Liquid Metal

Cooling Systems

Thermal management is a serious concern in the reliability of high power computing and communications systems. Today's microelectronics often need cooling for power dissipation densities above 100 W/cm^2. As a result of these serious thermal issues, higher performance and greater reliability are extremely tough to attain. Cooling requirements exceed the capabilities of state-of-the-art finned heat sink structures, heat pipes, forced air cooling and other methods. Consequently, new approaches such as single- and two-phase liquid cooling systems are being employed. High vapor pressure and high thermal conductivity are making liquid metals attractive for high pressure cooling applications, such as in the nuclear power industry [1]. Liquid metal cooling can be used in defense and space electronics, medical devices and power generation.

Introduction

Liquid metal cooling technology is based on cooling loops that act as typical heat pipes. They rapidly transfer heat from a heat source to a radiator, which is then cooled down either actively or passively. Liquid metal provides significant advantages over other single-phase liquid cooling solutions. Table 1 summarizes the thermophysical properties of several liquid metals as well as water. The thermophysical properties of a liquid metal give it the ability to cool extremely high heat fluxes. Unlike water, it can absorb more heat without changing phase and becoming a troublesome gas.

Table 1. Thermophysical Properties of Liquid Metals and Water.

Property	Water	Gallium	NaK (Sodium-Potassium Alloy)	Hg
Density (kg/m^3)	998	6100	872	13599
Melting Temperature (°C)	0	29.8	-11.11	-38.8
Boiling Temperature (°C)	100	2205	783.80	356.8
Thermal Conductivity (W/mK)	0.61	28	25.30	7.8
Heat Capacity (J/KgK)	4181	373	1154	140
Viscosity (10^{-3} N.s/m^2)	0.85	1.96	0.468	1.55
Kinematic Viscosity (10^{-8} m^2/s)	85.5	32	53.7	11.4
Prandtl Number	6.62	0.0261	0.0213	0.0278

Besides providing excellent heat transfer, the high electrical conductivity typical in this class of fluids offers the potential for efficient, compact motion using electromagnetic pumps instead of hydraulic ones. It should be noted that in most liquid cooling systems, the low thermal conductivity of the working fluid (e.g. water) may lower its effectiveness as a heat transfer fluid. This results in greater hydrodynamic pressure drops in the fluidic loop, and increased electrical power dissipation in the water pumps. Many of the available water pumps have poor reliability and often have mechanical limitations (e.g., orientation-dependent performance, moving parts and noise).

The two major advantages of liquid metals lie in their superior thermophysical properties for extracting heat [1], and in the ability to pump these liquids efficiently with silent, vibration-free, non-moving magnetofluiddynamic (MFD) pumps [2]. Furthermore, closed loop systems enable gravity-independent cooling systems. As such, liquid metals offer an attractive solution for current and future high power density cooling challenges.

A liquid metal cooling system has three components: the cooling head, an electromagnetic pump and a storage tank that also includes a heat exchanger. Figure 1 illustrates the typical components of a liquid metal loop for cooling laptop computers [2].

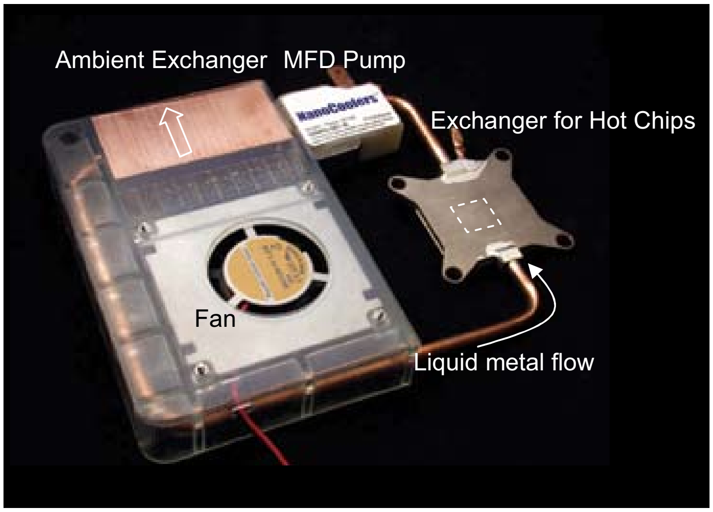


Figure 1. Liquid Metal Cooling Loop for Mobile Applications (nanoCoolers) [2].

Due to the high electrical conductivity of liquid metals, a low voltage but high electric current are generally needed to drive the MFD pump [3]., A large Lorentz force, which depends on electric current, is needed to overcome the flow resistance. In Miner and Ghoshal's work, a large current (up to 15–30 A) was used to drive the MFD pump. This makes the device rather impractical [1]. Therefore, the MFP pump design must be optimized to be driven at the lower current. It should be noted that liquid metal cooling must contend with a very large MFD pressure drop caused by the Lorentz force [4].

