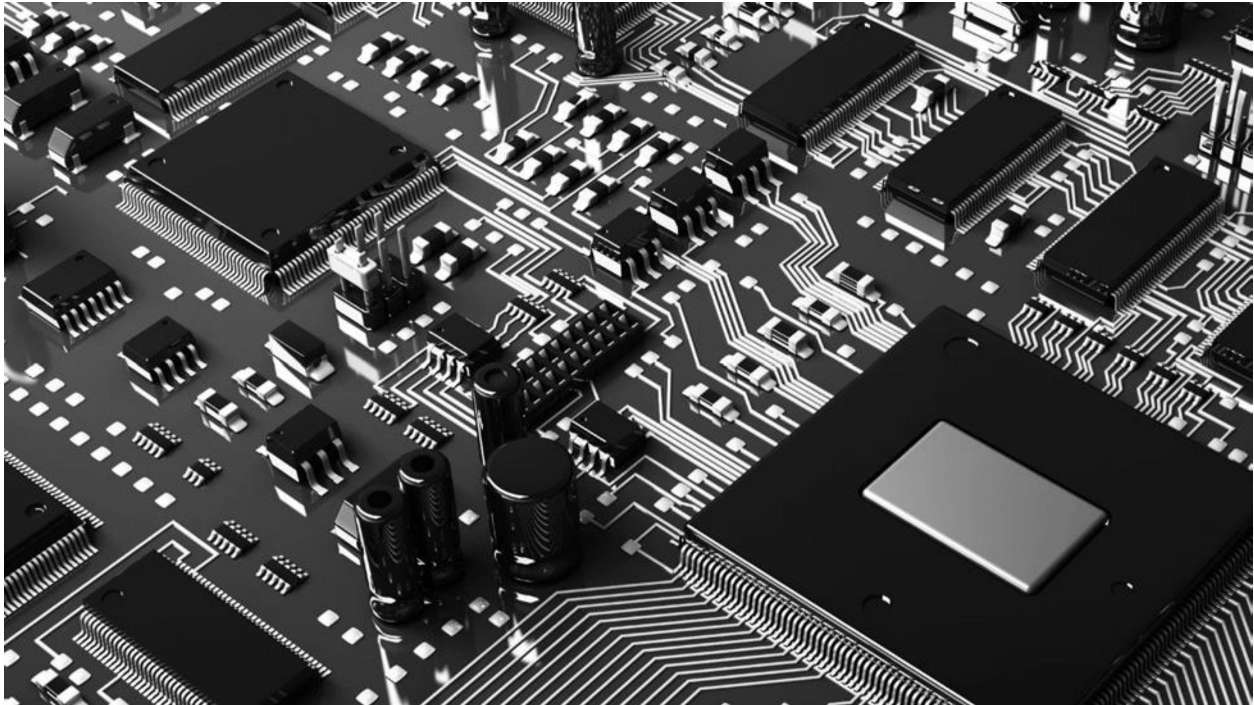

Minimizing CPU Overheating with Liquid Immersion Cooling

Improving operational performance in technical environments

Introduction

The Central Processing Unit (CPU) generates a great deal of undesirable heat in modern computing systems. The CPU is responsible for processing most of the data within systems and is often referred to as a computer's central processor or simply processor. As data is processed within a system, heat is generated. Once heat thresholds are exceeded, CPUs are placed at risk of malfunction or permanent damage.

As microprocessors decrease in size, heat dissipation issues become increasingly prevalent. Moore's law predicts the number of transistors placed on integrated circuits will double every two years. As CPUs continue to decrease in size while exponentially increasing in power each year, adequate cooling methods will increasingly become an integral part of new design planning efforts. Figure 1 shows the evolution of module-level heat flux in high-end computers over several decades. As shown, module heat flux has continued to creep upward with each passing year.

