Two-Phase Cooling of Electronics with Multi-Microchannel Evaporators

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ABSTRACT

With the limit of air for the cooling of electronics being approached, new cooling technologies are required capable of operating in harsh military environments. This paper addresses the use of two-phase refrigerant cooling within microchannels as a viable and reliable option. Simulations comparing two-phase refrigerant cooling over single-phase cooling (using water and a water-glycol mixture) show that two-phase cooling outperforms single-phase cooling at numerous fronts. Compared with single-phase cooling, two-phase cooling is capable of maintaining chip or electronics temperatures at much lower temperatures for the same flow rates, has more uniform chip temperature gradients, has 40-80 times lower pumping power requirements and can maintain heat fluxes in excess of 150 W/cm^2. It was further shown that chip temperatures could be successfully kept below the maximum operating temperature of 85°C when using refrigerants that are at a saturation temperature of 60°C. Further advantages of the use of refrigerants over water were highlighted, such as electronic compatibility, pumping power, piping, harsh climates, material compatibility, fouling or organic growth, erosion, hot-spot management, heat dissipation and complexity.

1.0 INTRODUCTION

Thermal design in military electronic hardware is of critical essence, as it determines its operational range and could limit its allowable operating capabilities. Howard [1] notes that most sources state that 70% of all electronic failures in the military are thermally related. The main issue has to do with the environment in which these electronics need to operate.

Most electronics in the military are cooled by traditional air-cooled systems. However, the environment often limits its cooling potential as operating conditions are often in regions where temperatures are as high as 50°C or as low as -40°C. Dessert conditions, where high concentrations of dust and sand are involved, often deteriorate the cooling performance once it gets into the electronic components. Some solutions are to encapsulate all the electronic components and use filters to keep the sand and dust out. However, this also reduces the cooling performance as space for free air to move between components is reduced.

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Furthermore, new electronics are typically "sinonomous" with higher heat flux cooling requirements, which is driving the technological change away from air cooling. For example. with the increase in package densities of CMOS circuit technologies in computer CPU's, air cooling has nearly reached its maximum cooling capacity in computers. The maximum heat load for air cooling was reported to be around 37 W/cm^2 [2], although higher heat fluxes of 60-80 W/cm^2 have been achieved [3] but under carefully controlled conditions.

The two leading solutions are to make use of liquid (water or a glycol solution)cooling, or two-phase cooling (refrigerant such as R134a or R236fa). Such cooling schemes are of great interest to the IT industry to reduce energy demands [4]. Leonard and Philips [5] showed that the use of such new technology could produce savings in energy consumption of over 60% using water, while two-phase cooling will require even less [6]. Although energy savings is not the main concern for military applications, the fact that such a technology brings about such savings shows that it is very effective. The other important feature of liquid and two-phase cooling heat sinks is their very high heat transfer coefficients compared to air, which allows them to enter at a much higher temperature and still remove all the heat, eliminating the need to refrigerate the coolant as is often done with air.

One of these technologies, the principle one, is to make use of microchannel coolers. These heat sinks have a large number of parallel, high aspect ratio microchannels that can increase the effective coolant's heat transfer surface area by a factor of 10 or more. They coolers have shown to be capable of removing high heat fluxes while maintaining chip temperatures below their maximum limit. They are also characterised in having low pumping power requirements. The aim of this article will be to highlight the most recent technology advancements in multi-microchannel evaporative cooling using refrigerants with a direct comparison versus single-phase liquid cooling.

2.0 REFRIGERANTS AS COOLANTS

The use of synthetic refrigerants have had a long and successful history since its introduction in the 1920's. The first synthetic refrigerant went under the trade name Freon of Dupont, which was a chlorofluorocarbon (CFC). However, environmental concerns has seen the phase-out of such refrigerants. The introduction of the Montreal Protocol in 1987 [7] has seen the phase-out of all chlorofluorocarbon (CFC) refrigerants by 1996 and 2010 for non-Article 5 and Article 5 countries, respectively. Transition hydrochlorofluorocarbon (HCFC) refrigerants are to be completely phased out by 2020 and 2040 for the respective countries. These two refrigerant types have been identified as depleting the ozone layer, hence its phase out.

