Proceedings of:
2001 ASME International Mechanical Engineering Congress and Exposition
November 11–16, 2001, New York, NY

DESIGN AND FABRICATION OF A MICRO-CPL FOR CHIP-LEVEL COOLING

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ABSTRACT

This paper summarizes the development of a micro-CPL designed for chip-level cooling. This research indicates that there are numerous fundamental issues regarding the thermofluid dynamics at small scales that are poorly understood. These issues, which can often be ignored at macro-scales, will be critical as devices such as micro-CPL's and heat pipes are optimized in order to handle the increasingly large thermal loads of modern technology.

INTRODUCTION

As the power supplied to electronic packages and Microelectromechanical Systems (MEMS) type devices increases, the question of thermal management becomes critical. The current mandate for power is reflected in everything from personal computer micro-processors to electronic packages required for unmanned aircraft. This, coupled with the demand for smaller systems, creates heat fluxes which become the most limiting factor in the production of micro-devices. Conventional methods of heat removal are simply not capable of dealing with the thermal gradients which lead to material failure. It therefore becomes necessary to look beyond traditional thermal management schemes, and develop techniques to deal with the cooling of micro-devices.

A micro-cooler based on MEMS technologies could be placed in direct contact with, or integrated directly into the micro-processor, sensor, or other electronic chip for which cooling is required and could maintain an optimal temperature. The advantages of this approach are three-fold. First, it allows for precise temperature control at the chip-level. Second, the overall cooling is more efficient because specific heat sources within the electronics package may be targeted. Third, the overall size of the electronic system can be kept small.

This paper presents an overview of several years of work that have been described previously as a framework to discuss interesting, but poorly understood, phenomena associated with micro-scale heat transfer.

CAPILLARY PUMPED LOOPS (CPL)

Capillary Pumped Loops (CPL) are similar to heat pipes in that the large effective thermal conductivity of a CPL is derived from the vaporization and condensation of its working fluid. The main difference between the two approaches is that in a heat pipe the vapor and liquid flows are in contact and run counter current to each other whereas in a CPL the vapor and liquid flows are separated into individual channels. This provides three advantages: first, this increases thermal isolation between the vapor and liquid (Dickey and Peterson, 1994), secondly, this provides for significantly improved geometric freedom by separating the evaporator and condenser, and finally, because the wicking structure has been removed from a majority of the device, the pressure drops are reduced along the vapor and liquid lines, allowing for larger mass flow rates under the capillary pumping limit.

Research on CPL's started in 1961 when Laub and McGinness began to investigate a two-phase thermal control system called a Capillary Pumped Loop (CPL). While they only examined a capillary pumped vapor generator, their work was later expanded on by Stenger in 1966, who reported on two CPLs capable of transporting more than 800 W over 50 ft. Since then, the CPL has been rigorously examined, and observed to be governed by the same limits as heat pipes. One–dimensional paradigms to design and predict their performance have been established (Dickey and Peterson, 1994).

There are many challenges in transitioning MEMS technologies to this specific application. While some of the challenges relate to micro-fabrication design including material and geometric characteristics and overall flow dynamics. Many of the technical challenges bring up extremely interesting problems relating to the physics of micro-heat transfer and fluids mechanics. A few of these issues that have been identified in our research will be discussed, or rather, presented below. These issues relate to the physics of micro-scale heat transfer and phase change phenomena including interfacial dynamics.

The development and optimization of such systems will require better understanding of these physical issues. Eventually, a thermal management system could consist of a new family of pumps and valves to control liquid or vapor transport within the micro-CPL as well as innovative micro scale heat acquisition and rejection regions.

MICRO-CPL DESIGN

Figure 1 shows a schematic of the first passive three-port CPL that we fabricated for experimental investigation of CPL performance (Kirshberg, et al. 1999). The flow channels and access holes are etched into silicon and a glass cover is bonded on top in order to allow visualization of the fluid dynamics. In the design shown, the wicking structure for both the evaporator and condenser are etched into the glass although systems have been made with the wicking structure etched into the silicon. In an actual system, it would be anticipated that the wicking structure would be fabricated on the bottom of the chip to be cooled which would then be bonded directly onto the appropriate flow channels.

