International Journal of Modern Engineering Research (IJMER)
www.ijmer.com Vol.3, Issue.1, Jan-Feb. 2013 pp-336-341 ISSN: 2249-6645

High Heat Flux Micro-Electronics Cooling

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Abstract: *The temperature of an electronics device rises fairly linearly with increasing device heat flux. This relationship is especially problematic for defense electronics, where heat dissipation is projected to exceed 1000W/cm^2 in the near future. This paper study explored the benefit of cooling the electronics device using indirect refrigeration cooling system .In this system the heat sink in a primary pumped liquid loop, reject heat to a secondary refrigeration loop. It was being explored for two phase cooling of ultra high power electronic component .For effective and efficient thermal management of electronic systems active control methods desired to suppress inherent flow instability especially in transient applications. The inclusion of the vapor compression cycle in the two loop system elevates the temperature difference between the refrigerant and the ambient cooling media, resulting in increased system cooling capacity.*

Keywords: *High heat flux Refrigeration system Two-loop cooling*

I. Introduction

Recent liquid cooling research efforts have culminated in numerous cooling solutions that are capable of tackling mostly the 50-150 W/cm^2 range Mudawar et al. [1].Defense electronics represent a specialized class of devices that have for the most part followed the heat dissipation trends of commercial devices. However, a new generation of devices for defense radars and directed-energy laser and microwave weapons are approaching 1000 W/cm^2 [1], which exceeds the capabilities of today's most advanced liquid cooling solutions. This trend was the primary motivation for the present study. The goal here was to develop advanced thermal management schemes that can remove very large heat fluxes from advanced defense electronics while maintaining device temperatures below 125°C. The large transient heat loads were imposed and needed to be efficiently and effectively dissipated. Conventional cooling solutions were inadequate for dynamic thermal managements of compact electronic systems. Two-phase cooling technology can provide effective schemes to address some of the high-heat-flux electronics cooling challenges was described by Lee and Mudawar [2].

The difficulty in implementing even the most aggressive liquid cooling scheme was that, for a given resistance between the device and coolant and fixed coolant temperature, the device temperature increases fairly linearly with increasing heat dissipation rate. This relationship could easily bring the temperature of the device above its maximum limit when dissipating high heat fluxes. For a device operating slightly below its maximum temperature limit, dissipating increasing amounts of heat requires reducing the temperature of the liquid coolant. This trend would ultimately drop the coolant temperature below ambient temperature, requiring the use of a refrigeration system to sustain the cooling. Further reducing the coolant temperature allows the device to operate well below its maximum temperature limit. This latter benefit, coupled with enhanced reliability and device performance, was the primary reason behind the recent introduction of a number of commercial systems that capitalize on low temperature cooling. Due to the inherent subcooled boiling advantage, two-loop cooling systems have been demonstrated to be far more effective at dissipating high-power heat fluxes. Such systems can provide the flexibility of choosing different working fluids and pressure levels in the primary and secondary loops, and also offer the scalability for the removal of multiple distributed heat loads with a centralized chiller.

For many years cooling technology has played a key role in enabling and facilitating the packaging and performance improvements in each new generation of computers. The role of internal and external thermal resistance in module level cooling was discussed in terms of heat removal from chips and module. The use of air-cooled heat sinks and liquid-cooled cold plates to improve module cooling is addressed by Richard et al.[3]. Immersion cooling as a scheme to accommodate high heat flux at the chip level was also discussed. Cooling at the system level was discussed in terms of air, hybrid, liquid, and refrigeration-cooled systems. The growing problem of data center thermal management was also considered. To achieve the holistic design it will be necessary to develop advanced modeling tools to integrate the electrical, thermal, and mechanical aspects of package and product function, while providing enhanced usability & minimizing interface incompatibilities.

