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PUMPED LIQUID MULTIPHASE COOLING

Dr. Robert Hannemann
Atlantic Technologies LLC
Boston. MA USA

Joseph Marsala
Thermal Form and Function LLC
Manchester, MA USA

Martin Pitasi
Thermal Form and Function
Manchester, MA USA

ABSTRACT

The performance limits of conventional cooling technologies are being reached in both military and commercial electronics and electro-optical systems. Pumped Liquid Multiphase Cooling (PLMC) provides significantly enhanced thermal management capabilities for these systems using mostly-conventional components and working fluids. PLMC is highly scalable and reliable. Energy efficiency is very high, surpassing conventional techniques by up to two orders of magnitude. This paper describes the basic PLMC technology and presents experimental results from several prototype embodiments of the technology

INTRODUCTION

The thermal control of electronic and electro-optical devices and systems is an integral part of their design and performance. Historically, commercial electronic systems such as computers and telecommunications switches have been cooled by natural and forced convection using ambient air. Wherever possible, military and defense-related systems also use air cooling, but in many cases single-phase liquid cooling (usually using chemically-treated water as the working fluid) has been required. Examples of such systems include high-energy laser arrays and high-power radars.

For microprocessor-based commercial systems, cooling is recognized as a key technology required for continued progress. In general, there is agreement as to the general trends. Shown in Figure 1 are the predictions in 1993, 1999, and 2002 for the heat generated by high-end devices – microprocessors and microcontrollers [1,2,3].

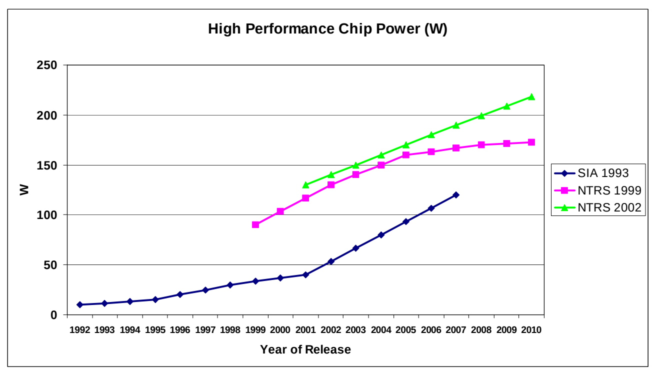

Figure 1: Industry power dissipation forecast

It seems clear that chip powers will exceed 150 W by the middle of the decade; this is generally beyond the capabilities of even “heroic” air cooling (~100W) given chip packaging constraints and operating temperature limits. It is also clear that expectations for power dissipation are *rising* as time goes on. Another key metric is the heat flux at the chip level, predictions for which are shown in Figure 2 [1,2,3].

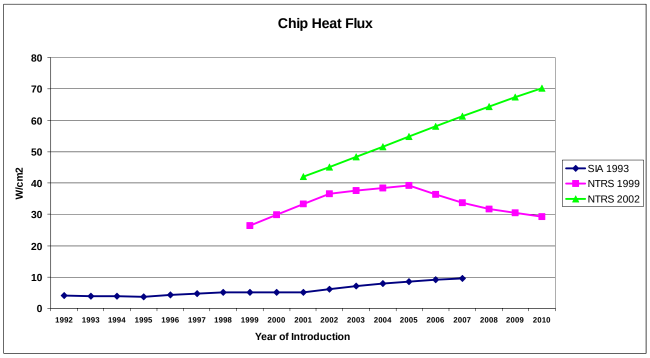

Figure 2: Chip heat flux forecast

While much attention has been placed on these thermal limits, cooling is also an issue at the data center level. Figure 3 portrays the trends in terms of overall power dissipation per unit floor area. Both telecommunications equipment rooms (both central offices and remote huts) and computer rooms have reached their limit for thermal density given current cooling approaches relying on in-room air conditioning units.

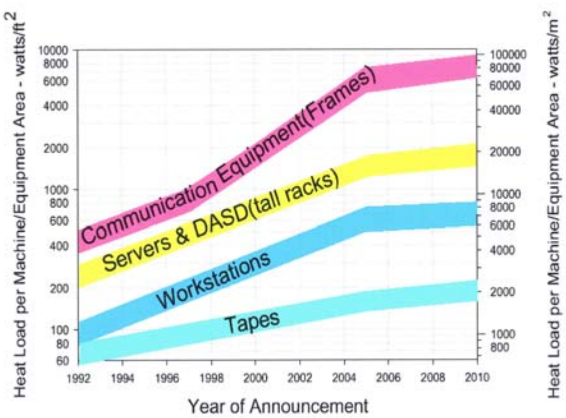

Figure 3: Rack/equipment room heat load forecast [4]