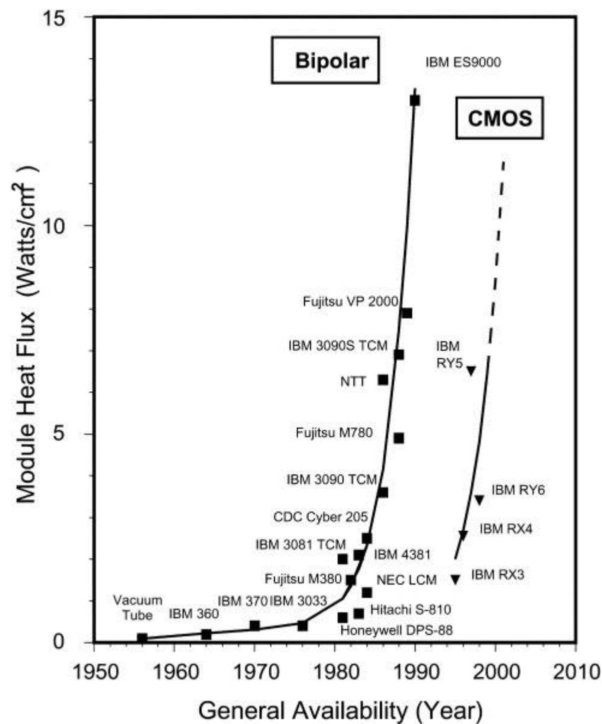

Figure 1: Evolution of module level heat flux in high-end computers [1]

An experiment was conducted to evaluate liquid immersion cooling designed to mitigate CPU overheating through the use of a commercially available synthetic petroleum fluid – Opticool Fluid.

Issues with Air Cooling in Technical Applications

Air-cooling, which incorporates the use of fans, is currently the prevalent method of cooling CPUs in computing environments. It has several advantages including reduced cost, relatively low noise, and is free of piping elements, tubes and cables. [2] The main function of fans is to pump air so that heat is effectively carried away from the CPU assembly. Air pressure can vary by incorporating fans in series (placed on top of one another) or parallel configurations (side-by- side). [3] The serial setup increases the discharge pressure while the parallel setup increases the area coverage.

Based on several studies completed in recent years [1][2][4][5][6][7][8][9], air-cooling technology is insufficient to keep up with the growing requirements of CPU cooling in the marketplace.

Heat Transfer Overview

Fluid flow can be laminar (steady state) or turbulent, and heat might be transferred with and without phase change. In addition, the flow regime might be treated as Newtonian or non- Newtonian. Appropriate theoretical and empirical heat transfer equations have been developed for different velocity profiles, flow regimes and flow geometries. For the ideal case of fluid flow in a shell-and-tube exchanger, heat is transferred by radiation and convection to tubes via conduction through tube walls and by forced conduction from the internal wall surface to the bulk fluid. The basic equation governing all such heat transfer is

$$Q = UA\Delta T \qquad \text{(Eq. 1)}$$

where *Q* represents heat transferred in unit time, *U* represents overall heat transfer coefficient, *A* represents available surface area and ΔT represents temperature gradient between the source and the sink (or the inlet and the outlet). If multiple fluids or separating walls are used, then the overall coefficient *U* can be decomposed into individual coefficients *h*, each representing a particular medium. [10]

In instances of conductive heat transfer through several layers of materials, the thermal resistances can be added in series to obtain the total temperature gradient. This is shown in Figure 1 below, where x_i represent media thickness and k_i represent thermal conductivities:

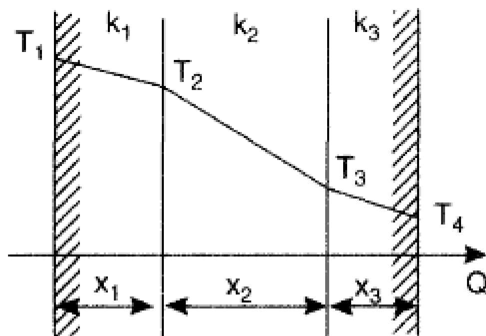

Figure 2: Conductive heat transfer through composite media. [11]

With reference to the above figure, the thermal gradient T_1 – T_4 is

$$T_1 - T_4 = \left(\frac{x_1}{k_1 A} + \frac{x_2}{k_2 A} + \frac{x_3}{k_3 A}\right) Q$$

(Eq. 2)

where Q becomes the ratio of total driving force to total thermal resistance per unit area. [11] In instances of convective transfer, which is often the principal mechanism in liquid cooling, the heat transfer coefficient may be expressed as a dimensionless relation known as the Nusselt number, or as a dimensional equation. Convection is distinguished between natural (fluid movement caused by the transfer process itself) or forced (fluid movement caused by an externally applied force); in the former, the Nusselt number for external spaces is