II. Direct Versus Indirect Liquid Cooling

A) TWO PHASE SPRAY COOLING

Due to resistances of the different layers of materials separating the chip from the liquid coolant, a relatively large temperature gradient is incurred when dissipating high heat fluxes in indirect liquid cooling.. These resistances may be completely eliminated by direct liquid cooling of the chip. However, having liquid come in direct contact with the chip's surface limits cooling options to a few dielectric and inert coolants. Unfortunately, the thermo physical properties of these coolants are quite inferior to those of common coolants such as water/ethylene glycol. Direct liquid cooling is therefore advantageous only when its convective thermal resistance is smaller than the sum of the convective, conductive and contact resistances of the indirect cooling .Because heat spreading plays a minor role in a direct cooling system, high-flux chips may be packaged quite close to one another, greatly reducing both the weight and the volume of the cooling system. Given the inferior thermo physical properties of dielectric coolants and the strong dependence of cooling performance on convective resistance, the viability of a direct cooling system is highly dependent on the ability to achieve very large convective heat transfer coefficients. This goal can be realized by adopting a highly effective liquid cooling configuration (e.g., spray, jet impingement, micro channel flow) and also by capitalizing on the benefits of phase change was discussed by Mudawar et al.[1].

B) TWO PHASE MICROCHANNEL COOLING

The use of low temperature refrigeration to maintain low device temperatures while dissipating high heat fluxes. Both direct and indirect refrigeration cooling configurations were examined. In the direct cooling system, a micro-channel heat sink serves as an evaporator in a conventional vapor compression cycle using R134a as working fluid. In the indirect cooling system, HFE 7100 used to cool the heat sink in a liquid loop that rejects the heat to a secondary refrigeration loop. Found some Key from the study are as follows by Lee and Mudawar [2].

(a) Two drastically different flow behaviors were observed Because of compressor performance constraints, mostly high void fraction two-phase flow patterns prevail in the R134a system, dominated by saturated boiling. On the other hand, the indirect refrigeration cooling system facilitates highly subcooled boiling inside the micro-channel heat sink.

(b) Different pressure drop trends were observed. With R134a saturated boiling, pressure drop increases with increasing heat flux, but this increase becomes milder as most of the flow was converted to vapor. Pressure drop with HFE 7100 subcooled boiling first decreases with increasing heat flux because of decreasing viscosity in the single-phase liquid region. Pressure drop begins increasing following the commencement of boiling. Increasing mass velocity at high fluxes actually decreases pressure drop because of a reduction in void fraction.

(c) The convective heat transfer coefficient for the R134a and HFE 7100 systems follow opposite trends relative to Thermodynamic equilibrium quality.For R134a(Refrigerant) the heat transfer coefficient was highest near xe = 0 and decreases monotonically with increasing xe. On the other hand, the convective heat transfer coefficient for HFE 7100 increases with increasing xe below xe = 0. Highest h values are about equal for the two fluids.

(d) While the R134a system can produce fairly large h values, its cooling performance is limited by low CHF. Because of its high CHF, the indirect cooling system better suited for high-flux heat dissipation. Tests with this system yielded cooling heat fluxes as high as 840 W/cm^2 without encountering CHF.

(e) The results from both systems provide a global understanding of the cooling behavior of micro-channel heat sinks. These results are combined to construct a map of performance trends relative to mass velocity, sub cooling, pressure, and surface tension. Extreme conditions of near-saturated flow, low mass velocity, low pressure and high surface tension point to ‘micro-channel’ behavior, where macro-channel flow pattern maps fail to apply, instabilities are prominent, and CHF is quite low. On the other hand, systems with high mass velocity, high sub cooling, high pressure and low surface tension are far more stable and yield very high CHF values; two-phase flow in these systems follows the fluid flow and heat transfer behavior, as well as the flow pattern maps of micro channel.

III. Direct cooling system

MEMS device uses the electro hydrodynamic principles to pump and form an ultra thin film over a heated surface that requires cooling. It applied an electric field to a set of interdigitated inclined electrodes to pump and form a thin film and to remove heat by thin film evaporation process. Cooling rates of 35 W/cm^2 were obtained at a superheat of 19 ^{0}C. This smart cooling system will allow the direct attachment of a small, self-contained cooling device to the backside of an electronic component and can controllably remove heat from the electronic component describe by Darabi and Ekula [4].

