s)</td>
<td>325</td>
</tr>
<tr>
<td>CPL</td>
<td>Capillary pumped loop(s)</td>
<td>75</td>
</tr>
<tr>
<td>PHP</td>
<td>(Pulsating or oscillating) and heat pipe(s)</td>
<td>334</td>
</tr>
<tr>
<td>Vapor chambers</td>
<td>Vapo(u)r chamber(s)</td>
<td>117</td>
</tr>
</tbody>
</table>

*The term thermosyphon can also refer to single-phase thermosyphons. A rapid analysis of the abstracts shows that single-phase thermosyphons represent between 15% and 20% of the papers mentioning the term thermosyphons in their title.

Since the year 2000, the number of papers dedicated to heat pipes has continued to increase and now has reached about 250 papers per year. According to Larsen and von Ins (2010), the general annual growth rate of scientific publications is close to 5%, which implies a doubling time of about 15 years. With a doubling time of about 8 years, the growth rate of publications dedicated to heat pipes is much higher than the growth rate of all scientific publications. This enhanced research effort is mainly motivated by the increase in the heat flux density dissipated by the electronic components, which creates a need for efficient and reliable cooling systems. Thus, heat pipes, especially CPLs and LHPs, have been developed for terrestrial applications and these systems need to be optimized and perfectly understood in order to deal with gravitational and acceleration forces for onboard vehicle applications. At the same time, rising energy prices favor the use of heat pipes in numerous applications, either as a passive system to remove heat, to improve the efficiency of heat recovery systems, or to homogenize the temperature of various systems. Also, continuous progress in new materials and manufacturing processes enables heat pipes to be implemented in many other industrial applications.

Figure 4 illustrates the important developments in research on CPLs/LHPs over the last 15 years and on PHPs over the last 10 years. Together, they represent currently one-third of the papers devoted to heat pipes. The development of a reliable LHP would expand the use of heat pipes in many applications since they can transfer heat over a longer distance better than other types of heat pipes, while having low sensitivity to gravitational and acceleration forces. The development of PHPs has been mainly motivated by the low cost of these kinds of systems. Figure 4 also demonstrates that despite early research on thermosyphons more research remains to be done in this field. These systems continue to be optimized and studies have been undertaken to decrease their operating limits, especially in terms of heat power, heat flux density, and operating temperature.

Scientific issues involved in heat pipes are usually classified into four categories: evaporation heat transfer, condensation heat transfer, flow patterns in heat pipes, and capillary flows. In the present paper, another classification of the studies available in the literature over the period between 2010 and 2015 was selected:

- Research motivated by the heat pipe characterization;
- Scientific issues linked to working fluid behavior;
- Studies aimed at predicting the phase-change heat transfer in thin films; and
- Development of new heat pipe models.
This classification enables highlighting not only different scientific issues but also different scientific approaches that are used by research teams working on heat pipes. Indeed, the present paper is dedicated to the different approaches and current ways in which progress in the understanding of heat pipe can be made rather than directly to the scientific results themselves.

3. RESEARCH MOTIVATED BY HEAT PIPE CHARACTERIZATION

3.1 Determination of Heat Pipe Performance

From an industrial point of view, an important outcome of heat pipe studies is the determination of the overall performance of the various types of heat pipes. Performance can be typically expressed in terms of system thermal resistance and capacity to function in given operating conditions (imposed heat flux, ambient temperature, acceleration, orientation, etc.). Thus, many studies have been devoted to the determination of heat pipe performance, and the numerous prototypes that have been tested enable building important databases for each type of heat pipe. The thermal resistance of a heat pipe usually depends on the heat transfer at the evaporator and condenser. Thus, it also depends on many parameters such as the working fluid, the fluid fill charge, and the effective thermal conductivity of the wick (when exists), as well as other phenomena such as the operating regime and partial or total dry-out of the evaporator. For instance, the thermal performance of a LHP is often characterized by its operating curve (vapor or reservoir temperature as a function of heat power) and not by its thermal resistance. Determining heat pipe performance also leads to determining its operating limits, often detected by a sudden increase in thermal resistance or operating temperature. If the different limits have been well known from decades of research, then it is not so trivial to link the observed heat pipe behavior to a particular limit.