With global warming being a big concern, the Kyoto Protocol [11] sets binding targets for greenhouse gas emissions based on calculated equivalents of carbon dioxide, methane, nitrous oxide, hydrofluorocarbons (HFC), perfluorocarbons (PFC) and sulphur hexafluoride. The European Parliament has also set the timing for banning fluorochemical refrigerants having global warming potentials (GWPs) exceeding 150 for automotive air conditioners for new model vehicles effective from 2011 and for new vehicles in 2017 [12].

These protocols have led to the development of the so-called fourth generation refrigerants having a zero ozone depleting potential (ODP) and a very low GWP. Two of these refrigerants are R1234yf and R1234ze, seen as replacement refrigerants for HFC-134a. The first is primarily targeted for automotive air-conditioning systems while the second is targeted for electronic cooling applications. The refrigerants and their basic properties are listed in Table 1. Also listed is R236fa, mainly used as a fire suppressant, although it has also found its use in military applications. This is the replacement refrigerant for R114 and is mainly used because of its relatively low pressure when compared to the other refrigerants. R123 was a very promising refrigerant due

Table 1: Basic fluid and environmental properties of refrigerants at $T_{sat} = 25°C$.

	R134a	R1234yf [a]	R1234ze[a]	R123	R236fa	R245fa	R114
GWP [b]	1320	4	6	76	9650	1020	9880
ODP	0	0	0	0.012	0	0	0.94
Atmospheric Lifetime, years	14	0.030[c]	0.038[d]	1.3	240	7.6	300
Boiling Point @ 1bar, °C	-26.1	-29	-19	27.5	-1.4	15.1	3.6
Triple point, °C	-103.3	-150.4	-150.4	-107	-93.6	-102	-92.5
ρ_l, kg/m^3	1207	1094	1180	1464	1360	1339	1518
ρ_v, kg/m^3	32.4	37.6	-	5.9	18.4	8.6	7.8
h_{lv}, kJ/kg	177.8	149[e]	195[e]	171.4	145.9	190.3	135.9

[a] Classified fluid. All properties obtained from sources available in the public domain. [b] 100 year integration time horizon (ITH), $CO_2 = 1$. [c] Nielsen et al. [8]. [d] Søndergaard et al. [9]. [e] Estimate from Brown et al. [10].

to its high thermal efficiency [13], which translates to a much smaller CO_2 footprint due to lower pumping power requirements; however, due to the fact that it has an ozone depleting potential, albeit extremely low and negligible, it is set for phase-out and has been abandoned in nearly all chiller applications.

3.0 MICROCHANNELS

Microchannel cooling is a promising technology for use in high heat flux removal application. This is due to the low pumping power requirements for the amount of heat needed to be removed. Figure 1 shows some typical microchannel coolers having channel widths in the range of 50 μm to 200 μm and fin heights ranging from 50 μm to 2 mm. The copper fins were manufactured by a process called micro deformation technology (MDT), a patented process of Wolverine Tube Inc. [14]. Similar fins can also be produced in aluminium, which is another common heat sink material. Such fins have been integrated into high performance micro-evaporators in collaboration with the LTCM lab. Also included is a silicon microchannel cooler having fin heights of 560 μm, fin width of 42 μm and a channel width of 85 μm. These channels were made by a process called deep reactive ion etching (DRIE).

