REVIEW OF LITERATURE AND A PRELIMINARY EXPERIMENTAL INVESTIGATION ON START-UP INSTABILITIES IN AN R-11 THERMOSIPHON LOOP WITH APPLICATIONS IN MICROELECTRONIC CHIP COOLING

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ABSTRACT

A literature review on the recent applications and developments of thermosiphon loop is conducted. In particular, systems suitable for cooling of microelectronic chips are reviewed in greater detail. The advantages of using a thermosiphon loop in microelectronic applications are discussed. The instability and temperature overshoot at the start-up have been identified as major problems which require further investigation. An experimental thermosiphon loop facility is built for preliminary investigations. Qualitative results on instability and temperature overshoot are obtained by varying the time interval between shutdown and next start-up. For the conditions of the tests conducted, aging did not affect the results, but the liquid subcooling and the dissolved gases are suspected to play an important role in the start-up behavior.

NOMENCLATURE

θ - time interval between successive system shutdown and start-ups, minutes or hours
P - system pressure, bar

INTRODUCTION

A thermosiphon loop transfers heat from a hot source to a cold sink through the evaporation and condensation of the working fluid. This system is particularly suited for cooling of microelectronics chips. A thermosiphon loop can transfer heat from the interior of a microelectronic system to a central location where space limitations are less stringent. The advantages that a thermosiphon system enjoys over a conventional refrigeration system include: (1) absence of moving parts leading to a more reliable system operation, (2) increased choices for selecting a working fluid compatible with microelectronics chips since it does not have to go through a refrigeration cycle, (3) reducing the decomposition rate of the working fluid as the higher temperatures at the compressor discharge in a vapor compression refrigeration system are not encountered, (4) clean operation as no oil is circulated through the system. In comparison to pool boiling systems employing vapor space condensation, a thermosiphon loop offers more flexibility in terms of providing a centralized condenser with different feed lines to individual evaporator stations. Further, with the addition of a liquid circulating pump, a thermosiphon loop, higher heat transfer coefficients associated with flow boiling systems could be realized.

One problem associated with the boiling systems is the presence of an undesirable temperature overshoot at the start-up. The temperature overshoot effectively limits the maximum heat removal rate for which the cooling system can be designed during normal operation. The present study is aimed at obtaining the information regarding the heat transfer and instabilities at the start-up of a thermosiphon loop by conducting experiments on a simple unit fabricated in the heat transfer laboratory at the Rochester Institute of Technology as a part of the undergraduate design project. The understanding gained through this study will be useful in developing suitable strategies for designing thermosiphon systems for cooling microelectronics chips.

Objectives of the Proposed Study

The objectives of the present work are to (i) conduct a literature survey to study the developments in the design and operation of thermosiphon loops in different applications, and (ii) to develop a preliminary thermosiphon loop for studying the instability and temperature overshoot phenomenon at the start-up conditions. The literature review will be helpful in identifying the critical areas where further work is needed, and will also aid in the design and fabrication of the experimental
set-up. Due to the limited funding available for an undergraduate design project, the scope of the experimentation is limited to study the extent of the wall temperature overshoot and observe the system behavior at the start-up as a function of time interval between successive shutdown and start-ups.

REVIEW OF LITERATURE

Thermosiphon Loops in Chemical and Process Industry

Thermosiphon systems are routinely employed in chemical industries in reboilers which are essentially natural circulation evaporators. Design guidelines for reboilers may be found in any heat exchanger design handbook, (e.g., see Shah and Muller, 1985).

Application of thermosiphons as coupled heat exchangers in heat recovery systems has been the subject of recent studies by McDonald. The initial experimental study by McDonald et al. (1977) was limited to the performance of single loops. Results were obtained using two different working fluids, R-113 and R-11. The performance curves were presented in terms of loop conductance defined as the inverse of the effective thermal resistance offered by the thermosiphon loop between the heat source and the heat sink. The amount of refrigerant in the system, the angle of inclination of the evaporator and condenser tubes, and the source and sink temperatures were systematically varied. Evaporator dryout and condenser flooding were the two determining factors in arriving at optimum system performance.

Subsequently, Ali and McDonald (1977) simulated the performance of thermosiphon loops by utilizing the available empirical correlations for evaporation and condensation heat transfer coefficients, and single-phase and two-phase pressure drops. Based on the above simulation, McDonald and Ali (1977) generated performance characteristics of the thermosiphon loops which compared reasonably well with the experimental results. Further experimental studies on unidirectional (McDonald et al., 1978) and bidirectional (McDonald and Sampath, 1979) thermosiphon loops were conducted. In general, these studies indicate that the amount of refrigerant, or charge, is a very important factor in the system performance.