An Ideal Liquid Metal

To provide a practical cooling fluid, a liquid metal must satisfy the following requirements: non-poisonous, non-caustic, low viscosity, high thermal conductivity and high heat capacity. This is why liquid gallium is a perfect candidate to cool high power electronics components. In particular, gallium is well suited for computer chip cooling because of its low melting point (29.7 °C) and its latent heat of 80.1 J/g [5]. Because it has a large sub-cooling point, gallium can generally be kept in a liquid state at temperatures much lower than room temperature. Gallium's thermal conductivity is 28 W/m·K, which is far higher than that of air or water. This metal is also non-toxic and relatively inexpensive.

There are many benefits from using liquid gallium as a cooling fluid. Its low melting point and very low vapor pressure make it easy to handle. The metal's high thermal conductivity and heat capacity ensure it can be excellent for cooling applications [6]. Further, the low kinematic viscosity of liquid gallium improves its ability to remove heat, especially at the liquid-solid interface. And, because its surface tension is much higher than that of water, liquid gallium is immune to the presence of small cracks or channels in imperfect seals that would cause leaks if water was the cooling fluid. All of these compelling properties warrant the future application of gallium to chip cooling applications.

Impact on the Heat Transfer Coefficient

To better understand the use of liquid metal cooling systems, this section discusses the Nusselt number (*Nu*) for turbulent flows of fluids with moderate and low ratios of momentum diffusivity to thermal diffusivity (Prandtl number, *Pr*) in a circular tube. The Nusselt number for turbulent, fully developed flow with $0.6 \leq Pr \leq 160$, such as water, can be approximated by the Dittus–Boelter empirical equation [7]:

$$Nu_D = 0.023 \mathrm{Re}_D^{4/5} \mathrm{Pr}^{0.4} \tag{1}$$

$Re_D = uD/\nu$ is the diameter-based Reynolds number, where u is the average fluid flow velocity in a tube of hydraulic diameter D and ν is the kinematic viscosity.

For fully developed turbulent flow with low *Pr* (liquid metal), the turbulent heat transfer can be described using a formula that considers the influence of high thermal conductivity relative to turbulent induced mixing. For a *uniform heat flux*, the *Nu* can be calculated using the Sleicher–Rouse empirical correlation:

$$Nu_D = 6.3 + 0.0167 \mathrm{Re}_D^{0.85} \mathrm{Pr}^{0.93} \tag{2}$$

The heat transfer coefficient (h) is the rate that thermal energy is removed from a surface per unit surface area per temperature differential, and is related to *Nu* by the following:

$$h = \frac{Nu \cdot K}{D} \tag{3}$$

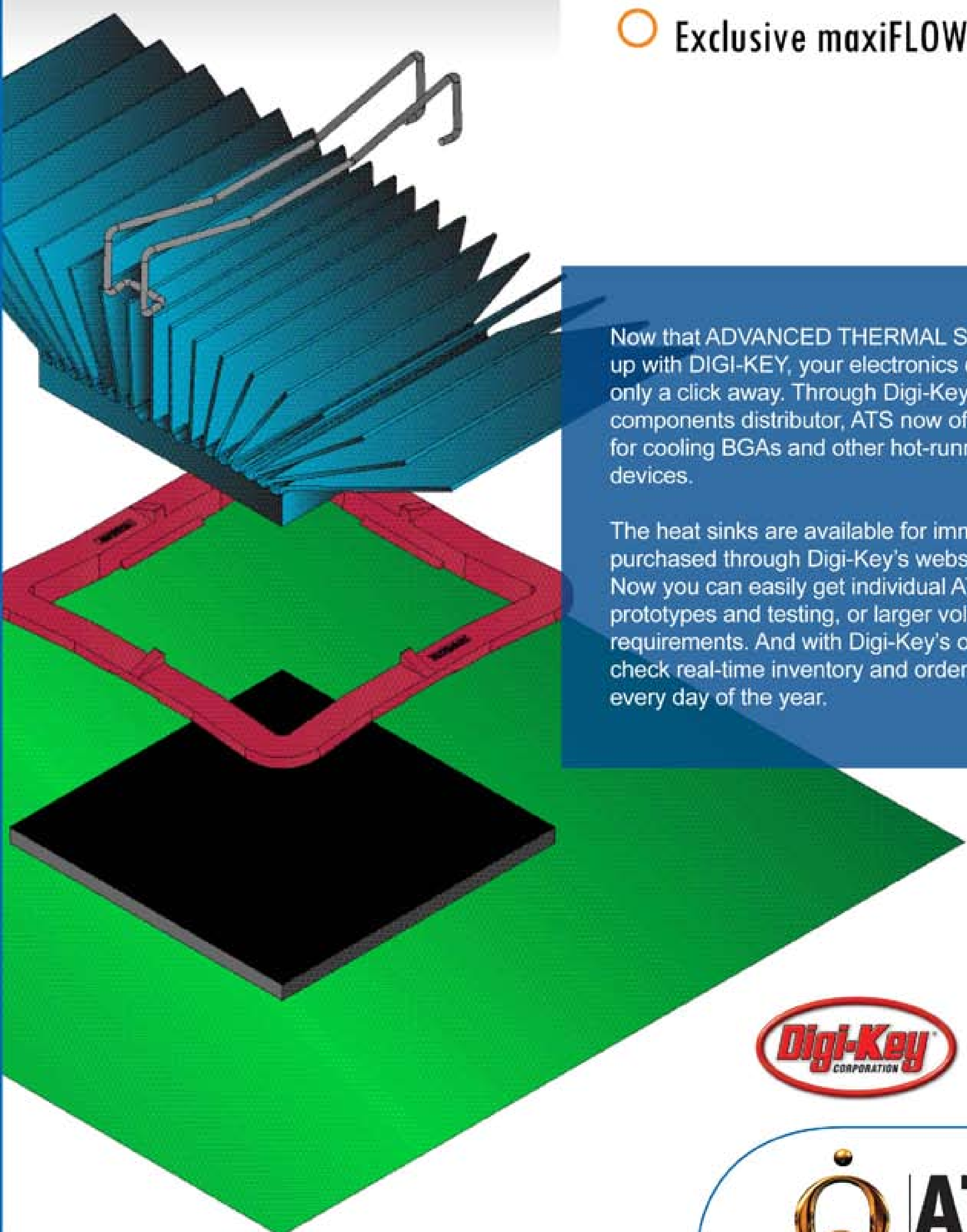
In Equation 3, K is the thermal conductivity and D is the characteristic dimension of the geometry. Combining Equations 1–3, the relative heat transfer coefficient for turbulent flow of a liquid metal (h_{lm}) and water (h_{water}) for a given pipe geometry is expressed as:

$$\left.\frac{h_{lm}}{h_{water}}\right|_{turbulent} = \frac{K_{lm}}{K_{water}} \cdot \frac{6.3 + 0.0167 \mathrm{Re}_D^{0.85} \mathrm{Pr}^{0.93}}{0.023 \mathrm{Re}_D^{4/5} \mathrm{Pr}^{0.4}} \tag{4}$$

ATS HEAT SINK DISTRIBUTION PARTNERS

DIGI-KEY CORPORATION

- 380+ High Performance Heat Sinks
- Online Ordering
- Next Day Delivery
- Volume Discounts
- Exclusive maxiFLOW™ Technology



Now that ADVANCED THERMAL SOLUTIONS has teamed up with DIGI-KEY, your electronics cooling solutions are only a click away. Through Digi-Key, the global electronics components distributor, ATS now offers over 380 heat sinks for cooling BGAs and other hot-running semiconductor devices.

The heat sinks are available for immediate delivery when purchased through Digi-Key's website and printed catalogs. Now you can easily get individual ATS heat sinks for prototypes and testing, or larger volumes for production requirements. And with Digi-Key's online tools, you can check real-time inventory and order parts 24 hours a day, every day of the year.

Digi-Key CORPORATION

To place an order, please visit www.digikey.com. To download a catalog of ATS heat sinks available through Digi-Key, please visit www.qats.com.

ATS ADVANCED THERMAL SOLUTIONS, INC.
Innovations in Thermal Management®

In a circular tube characterized by uniform surface heat flux and laminar fully developed conditions, the Nusselt number is a constant, independent of Re_D, Pr, and axial location.

$$Nu_D = 4.36 \tag{5}$$

By using Equation 5 for the laminar fully developed conditions in a tube, the ratio of the heat transfer coefficient of a liquid metal and water is given the ratio of thermal conductivities,

$$\left.\frac{h_{lm}}{h_{water}}\right|_{laminar} = \frac{K_{lm}}{K_{water}} \tag{6}$$

Figure 2 shows the ratio of the heat transfer coefficients for a typical liquid metal alloy and water for flow in a pipe of constant surface heat flux for turbulent flow given by Equation 4 and for laminar flow given by the ratio of thermal conductivities (Equation 6). The liquid metal potentially offers an order of magnitude improvement in heat transfer coefficient for laminar flows and at low Re_D turbulent flows.