It is worth noting that what happens in small channels in two-phase flows can be quite different than that for single-phase flows in small channels. While initial studies in the literature reported significant size effects on friction factors and heat transfer coefficients in very small channels in single-phase flows, more accurate recent tests and analysis done with very smooth internal channels have shown that macroscale methods for single-phase flows work well down to diameters of at least 5-10 μm. This is not the case for extrapolation of macroscale two-phase flow methods to microchannels, which usually do not work very well when compared to data for channels below about 2.0 mm diameter. It is therefore risky to extrapolate macroscale two-phase flow pattern maps, flow boiling methods and two-phase pressure drop correlations to the microscale, except for specific documented cases. Furthermore, many of the controlling phenomena and mechanisms change when passing from macroscale two-phase flow and heat transfer to the microscale. For example, surface tension (capillary) forces become much stronger as the channel size diminishes while gravitational forces are weakened.

Figure 2 depicts the buoyancy effect on an elongated bubble in 2.0, 0.790 and 0.509 mm horizontal channels. In the 2.0 mm channel, no stratified flow was observed while the difference in film thickness at the top compared

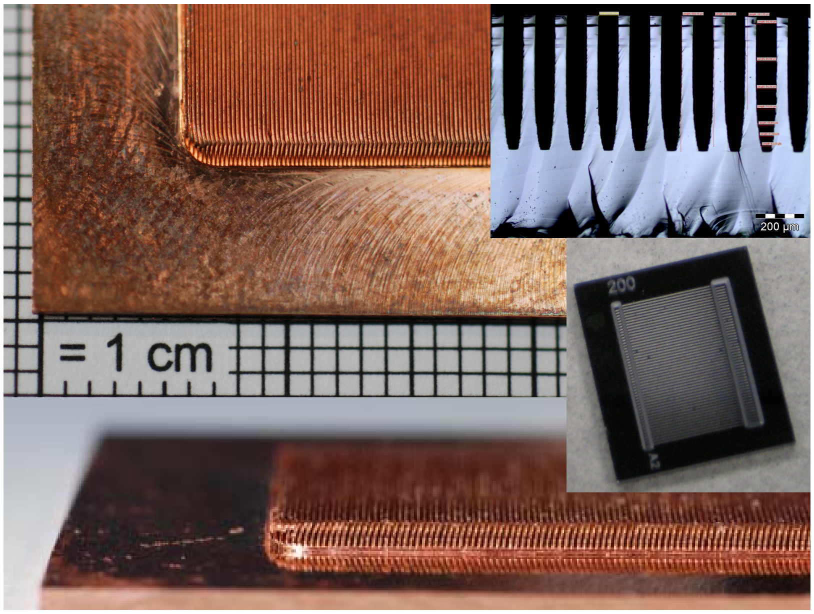

Figure 1: Examples of typical microchannel coolers in copper and silicon.

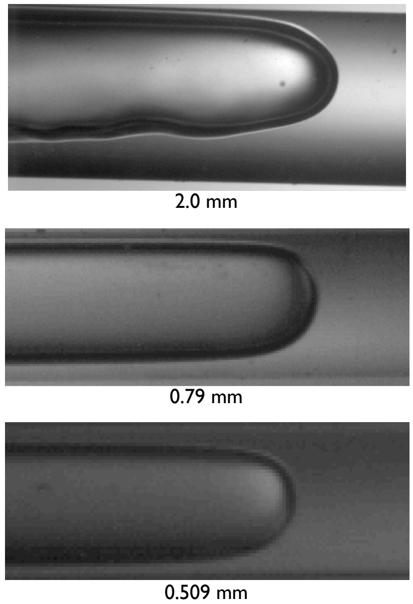

Figure 2: Images of slug (elongated bubble) flow in a 2.0, 0.8 and 0.5 mm horizontal channels with R-134a at 30°C at the exit of a micro-evaporator channel of the same diameter (images by R. Revellin of LTCM).