Trutassanawin et al. [5] designed, built and evaluated the performance of aminiaturescale refrigeration system (MSRS) suitable for electronics cooling applications. Their MSRS had the following components: a commercial small-scale compressor, a micro channel condenser, a manual needle valve as the expansion device, a cold plate micro channel evaporator, a heat spreader and two compressor cooling fans. A suction accumulator to avoid liquid flow to the compressor, an oil filter to return oil to the compressor and guarantee good lubrication, and heat sources to simulate the chips were also installed. HFC134a was the working fluid. System performance measurements were conducted at evaporator temperatures from 10^{0}C to 20^{0}C and condenser temperatures from 40^{0}C to 60^{0}C. The cooling capacity of the system varied from 121 W to 268 W with a COP of 1.9-3.2 at pressure ratios of 1.9-3.2. Their MSRS was able to dissipate CPU heat fluxes of approximately 40-75 W/cm2 and keep the junction temperature below 85^{0}C for a chip size of 1.9 cm^2. It was concluded that a new compressor design for electronics cooling applications was needed to achieve better performance of the system (the most significant losses occurred in the compressor, which was not designed for the operating conditions of electronics cooling). It was also recommended to study the development of an automatic expansion device and a suitable control strategy for the MSRS.

Experimental measure ements and numerical results were used to assess the thermal performance of the heat sink in relation to the performance of the refrigeration cycle. It provides several important thermal benefits such as high-flux dissipation, low surface-to-coolant resistance, and most importantly low device temperature. Higher heat transfer coefficients are possible with greater mass velocities. However, greater mass velocities are typically associated with wet compression conditions corresponding to evaporator exit quality below unity and liquid entrainment at the compressor inlet. Wet compression compromises compressor performance and reliability as well as refrigeration cycle efficiency. Wet compression must therefore be minimized by maintaining only slightly superheated conditions at the compressor inlet, or using a wet compression tolerant compressor. Another thermal disadvantage of a superheated evaporator outlet is the likelihood of a localized increase in the solid wall temperature towards the outlet, which can cause large thermal stresses at the same location. Practical solutions therefore needed to develop systems which were both wet compression tolerant and that include adaptive flow control to maintain the desired evaporator outlet quality describe by Lee and Mudawar [6].

IV. Impinging Jet Cooling System

A) SINGAL PHASE IMPINGING JET

Spray cooling has been identified as a potential solution that can dissipate 150–200 W/cm^2.While maintaining the chip temperature below 125 ^{0}C. Mudawar et al. [1] explores the viability and implementation of this cooling scheme. First, commercial coolants are assessed for their suitability to this application in terms of thermal, environmental, and safety concerns and material compatibility. In this assessment, HFE-7100 identified as the optimum coolant in all performance categories. Next, spray models are used to determine the HFE-7100 spray conditions that meet such stringent heat dissipation requirements. These findings are verified experimentally, demonstrating that spray cooling is a viable thermal management solution for hybrid vehicle electronics.

Jemmy et al. [7] adopts bi-technologies: single phase impinging jet and mini channels heat exchanger. The system has the cooling capacity of 200 W over a single chip with a hydraulic diameter of 12 mm. The equivalent heat flux was 177 W/cm^2. The cooling system maintains the chip_s surface temperature below 95^{0}C maximum when the ambient temperature is 30^{0}C. De-ionized water is the working fluid of the system. For the impinging jet, two different nozzles are designed and tested. The hydraulic diameters (d_N) are 0.5 mm and 0.8 mm. The corresponding volume flow rates are 280 ml/min and 348 ml/min. Mini channels heat exchanger has 6 (six) copper tubes with the inner diameter of 1.27 mm and the total length of about 1 m. The cooling system has a mini diaphragm pump and a DC electric fan with the maximum power consumptions of 8.4 W and 0.96 W respectively. The coefficient of performance of the system is 21.4

Amon et al. [8].Described the development of EDIFICE, an integrated evaporative spray cooling device micro-fabricated in silicon for package-level cooling of high-heat flux electronics. It combines efficient phase-change heat transfer utilizing latent heat of vaporization of dielectric coolants and on-chip control to provide localized, adaptive, on-demand cooling. To satisfy temporal and spatial heat removal requirements, it contains built-in software to provide on-demand cooling achieved through the control of droplet sizes, impingement frequencies and impingement locations based on the on-chip sensing of temperature, thermal gradients and dielectric film thickness. Basic experiments to develop and characterize micro-nozzles are reported, as well as experiments with chip surface texturing to improve spreading and boiling behavior. Current work on the project involves the fabrication of an actual miniature EDIFICE device and its testing and characterization in real electronics.

