OPTIMIZATION OF REFRIGERATION SYSTEMS FOR HIGH-HEAT-FLUX MICROELECTRONICS

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ABSTRACT
Increasingly, military and civilian applications of electronics require extremely high heat fluxes, on the order of 1000 W/cm². Thermal management solutions for these severe operating conditions are subject to a number of constraints, including energy consumption, controllability, and the volume or size of the package. Calculations indicate that the only possible approach to meeting this heat flux condition, while maintaining the chip temperature below 50 °C, is to utilize refrigeration. Here we report an initial optimization of the refrigeration system design. Because the outlet quality of the fluid leaving the evaporator must be held to approximately less than 20%, in order to avoid reaching critical heat flux, the refrigeration system design is dramatically different from typical configurations for household applications. In short, a simple vapor-compression cycle will require excessive energy consumption, largely because of the superheat required to return the refrigerant to its vapor state before the compressor inlet. A better design is determined to be a “two-loop” cycle, in which the vapor-compression loop is coupled thermally to a primary loop that directly cools the high-heat-flux chip.

INTRODUCTION
The removal of very high heat fluxes, up to 1000 W/cm², is required by some military and commercial electronics applications. Simultaneously, usually the electronic device temperature must be maintained below some threshold value, such as 50 °C. The combination of extremely high heat flux removal and low device temperatures necessitates the use of refrigeration to maintain satisfactory performance.

Several groups have investigated refrigeration cooling of electronic systems. A number of studies have examined how miniature, often termed mesoscale, refrigeration systems may be utilized for microelectronics cooling (see, e.g., [1, 2, 3, 4, 5]). A general review of electronics cooling approaches was recently given in [6]. Somewhat larger vapor-compression systems are already commercially available for desktop computers [7], and remain the object of study [8]. These systems are essentially conventional vapor-compression refrigerators applied to electronics cooling for the purposes of maintaining low operating temperatures, and generally do not involve the removal of extremely high heat fluxes.

In contrast, our focus here is on the design of macroscale vapor-compression refrigeration systems for high-heat-flux microelectronic systems. Such systems are of considerable interest in the recent literature (see, e.g., [9, 10]), but these are still largely confined to conventional vapor-compression systems. Our present work shows that, when considering the limitations on the evaporator exit quality imposed by critical heat flux avoidance, that the conventional vapor-compression cycle may not be the optimum choice. We compare a number of alternative system designs, and show that the optimum choice is a “two-loop” system in which the electronic device is cooled by a pumped loop that is cascaded with a conventional vapor-compression loop.
ANALYSIS

In order to cool the electronic component (chip) several types of refrigeration cycles are envisaged in this study. An evaporator is placed in thermal contact with the chip. This evaporator contains microchannels through which subcooled refrigerant flows. This way the heat from the chip is removed by the refrigerant flowing through the evaporator. In each of these cycles the refrigerant considered is R134a.

The following assumptions and constraints were adhered to in this study. The refrigerant entering the evaporator was always at -10°C (subcooled liquid) and at a pressure of 3 atm (44 psi). This inlet temperature is based on the estimated value of temperature difference between the heater surface and the refrigerant, obtained from Ref. [11], for heat fluxes close to 1000 W/cm².

For simplicity, the flow through the evaporator was assumed to have no pressure drop. This was done in order to simplify the calculations and to focus on the comparison between the various refrigeration cycles while maintaining similar operating conditions amongst them. Similarly, the refrigerant exiting from the evaporator was assumed to be of 20% quality. This constraint on evaporator exit quality helps to avoid critical heat flux conditions inside the evaporator. The chip is assumed to produce heat at 1000 W, which is transferred completely to the refrigerant flowing in the evaporator.

RESULTS AND DISCUSSION

In this study four types of refrigeration cycles are considered. From this point onwards in this text, these four cycles are referred to as cycle-1, cycle-2, cycle-3 and cycle-4.