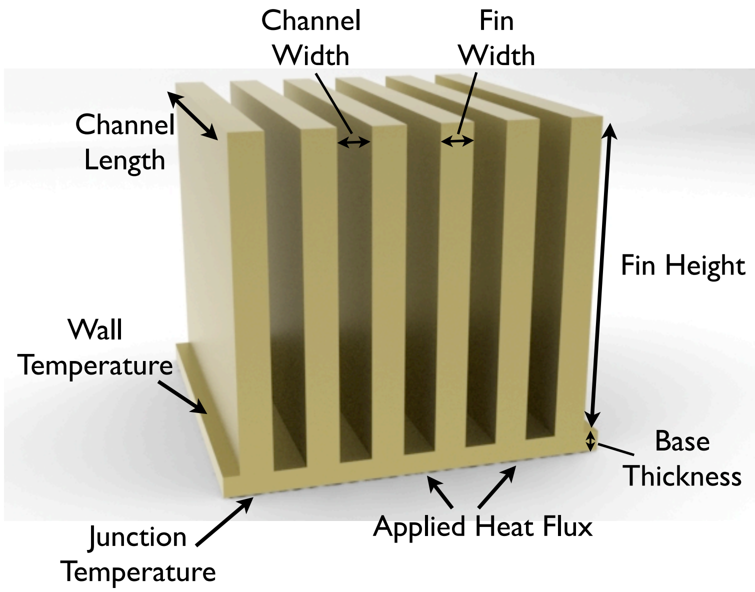

Figure 3: Schematic of a microchannel cooler.

to that at the bottom is still quite noticeable. Similarly, the film thickness in the 0.790 mm channel is still not uniform above and below the bubble. Instead, in the 0.509 mm channel, the film is now quite uniform. Interpreting these images and many others available in the literature, one ascertains that in small, horizontal channels that stratified-wavy and fully stratified flows disappear (more or less completely). This transition is thus perhaps an indication of the lower boundary of macroscale two-phase flow, in this case occurring for a diameter somewhat greater than 2.0 mm. The upper boundary of microscale two-phase flow may be interpreted as the point in which the effect of gravity (and its orientation) becomes insignificant, such that the bubble in the 0.509 mm channel is thus a microscale flow, with the transition occurring at about this diameter at the present test conditions.

4.0 TWO-PHASE VS SINGLE-PHASE COOLING SIMULATIONS

To aid in the discussion when comparing the two cooling methods, simulations are performed here on a standard microchannel cooler. This simulation will show the advantages of using two-phase flow over single-phase flow. The simulations were based on a chip footprint similar to that of an Intel Xeon processor (19.3 mm $\times$ 13.2 mm) [15]. This size is very similar to many high heat flux electronic components, such as IGBT's. The main focus of the simulation will be to maintain the chip or junction temperature below the maximum limit of 85°C. Aspects such as temperature uniformity, pressure drop and pumping power will be discussed.

A microchannel cooler with a fin height of 1700μm, channel width and fin thickness of 170μm and a base thickness of 1 mm is used, with heat fluxes ranging from 10 to 150 W/cm^2 and mass fluxes from 300 to 1000 kg/m^{2}s. Note that a Xeon processor dissipates 130 W of heat, which translates to a heat flux of approximately 51 W/cm^2. The fluids simulated for two-phase flow were R134a, R114, R236fa, R245fa, R123, R1234yf and R1234ze, while for single-phase flow water and a 50% water-ethylene glycol (EG) mixture were used. Figure 3 shows a schematic of the microchannel cooler used for the simulations.