Military systems typically must operate in significantly more taxing environmental conditions than their commercial counterparts. For certain systems, such as phased array radars, isothermal cooling (that is, thermal control subsystems providing near-isothermal conditions across the system) is important. For others, such as high-energy lasers, near-isothermal conditions are coupled with a requirement to handle extremely high heat fluxes. PLMC is capable of providing such thermal management. Thermal Form and Function LLC (TFF) is participating in a program sponsored by the Missile Defense Agency (MDA) that will characterize PLMC as applied to the radar cooling problem; the results of this program will be complementary to TFF's product development efforts for computer and other electronics and electro-optical cooling.

This paper will describe the basic PLMC technology, provide early results for commercial applications at several levels of the hardware hierarchy, and outline the application of this uniquely capable cooling technology to other military and industrial systems.

PUMPED LIQUID MULTIPHASE COOLING

In its simplest form, PLMC may be thought of as an *externally pumped heat pipe* thermal management system. Heat pipes are well known for their effectiveness in handling high heat fluxes with a very low temperature rise, but are inherently inflexible in their application (e.g., they are sensitive to orientation) and limited in the distance over which the collected energy can be transported. Heat pipes use capillary pumping to return liquid from the condenser end to the evaporator (heat load) end of the device.

PLMC eliminates wick structures for pumping and instead employs a high reliability, low flow rate pump to return condensed liquid to the evaporator / cold plate. The basic PLMC flow loop is shown in Figure 4.

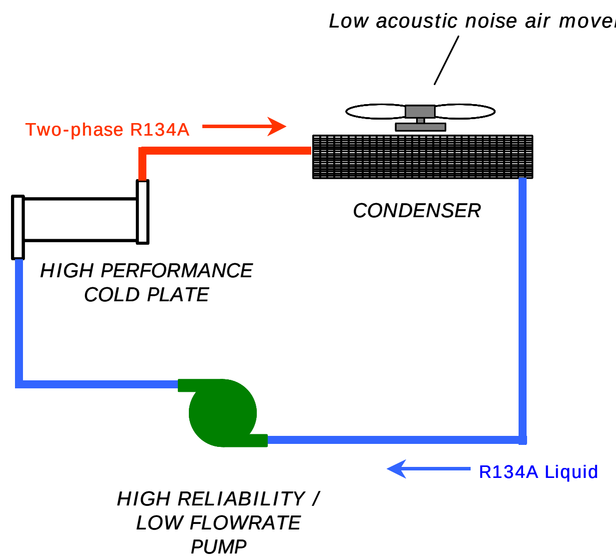

Figure 4: PLMC flow loop

The fluid (in this case refrigerant R134A) essentially goes through a Rankine cycle. In the cold plate, heat from the device to be cooled partially evaporates the coolant, thus providing a very high effective heat transfer coefficient (TFF has devised patent-pending cold plate structures that optimize the heat transfer in the cold plate). The coolant (ideally a two-phase mixture with a quality of perhaps 30%) then flows to an air- or water-cooled condenser (in Figure 4, an air-cooled condenser is shown) where heat is rejected and the fluid returns to the single-phase liquid state. A low-power, low-flow rate pump then returns the liquid to the cold plate.

PLMC has many advantages over other cooling techniques. Very high local heat transfer coefficients are possible in properly designed cold plates. Heat transport is very efficient; a kilowatt can be transported hundreds of meters with a pump that requires only a few watts of power. PLMC uses component technology that for the most part is proven and used in other applications. Near-isothermal cooling is possible for a number of devices in a system. When properly designed, a PLMC system is guaranteed not to suffer from environmental water condensation. In short, PLMC technology provides the highest performance, lowest cost, and most compact cooling for electronics and other systems available today. Finally, the approach is highly scalable – effective and efficient for applications with 100W heat loads (computers) as well as applications with 10s of kW heat loads (radar).

It is instructive to compare and contrast PLMC with single-phase liquid cooling using either standard cold plates or advanced microchannel heat sinks for electronics devices. Table 1 below provides comparative data for a 200W heat load operating in normal ambient conditions.

	Single-phase liquid loop	PLMC
Working fluid	Water	R134A
Flow rate (l/h)	35	7.5
Pump power (W)	20	2
Coolant temperature rise (deg C)	10	~0
Relative condenser size	2	1

Table 1: PLMC vs. liquid cooling

As can be seen, even if liquid cooling could provide the requisite thermal performance to maintain the operational limits of a 200W processor chip, PLMC provides significant benefits from efficiency, size, and weight perspectives.