(Eq. 3)

$$Nu = \left\{0.825 + \frac{0.387 Ra^{1/6}}{\left[1+(0.492/Pr)^{9/16}\right]^{8/27}}\right\}^2$$

where Ra, the Rayleigh's number and Pr, the Prandtl number, are dimensionless numbers corresponding to the flow velocity and fluid properties. [12] When we have steady flow of fluid past an immersed flat plate, two boundary layers develop. The first is hydrodynamic, within which velocity profile changes from 0 at the plate surface to flow velocity at the outer boundary; the second is thermal in which temperature profile changes from the plate surface temperature to the fluid temperature. These boundary layers are shown in Figure 2 below:

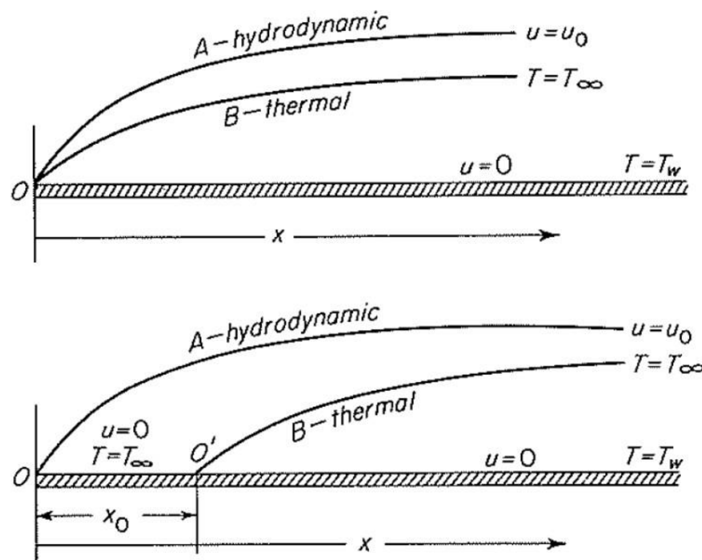

Figure 3: Hydrodynamic and thermal boundary layers for steady flow of fluid past an immersed plate. Fluid temperature is T_∞ and plate surface temperature is T_w; fluid velocity is u_0. Entire plate is heated at top while there is an unheated length x_0 at bottom. [13]

For the particular case of forced convection with laminar flow and no phase change, the temperature gradient at the wall is given by

(Eq. 4)

$$\left(\frac{dT}{dy}\right)_w = \frac{0.332(T_W - T_\infty)}{\sqrt[3]{1-(x_0/x)^{3/4}}} \sqrt[3]{\frac{c_p\mu}{k}} \sqrt{\frac{u_0\rho}{\mu x}}$$

where c_p is the liquid's specific heat, k is its conductivity, μ is its viscosity and ρ is its density. [13] The treatments of heat transfer for turbulent flow are more complex, but in the case of fully developed (or fully rough) flow of a Newtonian fluid, the velocity and temperature gradients within a tube have been observed to be parabolic. Empirical formulae for heat transfer with phase transition, for both natural and forced convection, have also been developed.

Raspberry Pi

The Raspberry Pi computing device was selected for this experiment due to it's condensed size and overclocking capability. Figure 4 shows the layout of the unit. The Raspberry Pi device is representative of ways that smaller component sizes are leading to more powerful computing. The device has been used for media streaming, home automation, and robotic applications, to name a few [14].
The Raspberry Pi is typically powered by 5V and 1-1.5A and can be overclocked to a maximum 1000MHz. As with other computing devices, the Raspberry Pi tends to overheat when overclocked or when excess voltage is applied to the device. The maximum operating temperature for the Raspberry Pi CPU is 85°C. As this experiment was conducted, the CPU never exceeded this temperature.