4.0.1 Junction Temperature and its Uniformity

Figure 4 shows the length averaged temperature of the junction of the micro-evaporator (*viz.* Fig. 3), which is calculated from the wall temperature at the base of the fins plus the conductive temperature difference across the copper die of 1 mm thickness. For the refrigerants the average temperature for all the mass fluxes (an average for the range from 300 to 1000 kg/m^{2}s) was used since their values did not change significantly (0.1 - 2°C). For water and the 50% ethylene-glycol mixture (EG), the junction temperature variation at mass fluxes of 300 (for both) and at 2000 and 2100 kg/m^{2}s, respectively, are given. The figure shows that the junction temperature is below the 85°C limit imposed on microprocessors for most fluids, except for R123, R114 and EG at heat fluxes greater than 110, 149 and 70 W/cm^2, respectively. These temperatures are directly related to the heat transfer coefficients. R134a has the lowest junction temperature over the range of heat fluxes, followed by R1234yf and R1234ze. The junction temperatures of water and EG are only comparable when their mass flow rates are increased to values of almost an order of magnitude greater than for the refrigerants.

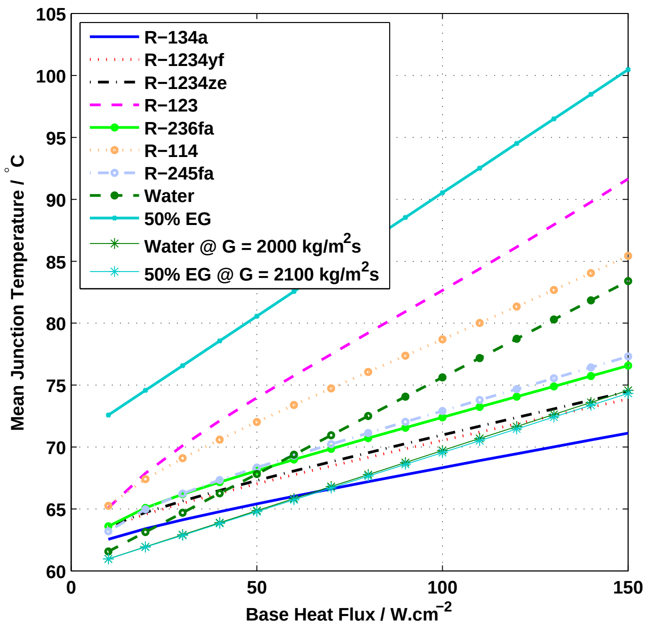

Figure 4: Junction temperature as a function of the base heat flux.

Another thermal design criterion to consider is the uniformity of the junction (chip) temperature. This is an important aspect with regard to the cooling of integrated circuits and electronics as too high a temperature gradient along their base surface will create an adverse non-uniform thermal stress. This could lead to the chip or electronics being damaged (silicon is very brittle) and also a breakdown of the thermal interface material.

The temperature uniformity can be expressed by taking the standard deviation of all the temperatures at the junction surface along the length of the channel of the chip, calculated for a specific mass flux and all heat fluxes. The standard deviations of all the fluids are given in Fig. 5 as the junction temperature uniformity. The overall trend is a decrease in uniformity with an increase in heat flux. Once again, R134a has the best temperature uniformity (the lowest curve), with temperature variations of less than 1°C at the maximum base

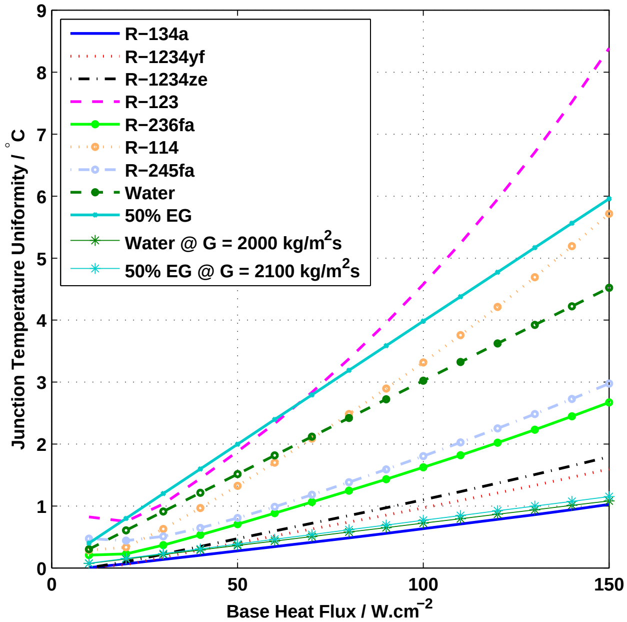

Figure 5: Junction temperature uniformity as a function of the base heat flux for a mass flux of 400 kg/m^{2}s.