As an example, Maydanik et al. (2014) recently proposed a review on the performance of LHPs with flat evaporators. Performance under various geometries, as well as the impact of the working fluid and the materials, was compared. Recommendations were then proposed in order to achieve good performance when designing an evaporator for a LHP. For instance, Maydanik et al. (2014) advised using a copper/water combination for the wick material and working fluid for a temperature range of 70–100°C. For lower temperatures, ammonia can be used but only with compatible material. Maydanik et al. (2014) also concluded that LHPs are mainly interesting to consider in system applications when the distance between the heat source and the heat sink exceeds 200 mm and when a loop thermosyphon cannot be used. This kind of review is very important for the scientific community because it enables summarizing the scattered data from a large number of articles.

Review articles that deal with heat pipe performance can also focus on a specific application instead of a specific type of heat pipe. For instance, Srimuang and Amatachaya (2012) presented a review of the scientific literature on heat pipe heat exchangers. They concluded that the effectiveness of a heat pipe heat exchanger was in the range of 0.16–0.825 and that the four main influencing parameters were the inlet temperature in the evaporator section, the hot and cold air velocities, the fin geometry, and the working fluid inside the heat pipe. This example highlights the fact that the main parameters strongly depend on the application in which the heat pipe is used and not only on the type of heat pipe itself.

Moreover, the performance of a heat pipe is not only limited to its thermal performance. For instance, Zhang et al. (2014a) studied the socio-economic performance of a solar water heating system that included a heat pump and a new type of two-phase loop thermosyphon. They highlighted the fact that three factors have to be prioritized: the energy efficiency, the economic revenue, and the environmental benefit. Zhang et al. (2014a) concluded that the performance of their novel loop thermosyphon, compared to traditional ones, depends strongly on the selected criterion and the location of the system (in their study, London, Shanghai, or Hong Kong). This example shows that reducing the heat pipe performance only to its thermal resistance minimizes the challenges that are faced by the heat pipe scientific community.

Besides academic papers, many patents are filed, in which specific geometries and configurations are proposed. Patents can deal with specific parts of heat pipe, such as condensers (Fried et al., 2013) or wicks (Asfia et al., 2014). Additional parts are also proposed, such as a reservoir filled with adsorbent material in order to deal with freezing
problems (Bonjour et al., 2013). The large number of patents filed each year demonstrates the strong link between the academic research on heat pipes and their industrial applications.

In general, each time a new heat pipe design is proposed the first step in studying a prototype is to determine its performance. As an example, Lachassagne et al. (2012, 2013) proposed a new kind of LHP, a CPL for integrated power, with a reservoir located above the evaporator. In their first paper they determined its performance, and subsequently proposed a model under steady-state conditions. Heat pipes also have to be tested under various operating conditions. For instance, Mameli et al. (2014) characterized a closed-loop PHP under microgravity conditions. They showed that their heat pipe is more affected by gravitational variations than by the gravitational level itself. They also concluded that the performance of their heat pipe was similar under microgravity conditions and when placed horizontally under normal gravity conditions. This kind of conclusion is important for the scientific community because it can limit the number of tests required under microgravity conditions, which are expensive and difficult to perform.

Eventually, the last step, after a prototype characterization, is to study its behavior in a real system. For example, studies can be found on solar applications (Zhang et al., 2014b); heating, ventilation, and air-conditioning applications (Wang et al., 2015); and electronic cooling applications (Kim and Kim, 2014). In general, these studies focus on the transient behavior of the systems and the authors often compare their measurements with the results of transient numerical models. Indeed, the scientific goals of these studies are often to check the relevance of models that are developed to predict the heat pipe performance of each specific application.

3.2 Capillary Structure Characterization

For capillary heat pipes, the development of models requires knowledge of the properties of their capillary structure filled with working fluids since they have a direct effect on the heat pipe performance. Consequently, the capillary structures are the object of great attention in heat pipe science. New ways of manufacturing new capillary structures are continuously being developed. For instance, Singh et al. (2014) presented a fabrication technique for a sintered aluminum evaporator of a LHP, and Santos et al. (2012) proposed an evaporator made of ceramic; their research will help to develop more advanced evaporators in the future.