Concentric tube thermosiphon offers a simplified system by using the annular region to boil off the refrigerant, which rises to a condensing space above. Condensed liquid is returned to the bottom of the annular region through the inner tube. Seki et al. (1981) studied the concentric tube thermosiphon, and proposed correlations for boiling heat transfer coefficient in annular spaces for design purposes.

Chen and Westwater (1987) employed a thermosiphon loop in the study of flow boiling heat transfer in compact heat exchangers. The thermosiphon loop had two circuits, one for boiling and other for condensing R-113, connected through a surge tank supplying liquid to the evaporator. This allowed close control of the liquid head in the surge tank. Chen and Westwater encountered the problem of flow oscillations at high heat duties in the evaporator. This was probably the result of temperature overshoots combined with instabilities resulting from various pressure drop oscillations during boiling in the heat exchanger and flow of liquid in the supply lines.

Thermosiphon Loops in Solar Energy Application

Two-phase thermosiphon loops are employed in solar energy application to transfer heat from the collector to a storage tank or to a secondary heat exchanger loop for heating or power generation applications. The important criteria here is the efficiency of heat transfer with a minimum temperature difference between the evaporator and the condenser. Some of the recent investigations described below deal with the experimental and theoretical aspects of heat transfer in thermosiphons employing a refrigerant as a working fluid.

Downin and Waldin (1980) investigated the phase change heat transfer in solar hot water heating application employing R-11 and R-114 as working fluids. Al-Tamimi and Clark (1984) studied the thermal performance of the entire system using R-11 as the working fluid. Spears and Waldin (1983) developed a testing procedure which is adopted by ASHRAE for determining the thermal performance of collectors containing a boiling liquid. A theoretical analysis of a thermosiphon loop with flat plate collector was carried out by Price et al. (1986) while Braven (1988) analyzed the heat transfer in a tilted thermosiphon evaporator which was employed in an evacuated tube solar collector. Cheng and Lee (1984) conducted experiments to study the operating and heat transfer characteristics of a thermosiphon loop using R-11. They conducted experiments on the evaporator and condenser to obtain the information on individual heat transfer coefficients as a function of heat flux, liquid charge level and the cooling water flow rate. The studies are useful in simulating the thermal performance of relatively large sized evaporator and thermosiphon loop applied in solar energy applications where the temperature overshoot or start-up instabilities are generally of little concern.

Thermosiphons as Applied in Heat Pipe Application

The heat pipes operate on the same principle as the thermosiphon loops being investigated here except that the liquid return to the evaporator in the heat pipe is generally accomplished through the capillary action of a wick. The work on heat pipes is not reviewed here in detail as the thermosiphon loop being investigated is wickless with an external liquid line between the condenser and the evaporator. Further, the initial temperature overshoot and instability at the start-up are not critical issues in the operation of the heat pipes. For a comprehensive summary of the available work on the theoretical principles and design considerations, reader is referred to the books by Ivanovskii et al. (1982) and Dunn and Reay (1976).

Thermosiphon Loops in Microelectronic Applications

The literature reviewed above shows that the thermosiphon loops have been investigated for overall performance; however some of the critical questions relevant to their application in microelectronics devices still remain unanswered. One of the most important concerns in microelectronics application is limiting the junction temperature below a certain prescribed limit. In the start-up phase of thermosiphon loops, the thermal behavior of the evaporator is of crucial importance. In the beginning, heat is transferred from the tube wall to the liquid refrigerant by natural convection. As the wall temperature rises further, the incipience of nucleate boiling occurs resulting in a
drop in the wall temperature, sometimes leading to an unstable operation. The temperature overshoot just before the incipience could be quite large, and may pose to be a limiting condition in the design of thermosiphon loops. Recent developments in nucleate boiling augmented surfaces have resulted in significant increases in heat transfer coefficients. The temperature overshoot at the incipience of boiling for these surfaces has been the subject of a few recent investigations.

Bar-Cohen and Simon (1986) discuss in detail the theoretical reasons for wall superheat overshoots at the boiling incipience of dielectric fluids. Danielson, Tousignant and Bar-Cohen (1987) investigated the pool boiling behavior of four most commonly employed dielectric fluids - FC-87, FC-72, FC-77 and FC-75 on platinum wires. The pool boiling curves showed significant temperature overshoots at the incipience of boiling. The main reason was attributed to the high wettability and high solubility of gases in these fluids.