V. Two-phase cooling systems

Two-phase cooling systems with high subcooled boiling had various flow boiling instabilities. Flow boiling oscillations may modify the hydrodynamics of the flow, introduce severe structural vibrations, generate acoustic noise, and can jeopardize the structural integrity of the system. But, most importantly, flow oscillations can lead to not hinder the thermal performance as premature initiation of the CHF condition. On the other hand, most of the existing studies focus on removing the heat at the device level, while active cooling at the system level had not received much attention especially for transient applications. Recently, these critical operational issues had been recognized and recommended by Garimella et al.[9].For future research: New ‘‘concepts for dampening or elimination of potential two-phase loop flow instabilities, and concepts for two-phase loop feedback flow control” are needed in active and transient thermal management of next generation military, automotive, and harsh-environment electronic systems.

Knowledge about flow instabilities was particularly important for better design, control, and performance prediction of any two-phase system, especially the design of large/fast transient electronics cooling systems [2,9]. In the two-loop refrigeration system, flow boiling instability was one of the biggest operation problems for effective and efficient dynamic thermal management of electronics.Which provides additional physical insight about two-phase thermal-fluid dynamics and proposes new concepts for model-based active flow instability analysis and control in transient electronics cooling systems under critical heat flux constraints. Advanced flow instability control strategies are based on dynamic thermal-fluid models. For boiling microchannel systems, no dynamic thermal-fluid model is widely accepted for transient and active thermal management study. Therefore, Zhanga et al. [10] use conventional-scale two phase flow models to evaluate general analysis and control methodologies, which could be extended to microchannel thermal-fluid systems.

Some alternative cooling approaches such as heat pipes, liquid immersion, jet impingement and sprays, thermoelectric & refrigeration mentioned by Trutassanawin et al.[5]. For refrigeration, the following possible advantages were cited: (i) one of the only methods which can work at a high ambient temperature, (ii) chip to fluid thermal resistances are considerably lower, resulting in lower junction temperatures, which could lead to higher heat fluxes being dissipated, and (iii) lower junction temperatures can also increase the microprocessor’s performance and increase the chip’s reliability. Possible “disadvantages” were characterized to be: (i) an increase in the complexity and cost, (ii) possible increase in the cooling system volume and (iii) uncertainties in the system reliability (moving parts in the compressor).

VI. Hybrid two-phase cooling cycle

Three micro-evaporator cooling cycles, one with a pump, one with a compressor and a hybrid of the two together, was proposed by Braz et al. [11] for cooling a computer blade server. The hybrid cycle is characterized by the interchangeability between the first two cycles, where the decision on the cycle to operate is based on the season (necessity or economical benefit for heat recovery) or the maintenance of cycle's driver. The main characteristics of each cycle are presented as well as the details of the micro-evaporator cooler for the blade's CPU .Analysis of the cycle overall efficiency and the potential for heat recovery shows that the best cycle to use depends mainly on the end application of the heat recovered. Four refrigerants were evaluated as the possible working fluids for cooling the microprocessors. HFC134a and HFC245fa were found to be the best choices for the desired application.

