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Review of Liquid Cooled Microelectronic Equipment

Lian – Tuu Yeh, Ph D & PE
ASME Fellow
Thermal Consultant
Dallas, TX
jjyeh2@aol.com

Abstract

The equipment power consumption is continuously increased at a fast pace. For the high power air cooled systems, large high performance fans are becoming a must for the high power systems in order to provide the necessary air flow rates. Two major concerns about these large fans are the power consumption and the acoustic noise of the fans.

The increased system power results in a significant increase in the power consumption and the operation cost of the equipment as well as its host facilities such as the date centers. For some cases, the system power is too high to be considered by air cooling. The only solution to the above situations is adopting the liquid cooling. The liquid cooling still has many advantages over the air cooled systems including not only able to support higher system power but also to reduce component temperature along with increased system reliability.

The purpose of this paper is to review how to employ the existing liquid cooling technologies to cooling of electronic equipment in various industries

Introduction

Because of advanced developments in circuit and component technologies, the electric circuit becomes more efficient and thus, heat dissipation from an individual transistor is also less as given in Figure 1[1]. Miniaturization of the circuits greatly decreases the size of individual devices and increases the number of circuits integrated on a single chip. The net result is that the chip heat flux (per unit surface area) has significantly increased in the past decades.

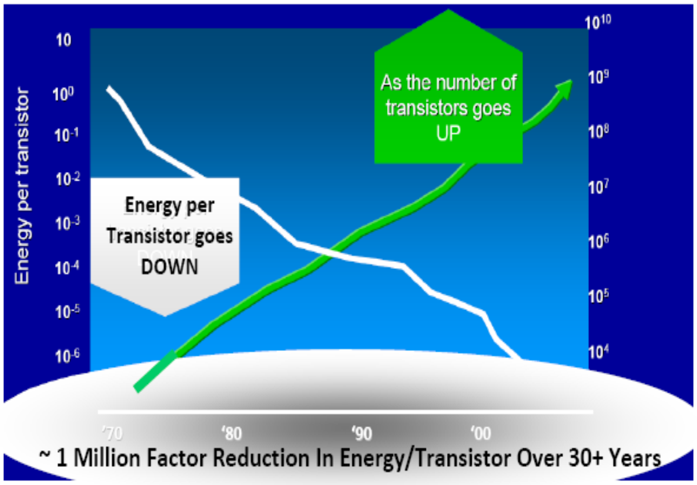


Figure 1 Incredible Performance Improvement of Transistors

The needs to increase the chip package density and reduce signal delay time between communicating circuits have led to develop the multichip modules starting in 1970 and is continued as today. The effect of these trends had on module heat flux for the bipolar and CMOS circuit technologies is presented in Figure 2 [2]. As can been seen in the figure, the heat flux associated with the bipolar circuit technologies steadily increases from the very beginning and has a big jump in the 1980s. Because of this significant increase in the heat flux, it becomes very difficulty to maintain the desired component temperatures and is forced to seek other more energy efficient chip design technologies. One of them is to adopt CMOS based circuit technology in early 1990s which results in significant reduction of chip power dissipation and also makes possible to use totally air cooled systems again. However, as can be seen in Figure 2, the module level heat flux for CMOS based circuit technology for today-systems has also reached to a critical level where new chip design technology may be needed. Until such new chip technologies can be developed, the only solution to resolve any thermal issues is adopting the liquid cooling.