APPLICATION TO RADAR SYSTEM COOLING

Phased array radar systems can benefit from the advantages of PLMC, which promises significantly reduced cost, size, weight and power over the currently used single-phase liquid cooling and vapor compression two-phase designs.

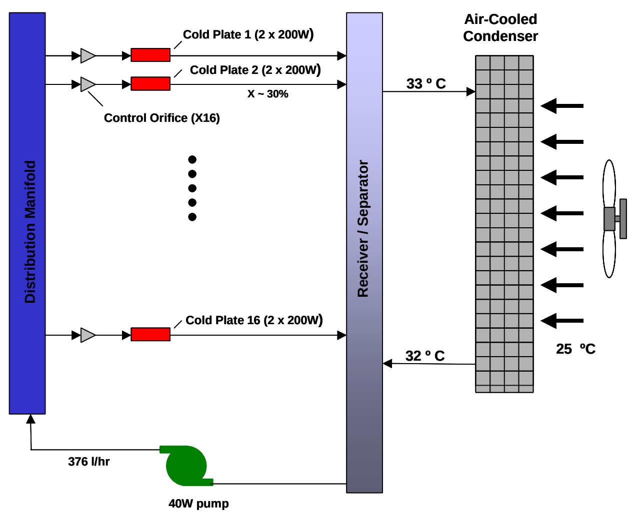

Figure 5: Demonstration radar cooling unit

Thermal Form and Function has built and tested a demonstration cooling system similar in size and power density to important radar cooling applications. The goal of the project was twofold: first, to demonstrate in hardware a PLMC system capable of isothermally cooling a total of 16 400W heat loads (for a total of 6.4 kW) at working-fluid temperatures below 33 ºC, and second, to successfully design and test a 400W heat exchanger / cold plate for the system with a fluid-to-cold-plate-surface thermal resistance of less than 0.02 K/W. The demonstration system block diagram is shown in Figure 5.

The demonstration unit was thoroughly instrumented to measure temperatures and pressures at key points in the working fluid cycle, and was equipped with sight-glass monitors to assess fluid quality. At the design heat load of 6.4 kW (16-400W cold plates) and 25 ºC ambient air temperature, the working fluid temperature was maintained at a (saturation) temperature of ~32 ºC with a relatively modest 376 l/h coolant flow rate. A 30% quality was desired, and achieved, at the exit of the cold plates; this provides a safety factor for cold plate dry-out. The system was stable, easily controllable (through fan speed), and provided essentially isothermal conditions for all cold plates.

In order to meet design objectives, custom cold plates were fabricated using TF&F's patented copper convoluted fin construction. Two 200W thermal loads (thin film heaters) were used for each cold plate. The cold plate design is shown in Figure 6 below.

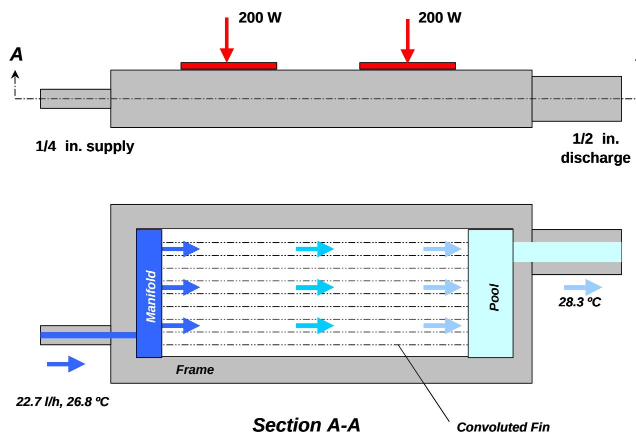

Figure 6: Demonstration unit cold plate (2.875 x 21.9 x 1.6 cm)

Typical operating conditions are indicated in the figure. Test data from 21 separate runs were used to determine the effective fluid-to-frame thermal resistance; values ranged from 0.009 K/W to 0.011 K/W, thus meeting the design objectives.

COMMERCIALIZATION

PLMC technology is applicable to a variety of electrical, electronic, and optical systems. The primary market target for TF&F is the information technology area (computers and telecommunications equipment).

As was pointed out in the Introduction, thermal management has become a serious problem at several levels, from hot spots on microprocessor chips, through processor packages, boxes, racks, and equipment rooms. PLMC is uniquely capable as a platform for computer cooling because it can address cooling issues at all these levels.