Cycle-1 follows a conventional refrigeration cycle and its schematic is shown in Fig. 1. A T-s (temperature-entropy) diagram for the same cycle is shown in Fig. 2. In this refrigeration cycle the refrigerant flows through the evaporator and absorbs the heat produced by the electronic chip. After that the refrigerant flows through a superheater, where it exits as superheated vapor. The reason for including the superheater in this cycle is to make the refrigerant superheated, so that it can be readily compressed without harming the compressor. Once the refrigerant gets compressed, it is cooled in the condenser by a cooling water supply flowing on the other side. After that it passes through the expansion valve and enters the evaporator at the desired condition (-10°C subcooled liquid).

Even though such a system could work in principle, in reality there are two major drawbacks of using such a conventional vapor-compression refrigeration cycle (Cycle-1) to cool the electronic chip. First, a lot of power is needed to superheat the refrigerant from a quality of 20% up to 100%. It is estimated that in the present scenario about 3.6 kW of power would be consumed by the superheater and about 0.3 kW would be consumed by the compressor. Secondly, it requires a chilled water supply that would cool the refrigerant down to very low temperatures (because of the subcooling requirement), which is unfeasible due to practical constraints. These characteristics of Cycle-1 are also summarized in Table 1, along with the results of the other three cycles.

In order to address the two challenges that arose in Cycle-1, some changes were made to the refrigeration cycle, and as a result Cycle-2 was created. Figure 3 shows the schematic of Cycle-2, where an economizer was introduced. This was done to accommodate a realistic temperature in the cooling water supply line (~ 10°C), and is accomplished by further expanding the refrigerant after it exits the evaporator (as seen in Fig. 3), and then using the economizer to remove heat from the refrigerant exiting the condenser.

Moreover the presence of the economizer has reduced the amount of energy needed to be supplied at the superheater. It is
observed that in this new setup, the superheater would require only about 2.2 kW and the compressor would consume 0.8 kW. Again, the results of Cycle-2 are summarized in Table 1. The T-s diagram for Cycle-2 is shown in Fig. 4.

Another concept was introduced to address the cooling of the refrigerant. In this cycle, the cooling results from a thermoelectric device (Peltier device). This cycle is denoted as Cycle-3, and its schematic is shown in Fig. 5 and its corresponding T-s diagram is shown in Fig. 6. This cycle requires only a pump rather than a compressor, which was used in both previous cycles (Cycle-1 and Cycle-2). Since a pump consumes less energy than a compressor, such a design would require relatively less power. Moreover, the introduction of a pump means that the refrigerant no longer has to be superheated, thus reducing energy consumption.

However, there are certain drawbacks of using a thermoelectric device to remove large amounts of heat. Typically, such devices have very low heat removal rate per unit area, hence a large number of such devices would need to be attached in series in order to achieve the total desired cooling. Also, in the given temperature range, the thermoelectric efficiency is not very high, and as a result it consumes about 2 kW of energy to transfer the heat from the refrigerant to the cooling water supply.

Finally, after analyzing the previous 3 cycles, one last type of cycle was envisaged. This cycle, referred to as Cycle-4, utilizes a two-loop system and is shown in Fig. 7. The corresponding T-s diagram for this cycle is shown in Fig. 8. A conventional vapor-compression cycle (the "secondary" cycle) is cascaded with a pumped-loop cycle (the "primary" cycle), which directly cools the electronic chip. No superheating of the refrigerant in the primary cycle is required. As a result this type of cycle consumes a very low amount of power (0.2 kW), and is clearly the best amongst the four cycles from an energy point of view.
evaporator exit quality, the energy consumption reduction enjoyed by the two-loop (Case-4) system becomes insignificant. Thus, there has to be a critical evaporator exit quality where use of a conventional or single-loop system may be a better choice. Figures 9 and 10 show a comparison of the electrical power consumed and the COP (coefficient of performance) respectively for the single-loop (Case-1) and two-loop configurations (Case-4) for various exit qualities. It can be seen that the two-loop system is more efficient than the single-loop system up to an exit quality of 0.89. For higher exit quality the single-loop system is a better choice because of the reduction in the energy required to heat the two-phase refrigerant mixture.