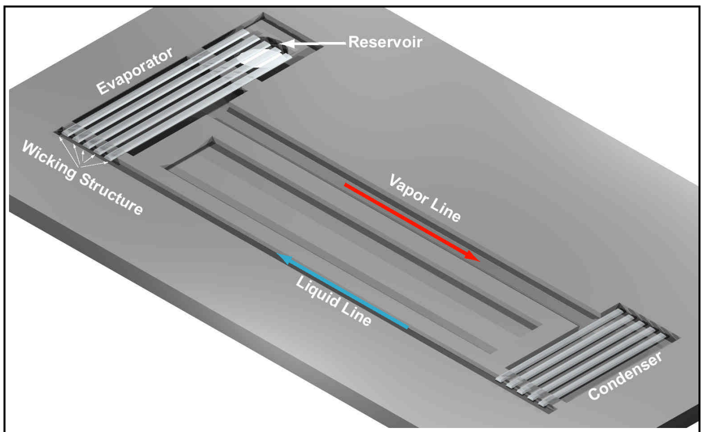

Figure 1. Schematic of the micro-CPL. The fluidic channels (gray) are fabricated from silicon, while the wicking structure (white) is etched into a borofloat glass cover plate

Table 1. Parameters for the first generation micro-CPL

Evaporator Dimensions	1000 x 500 µm
Condenser Area	5.0e+05 sq. µm
Vapor Line Dimensions	150 x 450 µm
Liquid Line Dimensions	150 x 150 µm
Vapor/Liquid Line Length	35 mm
Liquid Line Re Number	26
Vapor Line Re Number	430

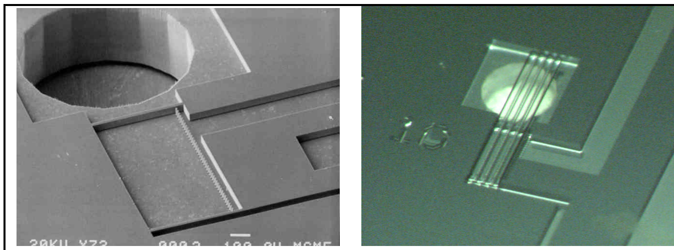

Figure 2. The evaporator section of the first generation micro-CPL without a cover (left) and with the cover showing the wicking structure (right).

Following the paradigm driving micro heat pipe design, a one-dimensional analysis used previously on macro-scale CPLs was adopted for the micro-CPL's design. The design approach was to predict the limits of capillary pumping and was based on the work of Dickey and Peterson with the inclusion of the pressure drop of the vapor line. This model provided limits on the lengths of the vapor and liquid lines (Table 1). The rest of the features including a 'fence' in the evaporator to reduce liquid in the vapor line were adapted from macro-scale devices or required by fabrication constraints (Figure 2). Despite the rather crude approach, the system actually worked (Kirshberg et al. 2000).

The next generation device, shown in Figure 3, increased the size of the evaporator section, improved filling characteristics with an additional port, improved the connection of the reservoir with the evaporator, and provided access for thermocouples (Kirshberg et al. 2000).

The performance of this device using a laser to heat the evaporator showed reasonable performance. The CPL removed approximately 4W from the laser input of 7.5W. In addition, the surface temperature of the CPL was 30° C less than that of a blank wafer. The wick dried out at 8W input power. (Pettigrew, et al. 2001). The performance of the device could be improved

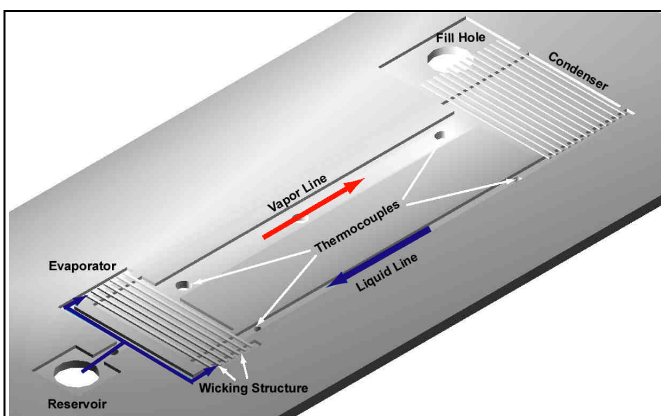

Figure 3. Schematic of the second generation micro-CPL.

by increasing the size of the condenser and by using materials that provide better thermal insulation between the vapor and liquid components of the working fluid.

UNANSWERED QUESTIONS

The micro-CPL presents an interesting set of thermofluid dynamical behavior. The main area where interesting things happen and that seems to be important for future development of miniature thermal control systems is the wicking structure and dynamic behavior of evaporation/boiling at small scales.

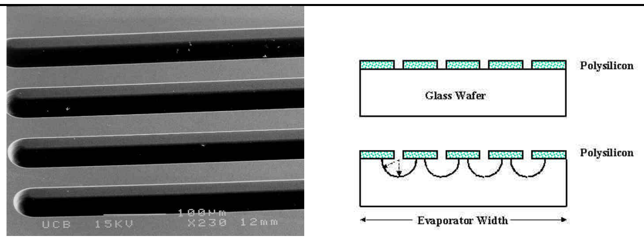

Figure 4. Wicking structure in the glass cover plate (left) and fabrication approach (right) that determines the geometry of the wick structure.