Besides developing new capillary structures with new techniques and new materials, a substantial challenge is determining the properties of existing capillary structures and developing predictive tools that can be used in heat pipe models. Measuring the permeability of a porous medium can be performed easily (Ameli et al., 2013; Hansen et al., 2015); however, the effective permeability of a capillary structure inside a heat pipe may be different from the bulk permeability of the medium because of the influence of the liquid–vapor interface. Measuring the global porosity can be easily performed by knowing the mass and volume of the wick. This method was used by Deng et al. (2013). However, it does not give any information about the distribution of the porosity in the wick, which is important to know in some configurations such as biporous wicks. Measuring the effective pore radius is also complicated because the contact angle between the fluid and the wick affects its value. For instance, Singh et al. (2014) used the bubble point testing method, which enables determining the largest pore radius, whereas Becker et al. (2011) characterized their wick by measuring the smallest radius of curvature of the interface before de-priming the wick. To characterize the pore size distribution, other methods need to be used, such as mercury injection or imbibition (Dullien, 2012); however, in practice these methods remain challenging.

From a thermal point of view, determining the equivalent thermal conductivity of a capillary structure is even more difficult. For example, this can be performed using a flash method (Ababneh et al., 2014); however, the measured value only takes into account conduction through the capillary structure and does not consider evaporation or condensation phenomena. More sophisticated setups need to be developed to take into account these phenomena (Iverson et al., 2007); however, there is a lack of experimental data and studies in this field.

3.3 Example of the Contribution of Inverse Methods

When direct measurements cannot be performed, another approach consists in using inverse methods. This approach is illustrated in this section with a novel method proposed by Revil-Baudard and Lips (2015). These authors aimed to determine the capillary structure properties from measurements of the overall performance of a flat plate heat pipe
under different inclination angles. Determining the thermal properties was based on an analytical method that was directly inverted: the equivalent thermal conductivities of the capillary structure at the condenser and evaporator were thus the outputs of the inverse method, whereas the temperature measurements along the heat pipe were the inputs (Fig. 5). This technique enabled a direct comparison between the properties of the capillary structure of various heat pipes even if the global thermal resistances of the systems were different. This was the first step in the construction of an experimental equivalent thermal conductivity database for the development of predictive tools.

Determining the hydrodynamic properties of a capillary structure—i.e., its effective permeability and effective pore radius—is more difficult since no direct measurement can be performed in a non-transparent heat pipe. The method is based on measuring the capillary limit for different inclination angles. The capillary limit is reached when the sum of the gravitational and frictional pressure drops is equal to the maximum capillary pressure that the wick structure can sustain. This leads to dry-out at the evaporator, and thus to an increase in the thermal resistance of the heat pipe. When the heat pipe is tilted in unfavorable positions the capillary limit decreases because of the effect of the gravitational pressure drop. The frictional pressure drop and the effective pore radius of the capillary structure can be estimated by assuming that the capillary pressure at the capillary limit is constant whatever the inclination angle (Fig. 6). This method has been successfully tested on a grooved flat plate heat pipe and validated by means of microscopy measurements. However, more studies are required in which this method is used with other capillary structures since the assumption of constant capillary pressure at the capillary limit of the heat pipe is not trivial.

This example deals with flat heat pipes; however, inverse methods can be used for a wide range of studies and are often the only way to accurately determine various parameters. For instance, Mehta and Khandekar (2014) used an inverse method to determine the heat transfer coefficient between a wall and a Taylor bubble train flow in a square cross-sectional mini-channel (5 mm × 5 mm). They coupled experimental data from infrared (IR) visualization with a numerical model that takes into account the three-dimensional (3D) conduction in the wall. The protocol for measuring the local heat transfer coefficient was far from simple and they concluded that the major challenges were to obtain sufficient spatial resolution to determine the local temperature gradients and to minimize the conjugate heat transfer effect in the system. This effect depends strongly on the wall thickness but also on the frequency and length of the bubbles in the flow.

In conclusion, even if a large number of papers are devoted to determining the heat pipe performance and/or the capillary structure properties, there is often a need to understand the phenomena that take place in the heat pipe itself since the models often assume a given heat pipe behavior, which is not always verified experimentally.