For personal computers and workstations, acoustic noise generation is a serious ergonomic problem. Even if thermal performance goals can be met with active air-cooled heat sinks, a significant acoustic benefit can be gained by using PLMC. This is because for moderate heat loads the PLMC condenser can be cooled via natural convection or using a low-speed, inherently quiet air mover.

For high-performance 1U and blade server configurations, thermal performance has become a limiting factor both for microprocessor operating frequency and processor density (that is, the number of processors per box). TF&F is currently working with OEMs on the implementation of PLMC for these configurations; a mockup of a 1U server application with dual processors, each dissipating 150W is shown as Figure 7.

Figure 7: 1U PLMC mockup

Dense, rack-based systems can be effectively addressed using a single pump, single condenser unit that allows hot swapping of PLMC-cooled modules. TF&F has prototyped such a unit aimed at the VITA34 backplane market with an equipment OEM; a drawing of this system is shown in Figure 8.

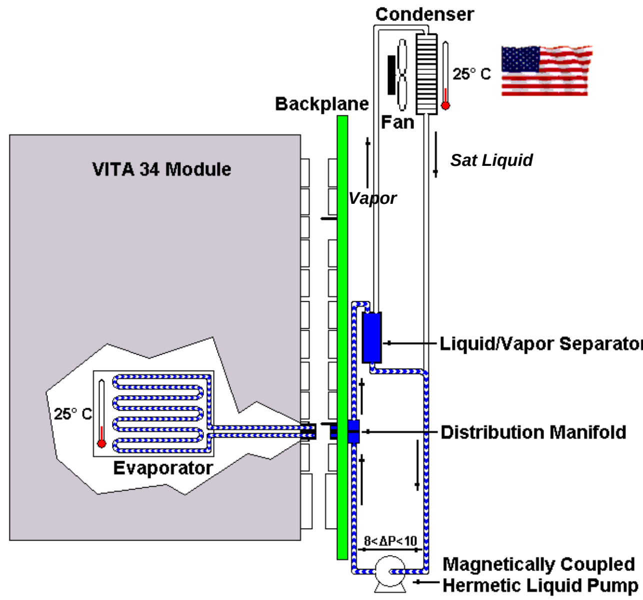

Figure 8: VITA34 multi-module system

A major pain point for operators of major computer room installations is the per-rack power dissipation, which will more than double over the next few years. Energy efficiency is also of serious concern at this level; over 40% of the energy used in "typical" installations is consumed by cooling equipment, according to a major computer room air conditioning manufacturer. State and federal governments are considering energy efficiency statutes for such installations.

PLMC is applicable for this problem as well. Shown in Figure 9 is a concept for a rack intercooler unit that provides thermal management within a densely populated equipment frame and draws on PLMC's capabilities in moving heat over long distances – the condenser can be located either at a remote location within the equipment room or outside the room altogether (for example, on the building roof).

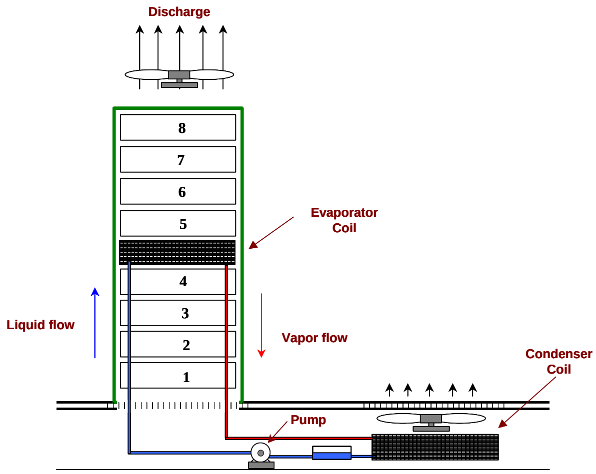

Figure 9: Rack Intercooler System

CONCLUSION

Thermal performance limits are being reached in a variety of applications, from microprocessors to large radar systems. Pumped liquid multiphase cooling (PLMC), essentially an externally pumped heat pipe cooling approach, promises to be effective across many applications. It is highly scalable, very energy efficient, and can provide significant performance, cost, size, and reliability benefits as compared with existing active air cooling or simple liquid-loop systems. While PLMC can be implemented with a variety of working fluids, Thermal Form & Function has favored R134A refrigerant, which is non-toxic, widely available, and environmentally friendly.

TF&F's technology and product development has been materially aided by applying PLMC to military and industrial systems, and is currently being commercialized as the ideal solution for the growing thermal management problems in commercial microelectronics.

The concepts described in this paper are protected by issued and pending US and foreign patents.

ACKNOWLEDGEMENTS

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