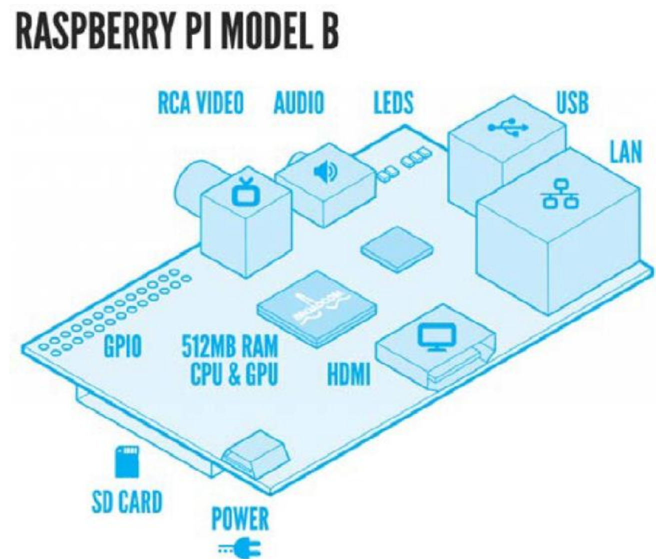

Figure 4: Diagram of Raspberry Pi Model B [15]

The thermal image below (Figure 5) shows that the CPU is one of the largest heat emitters when the Raspberry Pi is running at normal capacity. During this study, we focused exclusively on CPU temperature measurements.

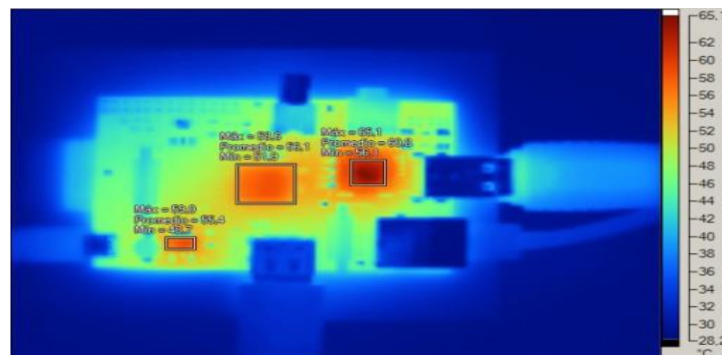

Figure 5: Thermal Image of Raspberry Pi Model B

Experimental Design

The general layout of the experimental setup used for this study is shown in Figures 6 and 7. Baseline CPU temperatures were measured with standard 5V input while unit was overclocked at 800MHz, 900MHz and 1000MHz respectively. Laboratory temperature was maintained at 20°C throughout the duration of the experiment. The immersion fluid was maintained at this same temperature during immersion testing as well. Measurements were recorded at device startup and in subsequent 1-hour increments. CPU temperatures were measured for both air cooling and immersion cooling with overvoltage levels of 6V, 7V, and 8V applied during 3-hour periods for each test, respectively. Overclocking speed of 1000MHz was maintained for the duration of the overvoltage testing.