Thermosiphon principle was applied by a number of investigators to improve the heat transfer from chips to heat sink by flooding the chips with a stagnant pool of boiling liquid, e.g., Kromann et al. (1986), Kohra et al. (1983) and Kiewra and Wayner (1986).

Anderson and Madawar (1988) investigated cooling of multichip modules using a liquid encapsulated gravity driven thermosiphon cooling concept. The multichip module is submerged in a stagnant pool of a dielectric Fluorinert (FC-72). Liquid Fluorinert is boiled off from the module, and the resulting vapor is condensed over a water cooled finned tube condenser surface placed in the vapor space above the liquid pool. Anderson and Madawar identified the uncertainty existing in the prediction of the incipient boiling point. The excessive superheats at the boiling incipience, and the thermal shock resulting from rapid heat dissipation following the inception may result in potential damage to the chips. They studied various augmented surfaces including low profile micro-fins, micro-stud and micro-groove surfaces, sanded and vapor blasted surfaces, square studs, and various arrays of drilled artificial cavities. Significant reduction in incipience temperature overshoot was observed for vapor blasted and inclined micro-groove surfaces. Micro-groove surfaces showed a modest increase in Critical Heat Flux (CHF), while micro-fins and micro-stud surfaces showed a considerable increase in CHF although the reduction in temperature overshoot was quite modest.

Ayub and Bergles (1988) performed nucleate pool boiling tests with R-113 on a number of GEWA-T deformed low fin external surfaces to accurately establish the incipient boiling characteristics. They report a number of studies in which large incipience temperature overshoots were observed over augmented surfaces. The GEWA-T surfaces tested showed multiple but quite small temperature overshoots. Similar studies were recommended by Ayub and Bergles for various augmentation surfaces under different aging conditions.

Park and Bergles (1986) investigated the performance characteristics of detachable copper heat sinks with different structured surfaces attached to them. They observed considerable reduction in temperature overshoot with microhole surfaces in R-113. Oktay and Schmeckenbecher (1974) found that plating nickel with an irregular dendritic structure directly on the chip surface eliminated the temperature overshoot with FC-88. Similarly, the effect of placing precise arrays of pins on flat copper surfaces in R-113 was reported by Messina and Park (1981), and on micro-fins and multilayered porous structures in FC-72 was reported by Nakayama, Nakjima and Hirasawa (1984).

Park and Bergles (1986) studied the effect of size of the heating surface on boiling characteristics of R-113. Under pool boiling conditions, the width of the heater did not have any significant influence on the heat transfer coefficient. The effect of height of the heater surface was studied for CHF, and it was seen that increasing height leads to a reduction in CHF due to larger population of vapor bubbles at the top of the heating surface.

Hwang and Moran (1981) investigated the nucleate boiling characteristics of substrate mounted silicon chips in FC-86. This study was prompted by the need to conduct electrical testing of chips before employing them in a Thermal Conduction Module (TCM). The chips were submerged in FC-86 bath with a closed loop consisting of a cooling system, a reclaimer and a circulation pump. For plain chip surfaces, the nucleate boiling curve indicated a wall temperature of 60 to 80 deg K above the saturation temperature. Also, a temperature overshoot of 25 deg K was observed. Hwang and Moran then tested chip surfaces enhanced by laser nucleation cavities of 3-15 microns diameter and observed considerable reduction in the wall temperature, as well as an improvement in the CHF. Another point to note is that in the vertical orientation, the top surface of the chip was considerably cooler than the bottom portion indicating an improvement in heat transfer caused by flow effects of the rising bubbles.

Boiling in narrow rectangular channels was investigated by Mond et al. (1986). They injected vapor bubbles at the bottom of the channel to study the effect of two-phase flow. They noted that the presence of passing bubbles improved the heat transfer rate at lower heat fluxes, while at higher heat fluxes the nucleate boiling on the heater surface was dominant and the passing bubbles did not make much difference.

Flow boiling and falling film cooling have been applied to microelectronic cooling by a few investigators. Chu (1986) provides some of the details of cooling a number of modules in a single gravity driven and mechanical pump assisted flow boiling system. He also discusses liquid jet impingement and falling film cooling systems.

The incipient temperature overshoot in direct immersion cooling with R-113 was investigated by Bergles and Kim (1988). They used a bubble generator below the vertical boiling surface, and observed a reduction in the temperature overshoot from 30 to 8 deg K for plain copper surface, and from 23 to 7 deg K on sintered copper surface.