While attempts have been made to study potential wicking structures for a micro-CPL, no one had previously fabricated an entire device (Holke et al., 1998). Our systems were developed more along the lines of what was possible, rather than an optimization of the structures. Figure 4 shows a typical wick structure etched into the glass cover plate. Wet etching, using HF was used so the wick has a semicircular cross-section. The working fluid, usually water, forms a meniscus as it evaporates and most of the heat transfer occurs at a small region at the side of the channel. Even assuming some sort of steady state, the thickness of the meniscus must decrease as the water evaporates along the length of the evaporator. This is an extremely difficult problem both experimentally and numerically/analytically.

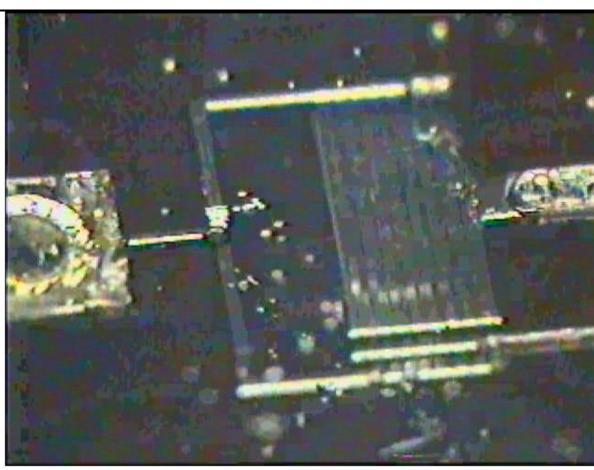

Figure 5. Operating evaporator of the second generation micro-CPL.

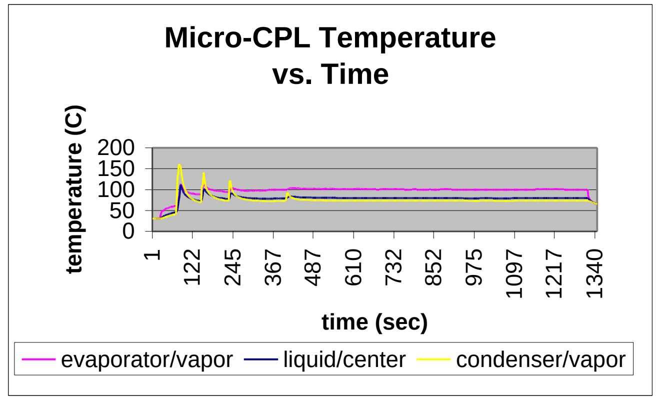

Figure 6. Temperature at three locations during start-up and steady run of the micro-CPL.

What was more surprising during our experiments on the micro-CPL was that steady behavior was never observed. Instead unsteady boiling occurred (Figure 5). Researchers at Stanford University have also found unsteady boiling regimes at the microscale (Zhang et al. 2001). However, despite the unsteady nature of the evaporative process, the resulting temperature at the evaporator remained remarkably steady (Figure 6) (Kirshberg, et al. 2000).

Size effects may be responsible to a large degree for the unsteady boiling observed in our experiments. However, there seems to be indications that surface tension effects may play an important role in the evaporator dynamics. Surface tension forces in micro-systems can be much more significant than in macro-systems because the small size creates situations where the radius of curvature is extremely small. High-speed videos of the evaporator of a micro-CPL using ethanol as a working fluid have recently been taken in the micro-heat transfer laboratory at UC Berkeley. Although transients exist in the evaporative process, they are much slower and less chaotic and violent. One of the main differences between ethanol and water is the surface tension.

This indicates that one possible factor in the unsteadiness could be thermal generation of surface tension gradients. Marangoni stress is associated with thermocapillary migration and has been worked on since the late 1950's (Young, Block and Goldstein 1959). This phenomenon can generate significant flows at the micro-scale and has been used to create micropumps (Debar 2001). At MEMS length scales, Debar showed analytically that a temperature difference of 0.1K across a 100 µm vapor bubble could generate a flow that approaches 1 - 10 cm/s. Temperature gradients will exist in the evaporator as a result of wick geometry and unsteady boiling, this may generate unsteady forces that create unsteady flows on top of or that interact with the nucleate boiling processes.

SUMMARY

The research summarized here shows that a micro-CPL is possible and actually works very well. The research has also indicated that there are numerous fundamental issues regarding the thermofluid dynamics at small scales. These issues, which can often be ignored at macro-scales, will be critical as devices such as micro-CPL's and heat pipes are optimized in order to handle the increasingly large thermal loads of modern technology.

ACKNOWLEDGMENTS

This research was begun under a grant from the Scientific and Technology Research Program for BMDO, and is now supported by DARPA under its HERETIC program. The fabrication was done at the Berkeley Sensor and Actuator Center, and would not have been possible except for the constant advice and support of its members. The work of Jeff Kirshberg, Kenneth Pettigrew and Kirk Yerkes is gratefully acknowledged, as are the contributions of Ralph Grief, Costas Grigoropoulos, and Jaewon Chung. The assistance and expertise of Don Reinmeuller in setting up the experiment at AFRL.

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