**FIG. 5:** Example of the comparison between an experimental temperature profile and the corresponding profile calculated by the inverse method for a flat plate heat pipe (Revil-Baudard and Lips, 2015; reprinted with permission from Elsevier, Copyright 2015)
4. SCIENTIFIC ISSUES LINKED TO WORKING FLUID BEHAVIOR

4.1 Toward a Better Understanding of the Operating Regimes and Fluid Behavior

The performance of a heat pipe often depends on numerous parameters and specific studies focus on understanding heat pipe behavior itself. For conventional capillary heat pipes, the operating conditions are bound by several limits that all lead to dry-out at the evaporator. For thermosyphons, PHPs, and LHPs, several operating regimes can be observed and recent progress has been made in their characterization. For example, Miscevic et al. (2012) and Kaled et al. (2012) studied the flow regimes and the transient behavior, respectively, of a CPL. They concluded that the pseudo-periodicity of the system was affected by the fluid motion and had a direct influence on the pressure drops in the loop. The operating regime is also of great importance in PHPs. Karthikeyan et al. (2014) studied the self-sustained oscillations in a PHP using an IR camera (Fig. 7). They characterized the different operating regimes and their impact on heat pipe performance.

Thermal measurements help to characterize heat pipe behavior; however, it is often important to deal with the behavior of the working fluid inside the capillary structure itself. Heat pipes are often studied as black boxes, and thus no direct observation can be performed inside the system. For the past 10 years, many research teams have studied transparent heat pipes, which allow a better understanding of the physical phenomena taking place inside the system. As an example, Lips et al. (2010b, 2011) used a confocal microscope to measure the pressure drops of the liquid inside one-dimensional and two-dimensional (2D) capillary structures. These experimental results enabled validating hydrodynamic models of liquid flow in grooves. However, this technology cannot be used to visualize liquid/vapor interfaces in other capillary structures, such as meshes or sintered wicks; the prediction of pressure drops in these types of capillary structures remains an important challenge. Confocal microscopy was also successfully used to measure the condensing film thickness in a silicon heat pipe (Lefèvre et al., 2010). Indeed, the geometry of the condensing film is of great importance in heat pipes because it directly affects the thermal resistance of the condenser. The contribution of confocal microscopy to the knowledge of flat heat pipe behavior is discussed here as an example; however, transparent systems have also been widely used to study thermosyphons (Smith et al., 2014), PHPs (Ji et al., 2013), and LHPs (Xu et al., 2014).

In order to study the liquid–vapor interface shape in detail, some studies have focused only on a subsystem of the heat pipe. For instance, El Achkar et al. (2012) studied the condensation of n-pentane in a microchannel that represents the condenser of a LHP. They measured the size and frequency of vapor bubbles during condensation and quantified the distribution between the sensible and latent heats of the phase change. On the other hand, Mottet et al.
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4.2 Research on New Fluids

Besides research on the fluid behavior inside a heat pipe, some studies have been dedicated to new kinds of fluids themselves. It is indeed of a great importance to choose an appropriate fluid for a particular heat pipe technology when using a specific application. The fluid properties must show a good trade-off between the high latent heat of vaporization, surface tension, and thermal conductivity, and the low viscosity for the whole range of operating temperatures. A given operating temperature corresponds to a given operating pressure that the heat pipe must be able to withstand. The compatibility between the working fluid and the other materials must also be perfect. This problem currently limits the use of flexible and/or lightweight heat pipes because of the poor chemical stability of materials such as plastics or polymer composites. An example of a compatibility table proposed by Mishkinis et al. (2010) is...
presented in Fig. 8, which shows that studies on fluid/material compatibilities can be contradictory and that more studies are required to obtain complete knowledge of the possible interactions between the working fluids and the wick and structural materials.

Other criteria, such as toxicity in humans and the environment must also be taken into account. For example, water can be an appropriate working fluid for an operating temperature range from 50°C to 150°C; however, low- and high-pressure problems can occur outside of this range. Moreover, freezing can also be a problem for heat pipes with certain kinds of capillary structures. Studies on new fluids are thus necessary. For instance, MacGregor et al. (2013) proposed a comparison of different working fluid performances for thermosyphons in order to replace R134a, which has been widely used, but may be banned in the near future. Other authors have also tested their prototypes with new refrigerants, such as R1234ze, which was found to be an efficient working fluid for LHPs (Yeo et al., 2014). For cryogenic applications, superfluid helium was also tested (Gully, 2015). In a general way, the definition of an efficient working fluid is still the subject of discussion. Since the initial approach of Chi (1976) to define a figure of merit for cylindrical grooved heat pipes, other figures of merit have been proposed. For instance, Launay et al. (2010) proposed figures of merit for working fluid in LHPs, whereas Arab and Abbas (2014) proposed a model to predict the thermal performance of a trapezoidal grooved heat pipe when changing the working fluid.