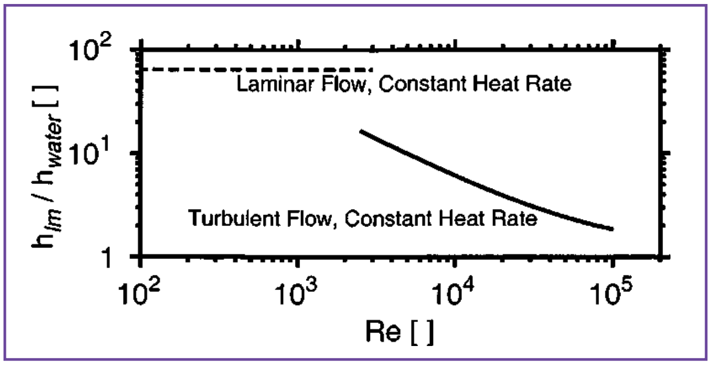


Figure 2. The Ratio of Heat Transfer Coefficients for a Liquid Metal Alloy and Water for Flow in a Pipe of Constant Wall Heat Flux as a Function of the Reynolds Number Re_D [1].

Figure 3 shows some of the experimental results of the heat transfer coefficients attainable with different fluids and cooling schemes. Air is the most affordable, and remains the most widely used coolant. However, the poor thermal transport properties of air greatly reduce its cooling potential, limiting its use to low heat flux devices. Better results are possible using fluorochemical liquids, while the most demanding situations are typically cooled with water. As seen in Figure 3, forced convection can greatly improve cooling performance relative to natural convection for all coolants [8,2].

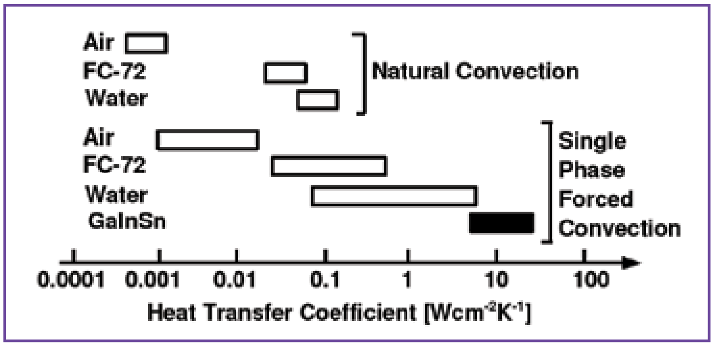


Figure 3. Relative Impact of Liquid Metals in High Heat Flux Cooling. The Heat Transfer Coefficients for Fluorochemicals and Water Were Obtained from Mudawar [8].

Summary

A review of the literature shows that liquid metal systems have a more powerful cooling capacity than water cooling, especially at a low flow rate or in high heat generation situations. The other benefit of liquid metal cooling is lower acoustic noise. Most heat sink and fan combinations generate rather loud noise as the fans circulate air over the CPU and through the system. Using an electromagnetic induction pump to drive the liquid metal means there are no moving parts – besides the liquid in the system – and thus it provides a more reliable cooling device. Liquid metals don't necessarily need to run at a very high speed, which also helps to reduce noise. Naturally, the broader use of liquid metal coolants depends on several factors. Among these are size, cost, weight and capacity. It must also be determined whether liquid metal cooling will provide a practical solution relevant to the end use of the electronics.

References:

1. Miner, A., and Ghoshal, U., Cooling of High-Power-Density Microdevices Using Liquid Metal Coolants, Applied Physics Letters, Vol. 85, No. 3, 2004.
2. Ghoshal, U., Grimm, D., Ibrani, S., Johnston, C., and Miner, A., High-Performance Liquid Metal Cooling Loops, Semiconductor Thermal Measurement and Management Symposium, 2005 IEEE Twenty First Annual IEEE, 2005.
3. Ma, K.-Q. and Liu, J., Heat-Driven Liquid Metal Cooling Device for the Thermal Management of a Computer Chip, Journal of Physics D: Applied Physics, Vol. 40, 2007.
4. Takahashi, M., Inoue, A., Aritomi, M., and Matsuzaki, M., Studies on Magnetohydrodynamic Flow Characteristics and Heat Transfer of Liquid Metal Two-Phase Flow Cooling Systems for a Magnetically Confined Fusion Reactor, Fusion Engineering and Design, Vol. 27, 1995.
5. Li, T., Lv, Y.-G., Liu, J. and Zhou, Y.-X., A Powerful Way of Cooling Computer Chip Using Liquid Metal With Low Melting Point as the Cooling Fluid, Forschung im Ingenieurwesen, Vol. 70, 2006.
6. Smither, R., Lee, W., Macrander, A., Mills, D., and Rogers, S., Recent Experiments with Liquid Gallium Cooling of Crystal Diffraction Optics, Review of Scientific Instruments, Vol. 63(2), 1992.
7. Incropera, F., DeWitt, D., P., Bergman, T., and Lavine, A.,, Introduction to Heat Transfer, Fifth Edition, 2007.
8. Mudawar, I., Assessment of High-Heat-Flux Thermal Management Schemes, IEEE Transactions on Components and Packaging Manufacturing Technology, Vol. 24, 2001.