Thermal designers of data centers and server manufacturers are showing a greater concern regarding the cooling of the new generation data centers, which consume considerably more electricity and dissipate much more waste heat, a situation that is creating a re-thinking about the most effective cooling systems for the future beyond conventional air cooling of the chips/servers. A potential significantly better solution is to make use of on-chip two-phase cooling, which, besides improving the cooling performance at the chip level, also adds the capability to reuse the waste heat in a convenient manner, since higher evaporating and condensing temperatures of the two-phase cooling system (from 60 to 95^{0}C) are possible with such a new green cooling technology. In the present project, two such two-phase cooling cycles using micro-evaporation technology were experimentally evaluated with specific attention being paid to (i) controllability of the two-phase cooling system, (ii) energy consumption and (iii) overall exergetic efficiency. The controllers were evaluated by tracking and disturbance rejection tests, which were shown to be efficient and effective. The average temperatures of the chips were maintained below the limit of 85 ^{0}C for all tests evaluated in steady state and transient conditions. In general, simple SISO strategies were sufficient to attain the requirements of control. Regarding energy and exergy analyses, the experimental results showed that both systems can be thermodynamically improved since only about 10% of the exergy supplied is in fact recovered in the condenser describe by Braz et al. [12].

A hybrid two-phase cooling cycle has been proposed and simulated by Braz et al.[13] to cool micro processors and auxiliary electronics of blade server boards with two-phase evaporating flow in the micro evaporator cooling elements. A simulation code was developed and 5 cases were simulated considering 3 different working fluids, HFC134a, HFO1234ze and water and different internal diameters of the pipes and elbows joining the components. The results showed that the liquid water cooling cycle has a pumping power consumption 5.5 times that obtained for the two-phase HFC134a cooling cycle, both considering a liquid pump as the driver of the fluid. When compared with the HFO1234ze cooling cycle the difference drops to 4.4 times. The simulation of the vapor compression cooling cycle showed higher pumping power consumption when compared with the other cycles simulated. However, this cycle can be justified when the waste heat at the condenser is recovered for applications such as district heating and preheating of boiler feed water. An exergy analyses of the cooling cycles, regarding the potential of exergy recovery at the condenser, showed a low overall exergetic efficiency (lower than 50%), meaning that improvements can be done to increase the thermodynamic performance of the cycles. When looking at local effects, such analyses showed that the driver and the $ME+MP_{AE}$ are the components with the lowest exergetic efficiency and would be the main components to be improved in terms of thermodynamic design. It was also shown that the overall exergetic efficiency of the vapor compression cooling cycle is strongly influenced by the compressor overall efficiency, which showed to be more exergeticaly efficient than the liquid pumping cooling cycle for an overall efficiency higher than 67%. A case study was developed to investigate the potential savings in energy a datacenter can make by implementing on-chip cooling with waste heat recovery. As an application for the waste heat, a coal fired power plant was analyzed. The results showed that, when compared with traditional air cooling systems, the energy consumption of the datacenter could be reduced by as much as 50% when using a liquid pumping cycle and 41% when using a vapor compression cycle. The overall consumption can be reduced even further if the recovered energy was sold to a secondary application, such as a thermal power plant. Power plant thermal efficiency improvements in the order of 2.2% are possible if datacenter waste heat was incorporated in the power plant's feed water. This could imply huge savings in terms of fuel as well as carbon tax due to a reduced carbon footprint.

A comparison of existing and predicted future miniature refrigeration systems reveals that of currently existing systems, only thermoelectric coolers (TECs) are commercially available. Ten years from now, however, it was likely that several types of mesoscale refrigerators will become available, including the vapor compression, Stirling, pulse tube, reverse Brayton, and orption refrigerators, in addition to improved TECs. Existing TECs are limited in their cooling capacity, due in part to their low efficiencies. These low efficiencies, which means that the coefficient of performance (COP) was less than one, results in more work having to be input to the TEC, compared to the amount of heat that the TEC can pump. Since both heat and work are dissipated at the hot end of the TEC (the "condenser"), this creates a thermal bottleneck between the hot end of the TEC and the ambient air heat sink. Thus, the performance of the TEC is much more sensitive to the thermal resistance between the TEC and the ambient air, compared to the thermal resistance between the chip and the TEC had been discussed by Phelan et al.[14].

After analyzing various cycle, it recognize that conventional vapor-compression cycle was cascaded with a pumped-loop cycle, which directly cools the electronic chip had better performance seen by Phelan et al. [15]. 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 it was best amongst the four cycles from an energy point of view. Evaporator exit quality, the energy consumption reduction enjoyed by the two-loop 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. 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. For high-heat flux electronics cooling the two-loop system performs better than the conventional vapor compression system or the other systems investigated.