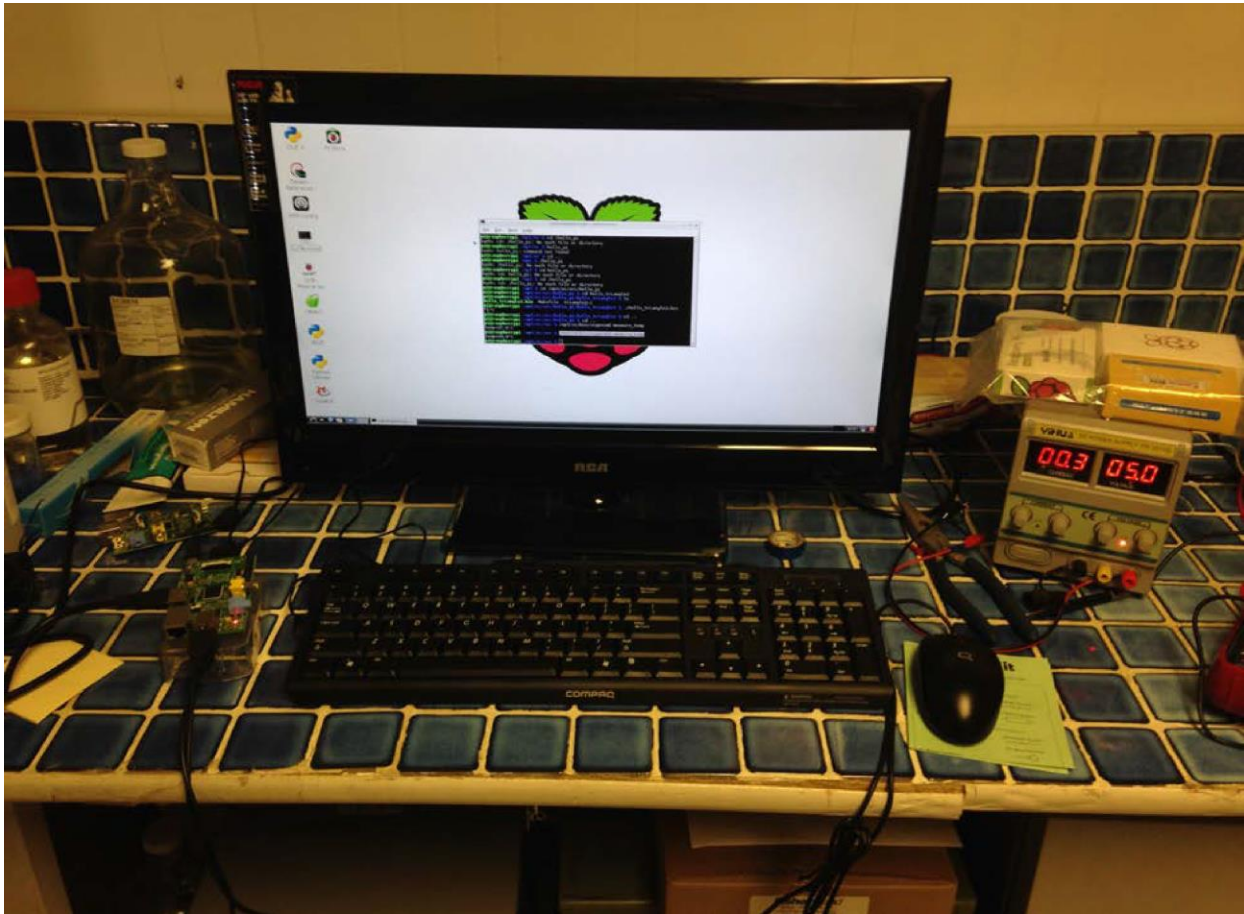

Figure 6: Raspberry Pi Model B computing device with standard 5V applied to power up.

CPU temperatures were obtained via the Raspberry Pi unit itself by using the following command sequence upon login:

```
/opt/vc/bin/vcgencmd measure_temp
ENTER
```

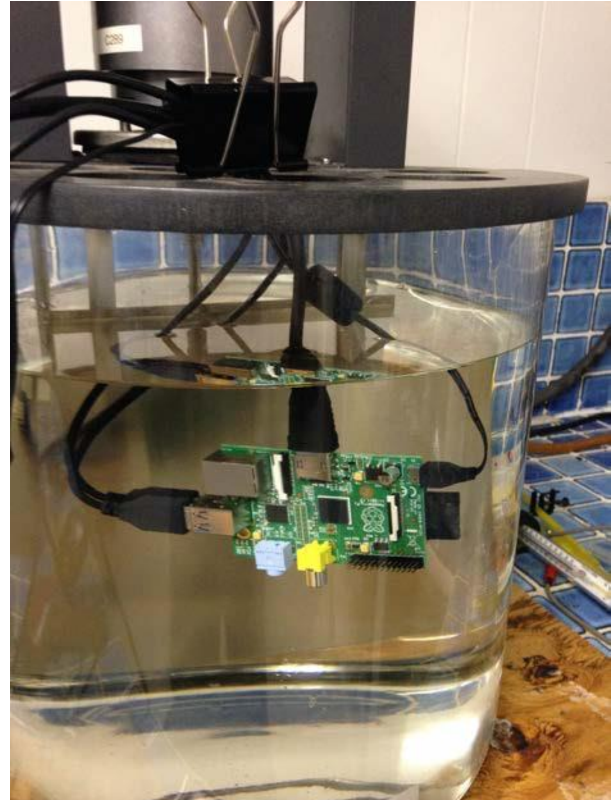

Figure 7: Raspberry Pi immersed in Opticool Fluid and powered up for temperature measurements.