heat flux, while R123 is consistently the worst refrigerant. The water-ethylene glycol mixture is only second to R123 from being the worst. However, by increasing the mass flux of water and EG to 2000 and 2100 kg/m^{2}s, respectively (starred lines in Fig. 5), their curves almost fall on top of that of R134a. This requires a considerable flow rate and will have a huge impact on pumping power requirements. After R134a, the new refrigerants R1234yf and R1234ze perform the best, with temperature variations always being 2°C or less along the length of the chip.

4.0.2 Pressure Drop and Pumping Power

Figures 6 and 7 show the pressure drops and required pumping power for the different fluids as a function of the base heat flux. Figure 6 shows that for refrigerants there is an increase in pressure drop with an increase in base heat flux. This is due to higher outlet qualities being reached, where pressure gradients are greater, for higher heat fluxes. For single-phase water and EG the opposite is seen where the pressure drop decreases slightly for an increase in heat flux. This is due to a decrease in fluid viscosity and liquid density as temperatures in the fluid are increased.

Pressure drops for the water can be much higher or much lower than for the refrigerants, depending on the temperature rise from inlet to outlet that is allowable. Keeping this temperature rise to a safe value of less than 2°C, one notices that the pressure drops of water and EG are respectively 3 and 7 times larger than for most of the refrigerants in Fig. 6. It should be remembered that the micro-evaporators using refrigerants all have an extra pressure loss at the inlet due to the use of an orifice to force good fluid flow distribution (included in the present calculations), which aids also in stabilising the flow. This orifice represents about 40-60% of the total pressure drop and could be reduced based on test data.

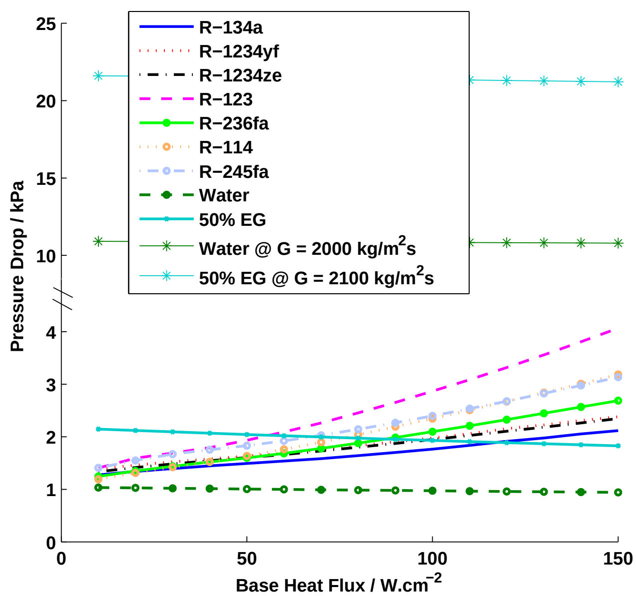

Figure 6: Pressure drop as a function of the base heat flux for a mass flux of 400 kg/m^2s.

The pumping power requirements are shown in Fig. 7. It was assumed that there are no losses and that the pump is operating under isentropic conditions. As can be seen, the pumping power requirements for all refrigerants vary between 10 and 20 mW, depending on the heat flux. To comply with temperature uniformity requirements, the required pumping power for water and EG would be on the order of 400 mW and 800 mW, respectively (refer to the starred lines). This is up to 40 and 80 times higher than the requirements for the refrigerants. Note that even at these high mass fluxes the junction temperature (Fig. 4) is still higher than what can be obtained for some of the refrigerants, especially at high heat fluxes.