Zhang et al.[16] were conducted experiments to investigate the effect of temperature oscillation on startup behavior and operating performance in a miniature LHP with flat evaporator of 8 mm thick. The evaporator with sintered copper powder wick is in series structure with compensation chamber and made of copper. Water is the working fluid. It is found that the LHP is able to start up at heat load of 15W with temperature oscillation. And the oscillating frequency of temperature rises and amplitude decreases with increasing heat load.Due to insufficient driving force and phase distribution of working fluid in the compensation chamber under different heat load in LHP temperature oscillation takes place. The development of unstable operation in the LHP was the reflection of the re-distribution of working fluid in the loop while the hydrodynamic and thermal equilibrium of the loop is broken and re-built repeatedly. For specific heat load, high operating temperature can improve the operating stability of LHP due to large capillary force.

VII. Summary

1) Micro channels: As this technique have greater industrial acceptance, it improved capability in both experimentation and analytical modeling. Specific issues include measurement of experimental heat loss, better understanding of inlet and exit plenum effects, better understanding of the conditions for the transition between macro channel transport and micro channel transport, control of flow instabilities in phase-change schemes, improved prediction of critical heat flux, and development of better heat transfer fluids.
2) Liquid cooling: Liquid cooling systems of different Forms, from spray cooling to heat pipe spreaders and thermosyphons, have been implemented in applications As varied as gaming systems and military electronics. Particular attention must be paid to containment and fluid Compatibility issues especially in the context of overall Cooling systems cost, as well as to the importance of judicious fluid fill ratios in heat pipes and thermosyphons Especially at high heat fluxes. Phase-change immersion cooling, while appropriate for prior-generation supercomputers, has not yet been embraced by system designers because of a lack of understanding of the boiling process, the role of enhanced surfaces, incipience hysteresis issues, and low critical heat flux values for dielectric fluids.
3) Compression refrigeration cooling: This staple of server thermal management systems being contemplated for mobile computing systems and desktop applications through the use of micro refrigeration systems. Some challenges include condensation issues, the need for extremely high reliability, and battery life. Challenges at the data center level include the need for improved site-specific design of cooling capability and the need for dynamic matching of local and global thermal parameters.
4) Air cooling: There is room for continued performance gains in air cooling through optimal design of heat sinks and air flows, and for a delineation of air cooling limits under different sets of constraints. Work continues in branching radial fins, skived heat sinks, ionic prime-movers, and active cooling with piezo-actuated jets. Recent EU tightening of fan noise limits further constrains fluid velocity. Jet impingement cooling continues to be viable for several applications. Need to pursue hybrid solutions that incorporate air cooling with heat pipes and thermoelectrics.

VIII. Recommendations for future research

1) Research in microscale cooling systems must continue at the present rate in order to meet the ever increasing cooling Requirements due to advances in electronics and optical devices.
2) Research areas must achieve a good balance between fundamental studies, analytical models, and verifiable experimentation for ALL components of the microscale system design.
3) Research teams must acquire the multidisciplinary skills required for true integration of the cooling system into electronic packages and devices.
4) Researchers must work in close collaboration with industry to reduce the time between experimentation and implementation of cooling approaches. Particular attention must be paid to cost drivers such as the mass of the thermal management system.
5) A library of cooling solutions covering the range of technologies, and preferably scalable from handhelds to servers and data centers, must emerge

IX. Conclusions

In order to diffuse high heat flux from chip heat sources and reduce thermal resistance at the chip-to-sink interface, there is a need to develop low cost, higher thermal conductivity, packaging materials such as adhesives, thermal pastes and thermal spreaders. Advanced cooling technology in the form of heat pipes and vapor chambers are already widely used. Further advances in these technologies as well as thermoelectric cooling technology, direct liquid cooling technology, high-performance air-cooled heat sinks and air movers are also needed. To achieve the holistic design referred to above, it will be necessary to develop advanced modeling tools to integrate the electrical, thermal, and mechanical aspects of package and product function, while providing enhanced usability and minimizing interface incompatibilities.

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