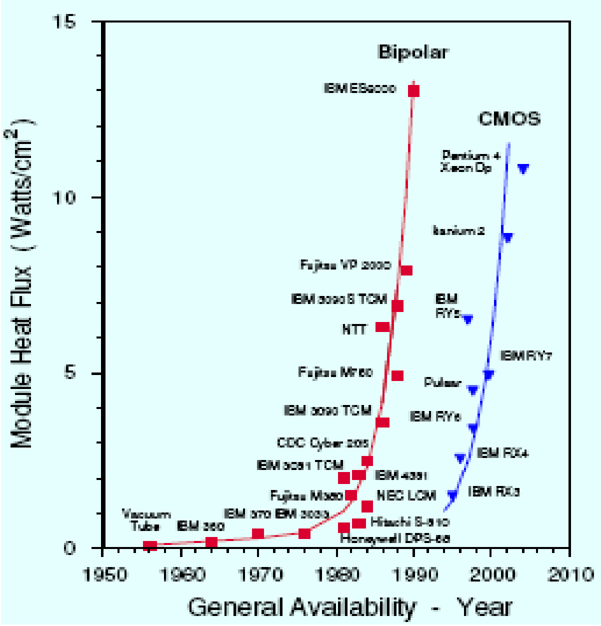


Figure 2 Chronology of Module Level Heat Flux in High-End Computers

Industry Trends of Liquid Cooled Equipment

The purpose of this work is to provide an in-depth review of trends of employing the existing liquid cooling technologies to the commercially available systems in various types of industries

1 Direct Immersion Cooled Chip Packages

The liquid-encapsulated module [3] as shown in Figure 4a was developed by IBM. The circuit board is immersed into a pool of subcooled perfluorinated liquid (FC-86) at 59 ºC. Heat generated by the immersed chips is carried by natural convection from liquid to the finned surfaces of the chamber walls and is then dumped into the ambient through the external air-cooled heat sink or to the water cooled cold plate. Each ship dissipates 4 watts with $\theta_{j\text{-}c}$ of 0.75 ºC/W. With the saturated temperature of 62 °C, the component junction temperature can be maintained at 85 °C. The total system powers are 200 and 300 watts for the external air cooled heat sink and water cooled cold plate, respectively.

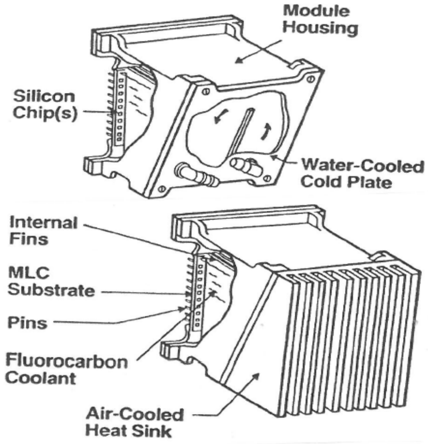


Figure 3 IBM Liquid Encapsulated Module (LEM)

Goodling et al [4,5] employ liquid jet of Freon 12 impinging on the back side a squire 4 x 4 array of silicon chips as shown in Figure 6. One of the problems of direct immersion cooling with liquid coolant is the residual ionic contamination by elements which can damage electronics circuits and cause failure. For example, even the purest form of a refrigerant may contain minute amount of chlorine or fluorine which will attack any exposed aluminum metallization on an IC chip. The separation between the coolant and the active surface of the wafer is achieved by impinging on the back side of wafer. This cooling scheme is very effective because it involves jet impingement boiling heat transfer.

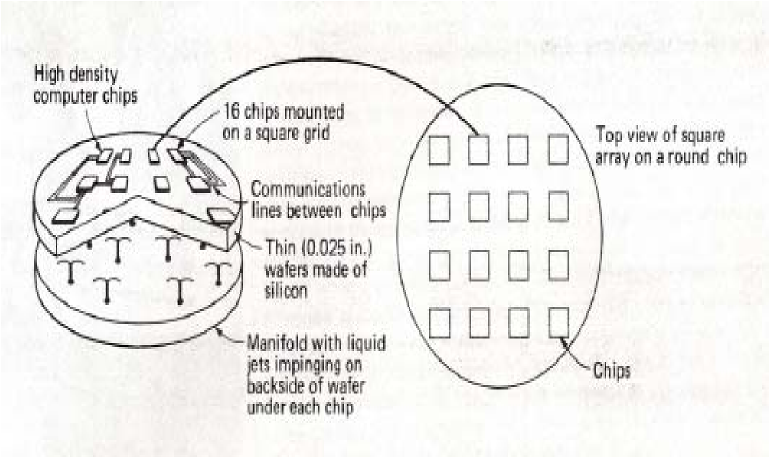


Figure 4 Schematic of Fluid Distribution System on Backside of Wafer

Iversen and Whitaker [6] developed a curved surface semiconductor cooling configuration which utilizes the flow boiling of FC-77 on curved surfaces. The semiconductor chips are mounted on individual units (molybdenum substrate) that bonded to the heat sink with each unit having its own curved heat transfer surface as shown in Figure 5. The curved surface greatly enhances the boiling process and the critical heat flux. With a fluid velocity of 54 cm/sec and a radius of curvature of 3 cm, the system can easily handle a heat flux of 200 watts/cm^2 using a dielectric fluid.