Besides new fluids themselves, contemporary heat pipe research has mainly focused on two new fluid families: self-rewetting fluids and nanofluids. Self-rewetting fluids exhibit an increase in their surface tension when their temperature increases. They often consist of a dilute aqueous solution of alcohol: in a certain range of temperatures, a concentration gradient occurs at the evaporator and the Marangoni effect adds to the temperature effect and helps in draining the fluid from the condenser to the evaporator. First studied for space applications (Savino et al., 2010), self-rewetting fluids have now been successfully tested in conventional heat pipes (Senthilkumar et al., 2012), thermosyphons (Karthikeyan et al., 2013) and even oscillating heat pipes (Hu et al., 2014). Self-rewetting fluids have proven their potential efficiency; however, more studies are still required to precisely predict their behavior. A nanofluid consists of a liquid base in which nanometric-sized metallic/non-metallic/ceramic particles are incorporated, quite often with surfactants to ensure their stability. Depending on their material, nanoparticles enable obtaining

![Compatibility table between the working fluids and the wick and structural materials (Mishkinis et al., 2010; reprinted with permission from the authors, Copyright 2010)](image)

FIG. 8: Compatibility table between the working fluids and the wick and structural materials (Mishkinis et al., 2010; reprinted with permission from the authors, Copyright 2010)
a working fluid with enhanced or tailor-made thermo-physical properties. In the last few years, numerous studies on nanofluids in heat pipes have been published. Liu and Li (2012) performed a review of the dedicated studies and concluded that depending on the type of nanoparticles, their size, and their concentration, nanofluids could significantly increase heat pipe performance, both in terms of thermal resistance and maximum heat removal capacity. The major effect of nanofluids seems to be the surface structuration of the evaporator, which affects the wettability of the wall as well as the boiling phenomenon (Stutz et al., 2011). These conclusions have been shared by other review articles recently published (Sureshkumar et al., 2013; Alawi et al., 2014). However, to date there are conflicting results and opinions on the efficacy of such fluids in heat pipe and thermosyphon systems. For instance, Khandekar et al. (2008) observed a decrease in the thermal performance of a PHP when nanofluids were used as the working fluids. Nanoparticle clogging affected the boiling phenomenon and the authors tried to quantify the effects of various mechanisms. More detailed research in this area needs to be undertaken for clarity (Buschmann, 2013). The effect of the wall structuration on the heat transfer is further discussed in Section 5.

Figure 9 shows the number of publications dedicated to nanofluids in heat pipes according to the Web of Science database. The number of papers increased rapidly between 2006 and 2010; however, since then it has decreased. Finally, the studies on nanofluids can be considered as studies on liquid–vapor phase-change heat transfer on nanostructured surfaces. However, the change in structural morphology of the wall depends on numerous parameters because it is time dependent and involves many aging phenomena of the nanofluid (aggregation, deposition, etc.). In conclusion, if the positive effect of nanofluids on heat pipe performance is well accepted, they mainly affect the heat transfer coefficient during the phase-change heat transfer and the pressure drops in the capillary structure. No phenomenon specific to heat pipes was observed, which could explain the decrease in the number of articles dedicated to nanofluids in heat pipes since 2010.

5. STUDIES AIMED AT PREDICTING PHASE-CHANGE HEAT TRANSFER IN THIN FILMS

Wall structuration (whether nano- or micro-structuration) can still be viewed as a promising track for improving the efficiency of heat pipes. The application of heat pipes is certainly the motivation behind many research studies on boiling or condensation heat transfer enhancement using structured surfaces. Regarding condensation, the objective is quite often to promote dropwise condensation by modifying the fluid wettability: making a surface (super)hydrophobic facilitates the roll-off of the droplets, which improves the overall condensation heat transfer. (Super)hydrophobic surfaces are generally obtained by acting on the surface chemical or physical characteristics to decrease the surface energy or by acting on the surface roughness (Bisetto et al., 2014). Different chemical coating processes for solid substrates with low surface-energy substances are currently being developed and evaluated, as explained by Sikarwar et al. (2011).

FIG. 9: Number of publications dedicated to nanofluids in heat pipes according to data collected from the Thomson Reuters Web of Science database (2015).
Regarding boiling (i.e., for application to thermosiphons), heat transfer enhancement techniques have been studied for decades, from the emergence of extended surfaces in the 1970s to the 1990s to the development of micro-structured surfaces, and more recently nanostructured surfaces, in relation to condensation. Extended surfaces are manufactured based on standard machining and metal processing. Micro-structured surfaces can be obtained using porous coatings or deformations of extended surfaces (e.g., low fin compression, fin bending, cutting, etc.), as described in Poniewski and Thome (2008). Nanostructuration relies on chemical processes (oxidation, etching, etc.) or nanoelectromechanical systems. Enhanced surfaces are usually used for two distinct purposes: either to increase the CHF or to increase the heat transfer coefficient.