4.1 Considerations needed to be taken into account

With the above simulations highlighting important thermal aspects of cooling of electronics, the next step is to discuss the various advantages of refrigerants over water or water-ethylene glycol mixtures. This is done below.

Compatibility with Electronics

When working with electronics, water leaks near electronics has to be avoided at all times. Refrigerants on the other hand are inherently dielectric fluids, meaning that even with a leak, the electronics will be safe from damage. In fact, some earlier generations of super computers, such as the CRAY-2 and CRAY T90, had their electronics submerged in refrigerants, making use of pool boiling as the main heat transfer mechanism.

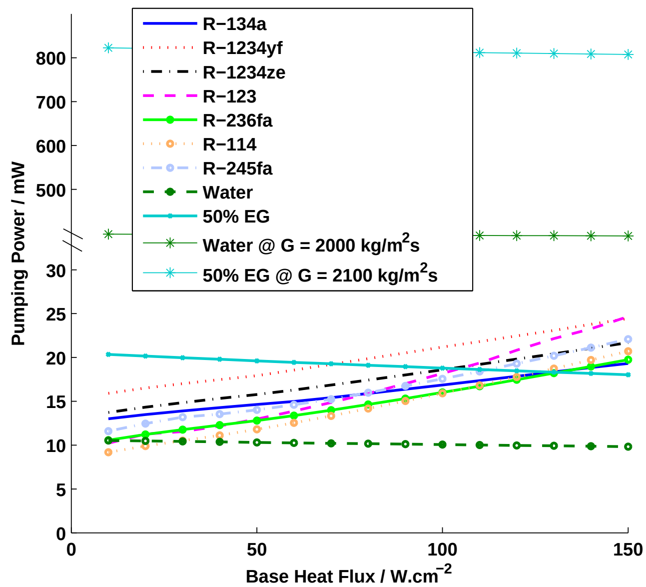

Figure 7: Required pumping power as a function of the base heat flux for a mass flux of 400 kg/m^{2}s.

Pumping power

From the simulations shown above, it was clear that refrigerants have a clear advantage versus single-phase fluids as the former's pumping power is considerably lower for the same heat removal rate. This is mainly due to two-phase cooling making use of the refrigerant's latent heat, which translates to lower flow rates. This also translates to smaller pumps being required, saving on initial costs and reduced weight and space requirements.

Piping

Due to the low flow rates obtained for the refrigerants, the piping used for the whole system can be much smaller in the system than for water or EG. It was shown, by simulations performed by Marcinichen and Thome [6], that for a cooling cycle using refrigerants, pipe diameters of 2.4-3 mm are typically required, while when using water this increased to 6-10 mm. Small diameter pipes are also advantageous as they are flexible and can be easily installed in confined spaces. The smaller diameter tubes also result in less copper being used, decreasing the overall weight of the system and also reducing the refrigerant charge in the system.

Harsh climates

A problem often encountered in cooling systems exposed to the environment is that the cooling fluid needs to be able to resist very cold and/or hot climates. Water freezes at temperatures below 0°C, which is much warmer than many of the winters on most places on the earth. Even for cooling systems inside aircraft, the use of pure water is not practical as temperatures are often as low as -50°C. Therefore a brine, which can consist of a water-ethylene glycol mixture, is usually used, which can withstand freezing temperatures of up to -35°C for a 50% v/v concentration of water and ethylene glycol. However, glycol added to water degrades the heat transfer performance and increases the required pumping power quite considerably, as shown from the simulations. Refrigerants, on the other hand, have very low freezing temperatures (< -100°C) and are ideal for harsh conditions. The critical point for most refrigerants are also on the order of 100°C, which is the upper limit of a two-phase system.