The problem of temperature overshoot was not observed under the flow boiling conditions with a falling film evaporator as reported by Grimley et al. (1987). They employed FC-72 and FC-86 on simulated multichip modules. Effect of micro-fins and micro-stud technique was studied and considerable improvement in heat transfer coefficient, CHF, or both were reported. The enhancement in heat transfer with an evaporating impingement jet of refrigerant R-12 from a conventional refrigeration system was studied by Goodling et al. (1987).

As reported by Bar-Cohen (1987), the future needs point toward further improvement in the heat transfer coefficient.
over pool boiling coefficients provided by dielectric fluids on plain silicon surfaces, and also toward employment of lower temperatures - near O C for optimum performance of GaAs FETs. The thermosiphon loop utilizing the more efficient flow boiling mechanism combined with the possibility of manufacturing a variety of augmented surfaces on microelectronic chips could lead to significantly higher heat removal rates as compared to conventional forced convection or pool boiling techniques.

The literature survey described above indicates that the temperature overshoot could be quite considerable during nucleate pool boiling. The extent of the temperature overshoot and its effect on the instability at the start-up in a thermosiphon loop are not clearly investigated in the literature. Such a study is thought essential before devising practical ways to overcome these problems. A preliminary experimentation is therefore conducted to qualitatively study this problem. The details of the experimental set-up and the preliminary results are described in the following sections.

EXPERIMENTAL SETUP

A schematic of the thermosiphon loop fabricated at the Rochester Institute of Technology is shown in Fig. 1. It consists of a vertical evaporator made of 9.53 mm ID and 203.2 mm long hard copper tube. It is mounted between two phenolic flanges which are held together by four connecting steel rods. This construction allows easy removal of the evaporator section so that different augmented tubes could also be tested in the subsequent phases of the work. Three T-type thermocouples are soldered to the tube in a slight depression made by a 1.6 mm (1/16") wide end mill. Two of the wall thermocouples are located at 2.54 cm from the top and bottom ends, and one is located at the middle of the tube. The thermocouple wires run along the tube circumference at one-half turn to reduce conduction losses along the thermocouple wires. Teflon coated nichrome wire is wound uniformly around the tube. The wire wound tube is tightly wrapped with two layers of 12.7 mm thick aluminum oxide insulation. Thermocouples are installed in the insulation at 12.7, 25.4 and 38.1 mm radially away from the tube. The outside surface of the insulation is covered with a reflective aluminum tape. A sight-glass was installed at the exit of the evaporator. This allowed the observation of liquid-vapor flow at the evaporator outlet.

The condenser consists of an inclined double pipe heat exchanger with R-11 vapors condensing inside a 12.7 mm ID copper tube. The cold water is circulated in the annulus. The length of the condenser is 660 mm and it is insulated with 25 mm thick insulation. The condenser was supplied with cold water from a Lauda constant temperature bath maintained to within less than ±0.01 deg C.

The liquid circulation rate through the evaporator is determined using a burette as shown in Fig. 1. In normal operation, the valve V8 is closed and the condensate flows through the glass buffer tube which acts as a reservoir of liquid R-11. For measuring the flow-rate through the system at steady-state, first the valve V8 is opened and the liquid in the burette is allowed to flow out. Then the valve V8 is closed and the time required for the liquid level to rise between two markings (10 ml of liquid volume) is measured.

The pressure in the system is measured with a Bourdon pressure gauge. It is used to measure the steady-state pressure in the system. The pressure gauge is inadequate to measure and record the fast transient pressure fluctuations at the inception of nucleation in the evaporator.

The thermocouple output is connected to Issac data acquisition boards which were installed in an IBM PC XT computer. The power input to the heater and the pressure gauge reading are recorded manually for each run.

The thermocouples were calibrated at ice point and steam point temperatures. The three thermocouple readings were within ±0.2 C after leaving the system unpowered for 24 hours.

RESULTS AND DISCUSSION

The objective of the experiments conducted was to obtain qualitative information regarding the instabilities and wall temperature overshoot at the inception of boiling. A total of ten test runs were carried out at a heat input rate of about 13.2 Watts. The main parameter which was varied in these runs was the time interval θ between two successive runs during which the heater power and the condenser cooling water circulation was cut off.