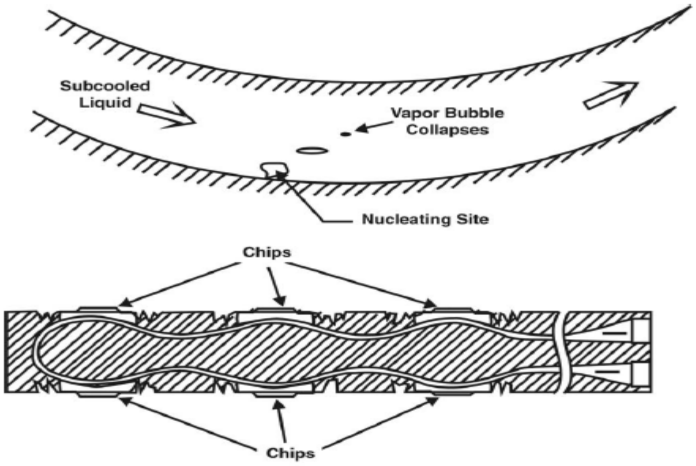


Figure 5 Curved-surface Semiconductor Cooling System

2 Computing Systems

Prior to 1980, the heat flux of the component based on the bipolar technology grows steady and gradually. However the chip power density sharply increases after 1980. It is clear that a more effective cooling scheme becomes necessity. One of most noticed liquid cooled computers in the earlier dates was IBM Thermal Conduction Module (TCM) for as shown in Figure 6 [7]. The first indirect liquid cooled TCM based system is the IBM 3081 which was released in 1980. Heat generated from microelectronics (chips) is conducted through individually spring loaded pistons to the cold plates on the top. The spring load pistons are employed to address the variations of the chip heights due to the manufacturing tolerances. To reduce the thermal contact resistance, air is replaced by helium to fill up the space in the individual piston because helium has a higher value of thermal conductivity. The construction of TCM is extremely complicated and costly. Water cooled TCM chip packaging technology base has evolved over three generations extending into late 1990s and the cooling capability at the chip and module levels has increased three-fold from 19 to 64 W/cm^2 and 3.7 to 11.8 W/cm^2, respectively.

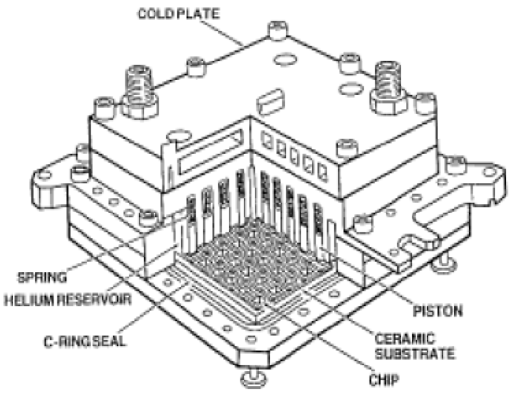


Figure 6 IBM Liquid Cooled Thermal Conduction Module

Liquid jet impingement was employed for cooling a large scale computer (Fujitsu M-780) as given in Figure 7 [8]. As shown in Figure 7, Rcond is the thermal resistance due to conduction from the chip junction to FTC (flexible thermal conductor) heat transfer plate surface, and Rconv is the thermal resistance due to convection (water jet impingement) from the FTC heat transfer plate to the coolant. The total thermal resistance is estimated to be 2.4 °C/W with chip power of 9.5W (336 chips on board). The coolant is supplied by the coolant distribution and control unit (CDCU) as shown in the left side of the figure.