Material compatibility

Refrigerants have a long and successful history in industry, with material compatibility well understood. Refrigerants are mostly used with copper and aluminium, with some of the longest refrigeration systems running for over 30 years. The use of water, on the other hand, is known to attack metallic components unless treated.

Organic/Fouling

Water is a form of life, with organic material likely to grow inside the system. Water is often treated to prevent organic growth, which normally leads to a degradation of heat transfer performance. Water also tends to foul the pipes, which can degrade the heat transfer performance considerably. In fact, fouling can be one of the main disadvantages when using water for electronics cooling since it could easily block the microchannels, rendering such a microchannel cooler unreliable. Refrigerants are not subject to organic growth or fouling.

Erosion

Erosion occurs due to the shear stress exerted by the flowing fluid on the channel wall. Guidelines for water inside copper pipes suggest that water velocities should be kept below 0.9-1.5 m/s. Erosion can lead to the thinning of the tube walls and, in the case of the microchannel cooler, the removal of the fins, which would degrade the performance. Furthermore, erosion would also contaminate the fluid, which would then need to be treated, and could adversely affect the fluid pump. Due to the high mass flow rates required when using water for electronics cooling, erosion will most likely be a concern. The flow rates (and velocities) of the refrigerants are typically much less and are known not to have erosive properties.

Hot-spot management

Not discussed in this document is the management of hot-spots on the microprocessors, which are common. It has been shown [16] that heat transfer coefficients during two-phase flow is a function of the heat flux as $\alpha \propto q^{0.7}$, which means that the heat transfer coefficient increases proportionally to the heat flux. A higher local heat transfer coefficient thus means that junction temperatures are kept lower under hot-spots with two-phase cooling, which will prolong the life of the microprocessor. This has recently been proved experimentally by Costa-Patry et al. [17] using a test element with 35 independent heaters and temperature sensors.

Heat dissipation

Refrigerants also have the advantage to dissipate heat to higher temperatures by making use of a vapour compression cooling cycle. Therefore, chip or electronics temperatures can be maintained at temperatures below ambient and heat can be discharged at temperatures well above. This allows for a larger service life in harsh operating conditions.

Complexity

Usually the most widely used reason *not* to consider a two-phase cooling solution in favour of a liquid cooling system is the "complexity" of two-phase flow. This complexity is primarily a problem of thermal designers without two-phase expertise, not the system itself. Engineers with two-phase expertise, for example, have been successfully designing refrigeration and air-conditioning systems for nearly a century, including applications in demanding environments.

5.0 CONCLUSION

This paper addressed two-phase microchannel cooling for electronics cooling purposes as a viable and reliable technology. A brief introduction to the differences between single-phase and two-phase microchannel flows were given, highlighting the fact that, if measured correctly, macro scale techniques can be used for micro scale single-phase flows. Two-phase flow, on the other hand, does not show these same effects, with a clear transition occurring at diameters of about 2 mm.

A simulation case study, performed on an Intel Xeon microprocessor having a heat flux of 51 W/cm^2, showed the thermal advantages of two-phase cooling over single-phase cooling. It was shown that two-phase cooling could maintain chip (electronics) temperatures well below the upper temperature limit with a low mass flow rate. Two-phase cooling also exhibited much more uniform temperatures across the microprocessor, which is advantageous as thermal stresses are much lower. It was possible to use water or ethylene glycol to obtain the same heat transfer performance but at the cost of much higher flow rates, which translate into pumping power requirements in the order of 40 to 80 times higher than for refrigerants.

Further advantages of refrigerants were also discussed, where the main points mentioned were electronics compatibility, pumping power, piping, harsh climate operation, material compatibility, organic or fouling problems, erosion, hot-spot management and heat dissipation.

To conclude, two-phase microchannel cooling is ideally suited for the military environment considering the facts given. It is clean, robust, reliable and ideally suited for situations where low power consumption is required, which is often the case for portable equipment. Two-phase cooling is more complex, but only for non-specialists.

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