Beyond a simple increase in the heat transfer area, extended surfaces can be employed to optimize the distribution of active nucleation sites or to favor the liquid flow around a heated wall. In addition, when reducing the size of the structures (down to micro- or nanometer size) that form the extension, additional phenomena can come into play, as reviewed by Kim et al. (2015) among many other reviews on the subject. For instance, while nucleation takes place within the pores of a porous coating, liquid can be fed to the nucleation site via capillary pumping. Micro- or nanoscale geometric effects (size as well as liquid flow distribution) can also favor bubble initiation, growth, and detachment, while the micro- or nanostructure will modify the fluid wetting characteristics, which will ultimately affect both the heat transfer coefficient and the critical heat flux (CHF). For example, the effect of nanostructuration with a Fe$_2$O$_3$ nanoparticle on the boiling curve of a 100 μm platinum wire is presented in Fig. 10 (Stutz et al., 2011): depending on the nanoparticle coating duration (and thus on the shape of the nanostructuration), the heat transfer coefficient can be increased or decreased but the CHF is always increased by this nanoparticle coating.

Finally, there have also been many attempts to take the benefits of the new possibilities offered by micro- and nanotechnologies to improve the wick structures that come into play in all the capillary heat pipes (Ranjan et al., 2011) where capillary evaporation occurs, especially in relation to LHPs. As a matter of fact, while the performance of these heat pipes is usually limited by both the ability of the wick to ensure capillary pumping and by its thermal resistance, microscale and (probably better) nanoscale objects (e.g., nanowires, nanotubes, etc.) should help improve both of these wick characteristics, such as leading to smaller menisci (i.e., increased capillary pumping), since they usually have greater thermal conductivity and allow for enhanced evaporation (Plawsky et al., 2014).

However, the difficulty in predicting the thermal performance of a heat pipe actually lies in the predominance of heat transfer through very thin liquid films. Numerous studies have aimed to determine the heat transfer coefficients during condensation or evaporation, but the models fail to reproduce the measurements, even for simple geometries such as grooves (Lips et al., 2010a). Studies dealing with micro-heat pipes (and thus with very simple geometries)

**FIG. 10:** Example of the effect of nanostructuration of the wall on the boiling curve obtained with a γ-Fe$_2$O$_3$ nanoparticle on a 100 μm platinum wire, where $\tau_c$ is the nanoparticle coating duration with pure water (Stutz et al., 2011; reprinted with permission from Elsevier, Copyright 2011)
are often limited to theoretical considerations, and there is a lack of experimental validation (Liu and Chen, 2013). For PHPs, Khandekar et al. (2010) pointed out that too many fundamental phenomena still need to be understood in order to achieve a complete model because of the pulsating and/or oscillating character of the Taylor bubble flow. Experimental setups were developed to study the evaporation and condensation phenomena in capillary tubes. For instance, Chauris et al. (2015) studied the evaporation of a thin film deposited by a moving meniscus. They highlighted the phenomena involved in the process and quantified the impact of each phenomenon on the global heat transfer by comparing their experimental results with a numerical model. They concluded that during the transit of a meniscus, most of the energy is transferred through the thin liquid film deposited by the meniscus but that the impact of the meniscus itself is not negligible.

Other recent studies have focused on heat transfer in thin films, but with no direct application to heat pipes. For example, Srinivasan et al. (2015) performed an experimental study aimed at understanding the mechanisms occurring during evaporation of an isolated liquid slug. They focused particularly on the drainage of the thin liquid film and found good agreement with Taylor’s law predictions. Kunkelmann et al. (2012) experimentally and theoretically studied the effect of the three-phase contact line velocity on heat transfer. They concluded that heat transfer in the contact line zone mainly depends on microlayer evaporation and transient conduction in the wall. On the scale of the liquid thin film, the properties of the wall are indeed found to be non-negligible and the coupling of the phenomena is complex.