Figures 2-4 show the effect of varying θ on the maximum wall temperature reached in the evaporator. The system pressure indicated in each figure corresponds to the pressure recorded by a pressure gauge at the start of each test. Figure 2 shows the results for the case when the system was started after θ=72 hours. The system pressure was 1.117 bar (1.5 psig). As the heater power and the cooling water circulation was started, the wall temperatures at the three location on the evaporator started rising. During this initial period, the middle thermocouple was always reading highest while the bottom thermocouple was reading the lowest. When the middle thermocouple reached a temperature of 48.9 C all three wall temperatures dropped indicating the inception of nucleation.
Fig. 2 Transient behavior of the thermosiphon loop at the start-up, $\theta=72$ hours, Heater Power 13.24 Watts, Initial system pressure = 1.117 bar

Fig. 3 Transient behavior of the thermosiphon loop at the start-up, $\theta=1$ hour, Heater Power 13.21 Watts, Initial system pressure = 1.220 bar

This was accompanied by a burst of a liquid-vapor mixture coming out as seen through the glass tube at the exit of the evaporator. The system operated fairly steadily following the nucleation with the system pressure gradually increasing to a steady-state value about 0.1 bar above the initial value at the beginning of the experiment.

Figure 3 shows the start-up characteristics of the system for $\theta=1$ hour. The system behavior is similar to Fig. 2 with $\theta=72$ hour except that the initial pressure is slightly higher at 1.220 bar (3.0 psig). The maximum temperature at the middle thermocouple was 53.3 C which is 4.4 C higher than the corresponding value in Fig. 2. However, since the saturation temperature for Fig. 3 is 3.9 C higher due to a higher initial pressure, the wall superheat at the inception in both cases is almost same. This suggests that the nucleation characteristics are unaffected by the change in $\theta$ from 72 hours to 1 hour.

Figure 4 shows a similar plot with $\theta=10$ minutes. The system pressure is 1.255 bar (3.5 psig) and the maximum wall temperature reached is 55.5 C which gives almost the same wall superheat at nucleation as for $\theta=1$ hour.

Fig. 4 Transient behavior of the thermosiphon loop at the start-up, $\theta=10$ minutes, Heater Power 13.23 Watts, Initial system pressure = 1.255 bar

Fig. 5 Transient behavior of the thermosiphon loop at the start-up, $\theta=168$ hours, Heater Power 13.33 Watts, Initial system pressure = 1 bar

In the steady-state operation of the thermosiphon loop, the wall temperature at the top location in the evaporator is observed to be always highest while the bottom thermocouple reads the lowest among the three wall thermocouples. This can be explained on the basis of the suppression of nucleate boiling of R-11 at higher qualities near the evaporator outlet.

In some cases when the evaporator was started after a long period of shutdown such as $\theta=168$ hours, a very different start-up characteristics was observed as shown in Fig. 5 for the initial pressure of 1.00 bar. When the middle wall thermocouple reached a temperature of 40.0 C, the wall temperatures at the three locations dropped to around 32 C and a sudden burst of liquid-vapor mixture was observed in the sight glass. The nucleation was thus started at a much lower wall superheat than any of the previous cases. However as the heating continued for about 180 sec, the wall temperatures started to rise again indicating that the nucleation had stopped. A second wall temperature excursion was observed when the middle thermocouple reached 45.5 C. However the second excursion was accompanied by a much stronger outburst of the
liquid-vapor mixture and the entire system experienced a severe jolt. A possible explanation for the above phenomena is given below. It is suspected that the dissolved gases in R-11 had deposited in the wall cavities when the system was not operational for a long time. These gases were responsible for causing the first nucleation at a lower wall temperatures. However as the subcooled liquid rushed to the tube walls, the nucleation could not be sustained and the wall temperature started to rise again. At the second excursion, the cavities were activated by the usual mechanism. This behavior is believed to be system-specific which would be affected by the amount of dissolved gases, the rate of system pressure rise, amount of liquid present in the system and the flow resistances.

In the current experimental investigation, the instantaneous pressure fluctuations in the system could not be measured accurately. Therefore the wall superheat at the inception of nucleation at various locations and the heat transfer coefficients along the evaporator tube could not be calculated. Further testing of the system with a sensitive pressure transducer is required to obtain accurate data on the transient and steady-state heat transfer characteristics. The experiments conducted here however clearly indicate that the temperature overshoot and the instabilities at the start-up could be quite significant and should be taken into account while designing a thermosiphon loop for microelectronic application.

CONCLUSIONS

A literature survey was conducted to highlight the recent developments on the two-phase thermosiphon loops in various applications. Their application in microelectronic cooling application is suggested and a preliminary work identifying the instability and temperature overshoot problems has been reported. It was observed that the temperature overshoot could be as high as 23°C above the steady-state operating value for the conditions tested in this investigation. No significant effect of aging was observed for tests conducted with intervals 8 = 10 minutes, 1 hour, 72 hours, and 168 hours. Further work is suggested to observe the instantaneous pressure fluctuations and the transient heat transfer characteristics at the start-up.

REFERENCES