Results

During baseline testing, 5V was applied to the Raspberry Pi during 3 overclocking tests. Results were as follows:

	Startup	1-Hour	2-Hour	3-Hour
700 MHz	34.2° C	39.0° C	47.6° C	48.3° C
900 Mhz	36.3° C	48.2° C	48.7° C	51.9° C
1000 MHz	37.4° C	54.1° C	54.6° C	58.4° C

As shown above, the maximum CPU temperature at 1000MHz after 3-hours of operation was 58.4°C. Next, temperatures were recorded as overvoltage was applied to the unit. Maximum overclocking of 1000MHz was maintained throughout. The results were recorded and graphed (Figure 8).

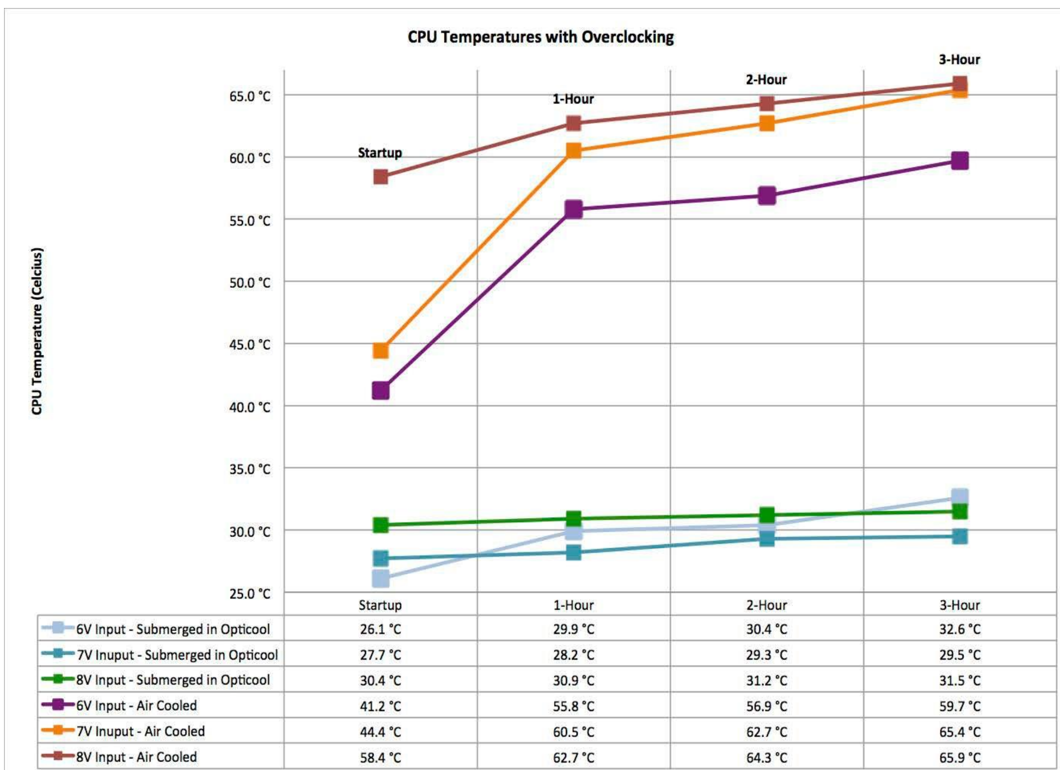

Figure 8: CPU temperatures with Overclocking/Overvoltage

During 36 hours of testing, the device maintained adequate operation however when 7-8V was applied to the unit, operation became extremely unstable. This occurred during both air and liquid cooling testing. This is likely due to a limitation of the CPU used for this board, however based on these findings, on-board processor power of the Raspberry Pi can be increased if a more powerful CPU were integrated into the design and combined with liquid immersion cooling.

Conclusion

As devices continue to shrink in size while increasing in power, performance improvements will continue to be plagued by increased power and cooling requirements. Furthermore, high temperatures negatively affect systems reliability as various components are exponentially dependent on operating temperatures. The results obtained during this experiment demonstrated how liquid immersion cooling can efficiently decrease CPU operating temperatures by as much as 50% or greater versus traditional air cooling. As discussed above, thermal management will become increasingly important in the future. Liquid immersion cooling with Opticool is a viable solution that may be applied in any number of applications including data center environments, underwater ROVs and electric engines, to name a few.

Opticool Fluid

OptiCool Fluid is an isoparaffin-based dielectric heat transfer fluid manufactured by Soltex, Inc. OptiCool has been used for over 10-years to cool electrical circuitry in transformers, RF and microwave transmission devices and computer systems.