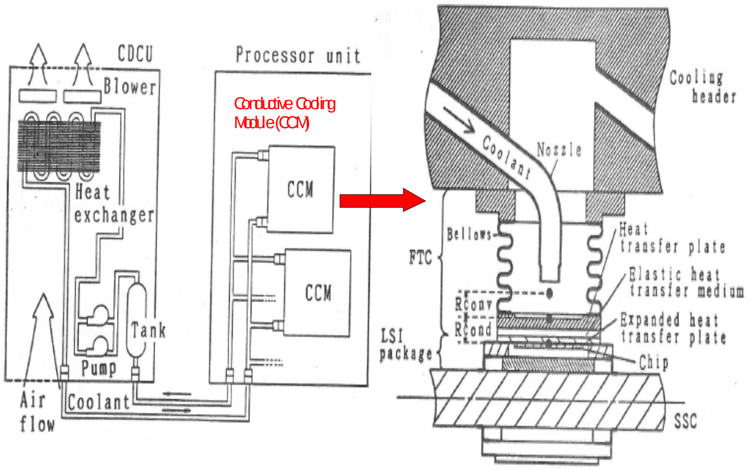


Figure 7 Fujitsu FACOM M-780 Computer

The NEC supercomputer SX-2 as illustrated in Figure 8 [9] employs a high density multi-chip package and a liquid (water) cooling module (LCM) structure which consists of a heat transfer block (HTB), a cold plate and 36 studs placed in machined holes in the HTB to insure good contacts with LSI chip carrier mounted on a multi-layer substrate. The cooling unit as shown on the left of the figure supplies the cooling water to the cold plate of LCM. The average thermal resistance is measured at 3.74 °C/W with the maximum system power of 3000W.

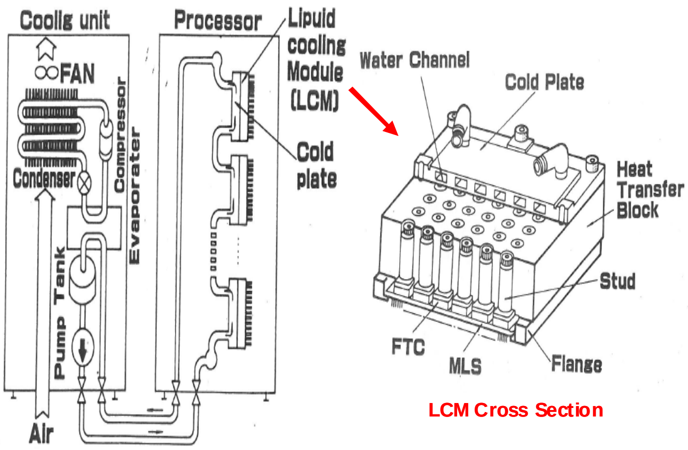
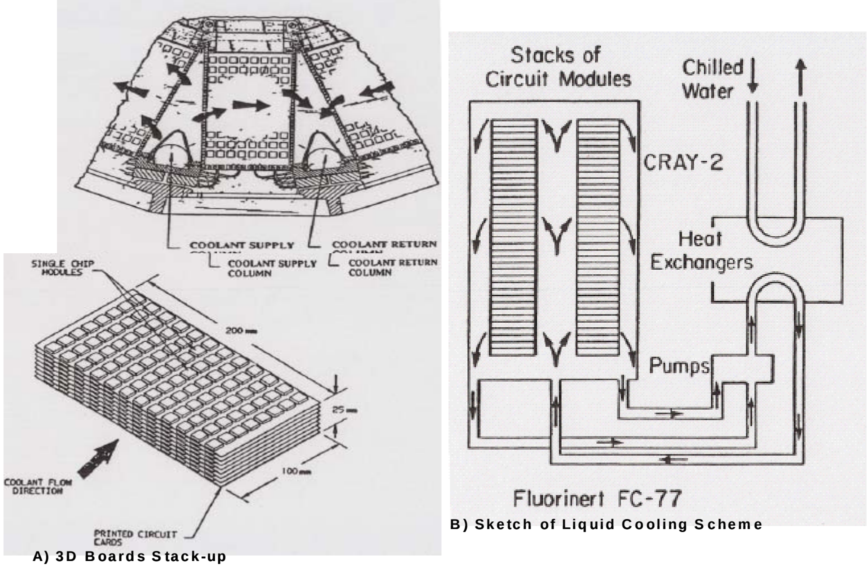