To highlight this complexity, a study performed by Rao et al. (2015) and dedicated to understanding a single-branch PHP is taken here as an example. This study illustrated the coupling of thermal and hydrodynamic phenomena, which could lead to self-sustained oscillations. The experimental setup in Rao et al. (2015) consisted of a single vertical and transparent capillary tube closed on one side that was connected to a reservoir on the other side. Two transparent water heat exchangers, acting as an evaporator and a condenser, were located along the heat pipe. This experimental setup did not intend to represent a real PHP but it could be viewed as a model to study some fundamental physical phenomena while avoiding the hydraulic interactions between the different branches of a real PHP. Depending on the temperatures of the reservoir, evaporator, and condenser, self-sustained oscillations of the meniscus were indeed observed. Rao et al. (2015) simultaneously measured the meniscus position, triple contact line position, vapor pressure, and vapor temperature. They described the four-stage cycle associated with meniscus oscillation and highlighted the main phenomena involved in the process (Fig. 11).

The observed cycle was the result of a balance between the pressure of the reservoir, frictional pressure drop, variations of pressure due to compression and expansion phenomena, and variations of pressure due to the change of vapor mass resulting from condensation and evaporation of the fluid. The four-stage shape was due to the difference in the time scale between hydrodynamic and phase-change phenomena. Rao et al. (2015) showed that the vapor was always superheated, which was in accordance with the conclusions in Gully et al. (2013). This enabled them to determine the instantaneous mass of vapor and to estimate the rate of evaporation and condensation in various zones of the liquid–vapor interface during a cycle using a thermal model. Condensation occurred mainly on the liquid film and evaporation occurred on the liquid film, which was particularly significant close to the triple contact line. For both evaporation and condensation, the phase-change rate was at its maximum when the meniscus was at its second bottom-most position.

Even if the conclusions of this study cannot be directly used to explain the overall principle of a real PHP because of its overly simplified behavior, this study is a good example of the complexity of the balance between thermal and hydrodynamic phenomena that can occur in this kind of system. This is particularly important in a PHP, but also in all kinds of heat pipes where evaporation through thin liquid films occurs. In the case of a PHP, no complete model is able to predict its behavior; however, progress in understanding the phenomena contributes to more realistic models.

6. DEVELOPMENT OF NEW HEAT PIPE MODELS

During the past few years, heat pipe models have indeed been improved. Both analytical and numerical models have been proposed at the scale either of a single phenomenon or of an entire system. The goal of the present paper was not to precisely describe a complete set of equations on which the models published in the literature are based, but rather to give a brief overview of the types of models that are still under development today.
FIG. 11: Description of the four-zone cycle and associated phenomena (Rao et al., 2015; reprinted with permission from Elsevier, Copyright 2015)
Concerning conventional heat pipes (thermosyphons and capillary heat pipes), two types of studies have been published: those addressing the progress in computational fluid dynamics (CFD) modeling, which has enabled the development of 3D thermal and hydrodynamic models (Wang, 2012); and those in which analytical models have been proposed (Lips and Lefèvre, 2014). Studies of the first type enable better integration of heat pipes in a more complex system, whereas studies of the second type give simple and accurate engineering tools for the design of heat pipes themselves. Some other specific studies have aimed at determining the wick properties by using detailed thermal and hydrodynamic models at the pore scale (Ranjan et al., 2012). These three different approaches are very complementary and each leads to better understanding of the phenomena involved in each type of conventional heat pipe.

Several studies have been devoted to modeling of LHPs. Siedel et al. (2015b) proposed a comprehensive review of the scientific literature on steady-state modeling. They highlighted the high number of models available and noted that most of them are numerical. In another study, the same authors proposed a complete analytical model that required low computational time compared to numerical models (Siedel et al., 2015a). These models are able to reproduce the experiments but are limited by a lack of knowledge regarding the wick properties (permeability and effective thermal conductivity) of the accommodation coefficient of the working fluid and the thermal contact resistance between the wall and the wick structure. The presence, or absence, of a vapor zone at the contact between the porous medium and the heat source is also a source of discussion. Mottet et al. (2015) developed a 3D model of a wicked LHP evaporator. They used a mesoscale approach with a pore network model. Their model enabled highlighting phenomena that a 2D model could not reproduce and the authors made a distinction between different regimes governed by different phenomena. The best regime was found to be when a two-phase liquid–vapor zone formed just at the contact of the evaporator casing. Their simulation can be used as a guide in the design of new wicks for LHPs.