OptiCool Fluid is a colorless, odorless, food grade isoparaffin oil. With very low viscosity and high thermal conductivity, OptiCool Fluid has extremely high heat transfer coefficients, making it ideal for removing heat from circuitry with high heat flux densities.

Contact Soltex to find out more about OptiCool Fluid and its electronics cooling applications.

www.soltexinc.com
Tel: 281-587-0900

Reference

[1] Chu, R.C.; Simons, R.E.; Ellsworth, M.J.; Schmidt, R.R.; Cozzolino, V., "Review of cooling technologies for computer products," *Device and Materials Reliability, IEEE Transactions on,* vol.4, no.4, pp.568,585, Dec. 2004.

[2] Mohammed, R.K.; Yi Xia; Sahan, R.A.; Pang, Y., "Performance improvements of air-cooled thermal tool with advanced technologies," *Semiconductor Thermal Measurement and Management Symposium (SEMI-THERM), 2012 28th Annual IEEE*, vol., no., pp.354, 361, 18- 22 March 2012.

[3] http://en.wikipedia.org/wiki/Computer_cooling

[4] Abbas, T.; Abd-elsalam, K.M.; Khodairy, K.H., "CPU thermal management of personal and notebook computer (Transient study)," *Thermal Issues in Emerging Technologies Theory and Applications (ThETA), 2010 3rd International Conference*, vol., no., pp.85, 93, 19-22 Dec. 2010.

[5] Ye Li; Tong Zhengming; Huang Liping; Chen Hao, "Studies on heat transfer performances of a heat pipe radiator used in desktop PC for CPU cooling," *Materials for Renewable Energy & Environment (ICMREE), 2011 International Conference*, vol.2, no., pp.2022, 2026, 20-22 May 2011.

[6] Mohammed, R.K.; Yi Xia; Sahan, R.A.; Pang, Y., "Performance improvements of air-cooled thermal tool with advanced technologies," *Semiconductor Thermal Measurement and Management Symposium (SEMI-THERM), 2012 28th Annual IEEE,* vol., no., pp.354, 361, 18- 22 March 2012.

[7] Chu, R.C.; Simons, R.E.; Ellsworth, M.J.; Schmidt, R.R.; Cozzolino, V., "Review of cooling technologies for computer products," *Device and Materials Reliability, IEEE Transactions on*, vol.4, no.4, pp.568, 585, Dec. 2004.

[8] Chien-Yuh Yang; Chun-Ta Yeh; Pei-Kang Wang; Wei-Chi Liu; Kung, E.Y.-C., "An in-situ performance test of liquid cooling for a server computer system," *Microsystems Packaging Assembly and Circuits Technology Conference (IMPACT), 2010 5th International*, vol., no., pp.1, 4, 20-22 Oct. 2010.

[9] Song-Hao Wang; Guang-Yi Lee; Wei-Zhi Wang; Zhi-Yu Wang; Chyi-Shyan Tsai, "An Innovative Active Liquid Heat Sink Technology for CPU Cooling System," *Electronic Packaging Technology, 2007. ICEPT 2007. 8th International Conference on*, vol., no., pp.1, 6, 14-17 Aug. 2007.

[10] Halliday, D., Resnick, R., & Walker, J. (2014). *Fundamentals of Physics*, 10th Ed. Chichester: John Wiley & Sons, Inc.

[11] Coulson, J. M. & Richardson, J. F. (1999). *Fluid Flow, Heat Transfer and Mass Transfer*, 6th Ed. Massachusetts: Butter worth–Heinemann.

[12] Maloney, J. O. (2008). *Perry's Chemical Engineers' Handbook*, 8th Ed. New York: McGraw-Hill.

[13] McCabe, W. L., Smith, J. C., & Harriott, P. (1993). *Unit operations of chemical engineering*, 5th Ed. New York: McGraw-Hill.

[14] Heath, N. (2012). *10 coolest uses for the Raspberry Pi*. Retrieved July 14, 2014 from http://www.techrepublic.com/blog/european-technology/10-coolest-uses-for-the-raspberry-pi/.

[15] Raspberry Pi Model B Schematic. Retrieved July 15, 2014, from http://www.raspberrypi.org/help/faqs/.