Figure 8 NEC SX-2 Cooling System

The Cray-2 supercomputer as shown in Figure 9 which was released in 1985 employed four vector processors with peak performance at 1.9 GFLOPS. Cray-2 employs direct immersion forced convection with insert Fluorinert liquid (FC-77) over circuitry as shown in Figure 9 [10] to solve the problem of high heat loads resulting from the dense packaging. In addition, it should also be noted that another novel approach is adopted to solve the high dense packaging issue. Instead of making one larger circuit board, so called each card, would instead consist of a 3-D stack of eight, connected together in the middle of the boards using pins sticking up from the surface. The boards are packed right on the top of each other as shown in Part (A) of Figure 9.



B) Sketch of Liquid Cooling Scheme

A) 3D Boards Stack-up

Figure 9 Cray – 2 Direct Immersion with Forced Convection Cooling

The hybrid cooling over the printed circuit boards has recently received considerable attention. In other words, the high power components on the board are cooled by the liquid while the rest components are still cooled by the air. IBM introduced the Power 575 Supercomputing Node as shown in Figure 10 [11]. The node is packaged in a space-dense 2U (88.9 mm) form factor. Users can deploy up to 14 water cooled nodes in a single frame (or rack). Each node includes 16 water-cooled processor modules and other air cooled components such as power supplies, memory modules, input/output assembly, and other supporting electronics. A full configured system is expected to dissipate up to 72 kW. Among them, 58kW (80%) of the total heat load is cooled by water and the remaining 14kW (20%) is cooled by the air. Each node is a modular computer. Any number of nodes can be accommodated in a rack and each one coupled to yet separable from the rack's bulk power and liquid systems.

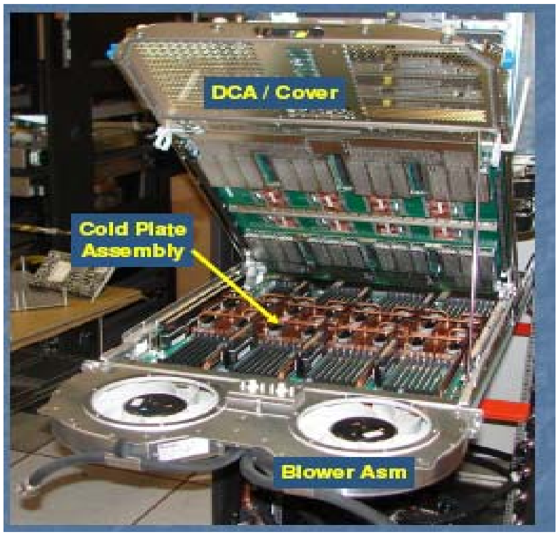


Figure 10 Photo of IBM P575

There are significant advantages and improvement of this system as compared with previous IBM computers. First, there is a 34% increase in processor frequency that results in approximately a 33% increase in the system performance over an air cooled counter part node. Second, the water cooled processor chips are at least 20 ºC cooler than the previous models which leads to better system reliability as well as reduction of gate current leakage and hence better power performance.

IBM Aquasar supercomputer [12] was developed by IBM Zurich Research Laboratory and the first unit was installed at Swiss Federal Institute of Technology (ETH) Zurich in 2010. The Aquasar is the first-of-a kind hot water-cooled supercomputer with water inlet at 60ºC and exit at 65ºC while keeping the junction temperature of the chips below 85ºC.. This innovative system consumes up to 40% less energy than a comparable air-cooled machine and its carbon footprint is reduced by up to 85% and estimated to save up to 30 tons of CO2 per year. The entire system of Aquasar is illustrated in Figure 11 consists of two types of water-cooled IBM BladeCenter servers (33 QS22 and 9 HS22 BladeCenter Servers) plus one air-cooled IBM BladeCenter servicer and achieves a peak performance of ten teraflops and has an energy efficiency of about 450 megaflops per watt. In addition, nine kW of thermal power are used for building heating system. Each water-cooled blade server is equipped with a microscale high performance liqid cold plate per processor as well as input and output pipeline networks and connections which allow each blade to be connected and disconnected easily to the entire system.