Other advantages, in addition to dramatically reduced power consumption, are also inherent in the two-loop system (Cycle-4) compared to the other systems. The secondary cycle (the vapor-compression loop) can be a commercially available “off-the-shelf” system, making it low cost and highly reliable. In the primary cycle (the pumped loop), the choice of refrigerant is no longer tied to the compressor design. Rather, one is free to select any refrigerant with desirable properties, such as high critical heat flux. Furthermore, the range of operating pressures in the primary cycle can be made much larger than for vapor-compression cycles, since the pressure rise is accomplished via an inexpensive pump rather than by an energy-intensive compressor. Finally, it appears easier to control the primary cycle to operate under transient conditions, compared to controlling a vapor-compression loop. The pump speed and expansion valve opening can both be rapidly varied to produce different evaporator conditions, without compromising the integrity of the system or damaging any components. We will explore the controllability and other aspects, such as optimum refrigerant choice, of the Cycle-4 system in future work.

For high-heat flux electronics cooling the two-loop system (Cycle-4) performs better than the conventional vapor-compression system (Cycle-1) or the other two systems investigated. However it is recognized that, above some
CONCLUSIONS

Four different types of refrigeration systems were evaluated for their potential to cool a high-heat-flux electronic component. The primary metric for comparison was the power consumption of the various cycles. Results show that a two-loop system, in which the vapor-compression loop is coupled thermally to a primary pumped loop that directly cools the high-heat-flux chip, consumes much less energy than a conventional single-loop vapor compression system. The simple vapor-compression cycle requires excessive energy consumption, largely because of the superheat required to return the refrigerant to its vapor state before the compressor inlet.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Subscript</th>
<th>Description</th>
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<tbody>
<tr>
<td>h</td>
<td>Specific enthalpy [kJ/kg]</td>
</tr>
<tr>
<td>m</td>
<td>Mass flow rate [kg/sec]</td>
</tr>
<tr>
<td>P</td>
<td>Pressure [atm]</td>
</tr>
<tr>
<td>T</td>
<td>Temperature [°C]</td>
</tr>
<tr>
<td>x</td>
<td>Quality [%]</td>
</tr>
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Subscripts

1, 2 ... 8 State Points
A, B... D State Points

ACKNOWLEDGMENTS

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REFERENCES


<table>
<thead>
<tr>
<th>Cycle #</th>
<th>Net Electrical Power Consumption1</th>
<th>Pressure (High/Low), in Primary Cycle</th>
<th>Advantages/Disadvantages</th>
<th>Remarks</th>
</tr>
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<tbody>
<tr>
<td>Cycle-1</td>
<td>~ 3900 W</td>
<td>4.8 atm / 3 atm</td>
<td>Very high power consumption</td>
<td>Unfeasible (due to very low Temp chilled water requirement, about -15°C).</td>
</tr>
<tr>
<td>Cycle-2</td>
<td>~ 3000 W</td>
<td>4.8 atm / 1 atm</td>
<td>Relatively simple design, Moderately high power consumption</td>
<td>Use of ‘heat recovery’ could reduce power consumption.</td>
</tr>
<tr>
<td>Cycle-3</td>
<td>~ 2100 W</td>
<td>3 atm / 2 atm</td>
<td>Low pumping power, Huge number of thermo-electric devices would be needed to produce the desired cooling (1000W).</td>
<td>High cost (&amp; large surface area requirement) of thermo-electric devices could be a hurdle.</td>
</tr>
<tr>
<td>Cycle-4</td>
<td>~ 200 W</td>
<td>3 atm / 2 atm</td>
<td>Very low power consumption, Slightly higher complexity.</td>
<td>Best case from the point of view of power consumption.</td>
</tr>
</tbody>
</table>

1. This includes the power consumed by the following devices ONLY – Compressor, Pump, Superheater.

Table 1: Comparison among the four cycles considered for the refrigeration system design.