At the scale of the system, transient models of LHPs have been proposed. For instance, Kaled et al. (2012) proposed a model classically based on the energy, mass, and momentum balances for the evaporator/reservoir, condenser, and transport lines. They concluded that the fluid motion participates in the pseudo-periodic behavior of the system. At the same time, Nishikawara et al. (2013) proposed a transient model that correctly predicted the experimental data, despite the presence of an overshoot temperature when the heat load changes, which was not observed experimentally.

An important part of the modeling works published in the last few years have been devoted to PHPs. On one hand, the increasing number of experimental databases has enabled the development of empirical correlations (Qu and Wang, 2013); on the other hand, some 3D CFD models have been proposed (Lin et al., 2013) and phenomenological models have been implemented; which have shown good ability in reproducing the chaotic behavior of PHPs (Nikolayev, 2011). In all cases, these models still have to be improved in order to take into account all physical phenomena, especially at the scale of thin liquid films and triple contact lines. Detailed models already exist to understand these phenomena, but their experimental validation remains challenging (Nikolayev, 2010).

7. SUMMARY AND CONCLUSIONS

This brief review of recent studies focused on heat pipes enables to highlight the main approaches used by research teams to increase the understanding of various types of systems. Both experimental and theoretical works have been proposed and the scale of interest in the studies varies from the system size itself to the scale of the very thin liquid film present in the evaporation and condensation zones. During the past five years, some significant advances have been achieved:

- The understanding of evaporation and condensation phenomena on a capillary scale has been improved, mainly thanks to new systems of visualization and instrumentation.
- New fluids and new materials have been successfully tested and have enabled increasing the performance of heat pipes.
- Major progress in the understanding of LHPs has now enabled developing this technology on an industrial scale.
- The models are now able to predict experiments satisfactorily even if improvements could still be achieved in the prediction of transient behavior and thermal resistances involved in the systems. From a technological point
of view, new geometries and types of capillary structures have also been proposed (bi-porous wick, multilayer wick, ceramic wick, etc.). A new challenge is now the miniaturization of the systems.

- The more impressive advances are probably related to the PHPs. Five years ago, even the main phenomena were not well identified. Models are now almost able to reflect their chaotic behavior and reliable predictive tools can be expected in the next few years.

However, several scientific questions still need to be answered:

- The predictive tools strongly depend on the capillary structure properties and the heat transfer coefficient during condensation and evaporation. Limited progress has been realized in developing satisfactory models or correlations, even for simple geometries.

- Several phenomena still have to be better understood in order to be correctly taken into account in the models. Boiling in the capillary structure of a flat heat pipe and coalescence and break up of liquid slugs and vapor plugs in PHPs are only two examples.

- The evaporation and condensation processes in relation to thin liquid films are not yet fully understood, especially the influence of the wall properties on these phenomena. If the case for fully wetting fluids is supported by some theoretical background research, partial wetting, which is present in real engineering systems, still needs to be understood.

To answer these questions, more studies will be required. First, experimental studies with visualization are essential because of the need to understand the coupling between the different phenomena involved in these systems. The lack of experimental data is even more acute for phenomena that act at the microscale. For instance, without knowledge of the accommodation coefficient, thermal models of phase-change heat transfer at the triple contact line cannot be validated. The real mechanisms leading to the onset of nucleate boiling are also not yet fully understood and this strongly limits the predictability of numerical models since they almost always need to be fitted with experimental data. Beyond this, there is a lack of reliable convective condensation models at low flow rates that are able to predict the heat transfer coefficients in small and bended tubes such as LHP condensers. Another challenge will be to couple these microscale models to system scale models. This difficulty arises partially from the fact that the physical, topological, and chemical properties of the materials are often poorly known. To answer this issue, more interactions should be created between the heat pipe research community and the material science research community.

One can also expect that progress in other research fields will bring new tools that will enable improving the current systems. For instance, progress in high-frequency microelectronics paves the way toward active control of heat pipes, and the continuous development of new materials increases the possibility of developing real flexible and lightweight heat pipes if the current problems of fluid/material compatibility in plastic heat pipes can be solved. Thus, one can conclude that the study of heat pipes will remain a challenging and exciting topic at least for the next couple of decades.

REFERENCES


Larsen, P. O. and von Ins, M., The rate of growth in scientific publication and the decline in coverage provided by Science Citation Index, *Scientometrics*, vol. 84, no. 3, pp. 575–603, 2010.