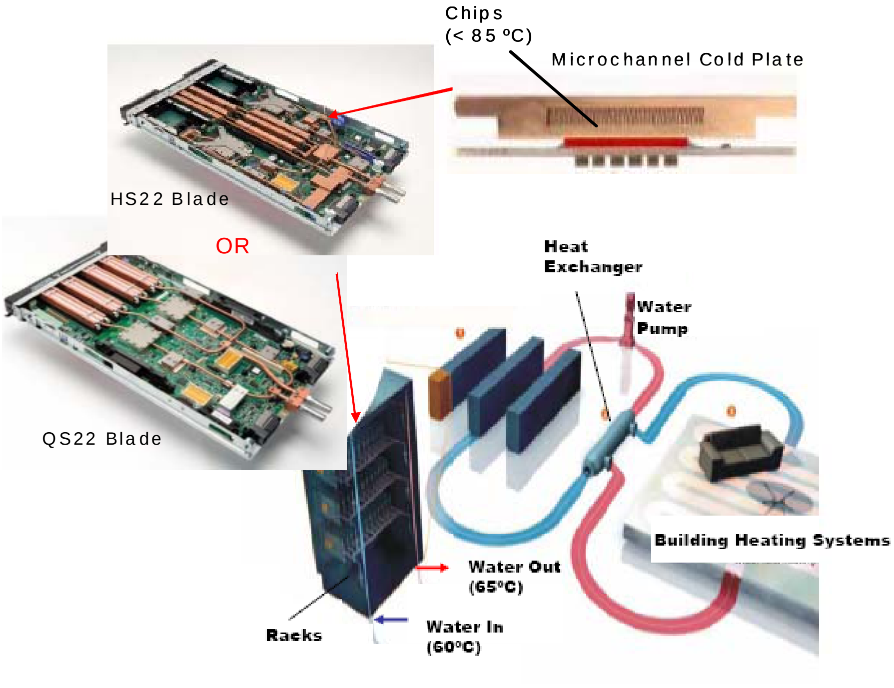


Figure 11 The Entire Water-Cooled System of Aquaras Supercomputer

Each water-cooled blade server is equipped with a microscale high performance liqid cold plate per processor as well as input and output pipeline networks and connections which allow each blade to be connected and disconnected easily to the entire system. The entire cooling system of Aquasar is a closed loop. The total heat load cooled by water is 12.5 kW and the required water flow rate at the inlet temperature of 60 ºC is 15 liter per minute (l/min) with the total system pressure drop of 0.5 bar (7.3 psi).

HP Apollo 8000 supercomputer as shown in Figure 12 was formally released in June of 2014. The HP Apollo 8000 utilizes the room temperature (75 ºF) water for cooling of the servers and hence this system does not have to be in a data center supported by chillers which are energy hungry and expensive. The total heat load of the system is up to 80KW supporting up to 144 severs per rack.

HP utilizes the so –called heat pipe dry disconnect to the servers as given in Figure 12. On the top of each server is a package that contains a series of heap pipes that removes the heat generated from the processors and other components and move it to the side where the thermal bus bar (cold wall) is. The heat is further carried away from the thermal bus bar by the circulating water and then finally hot water exits the system. It should be noted that the water does not enter into the servers' enclosures. This dry disconnection cooling schemes not only able to remove heat from narrow space inside the server by heat pipes to open spaces so that heat can easily be dumped to the water but also prevent any possible water leakage onto electronic components. However, this cooling scheme does pay the price thermally due to the additional thermal resistance at the interfaces (a) between the heat pipes and components and (b) between the heat pipes and the cold walls.

Water enters the system at 75 ºF and leaves at 95 ºF after picking up the heat from the thermal bus bars. The waste heat carried by hot water is then flowing to the building heating systems. The HP Apollo system is designed so that the maintenance on servers can be performed without disrupting any liquid loop.

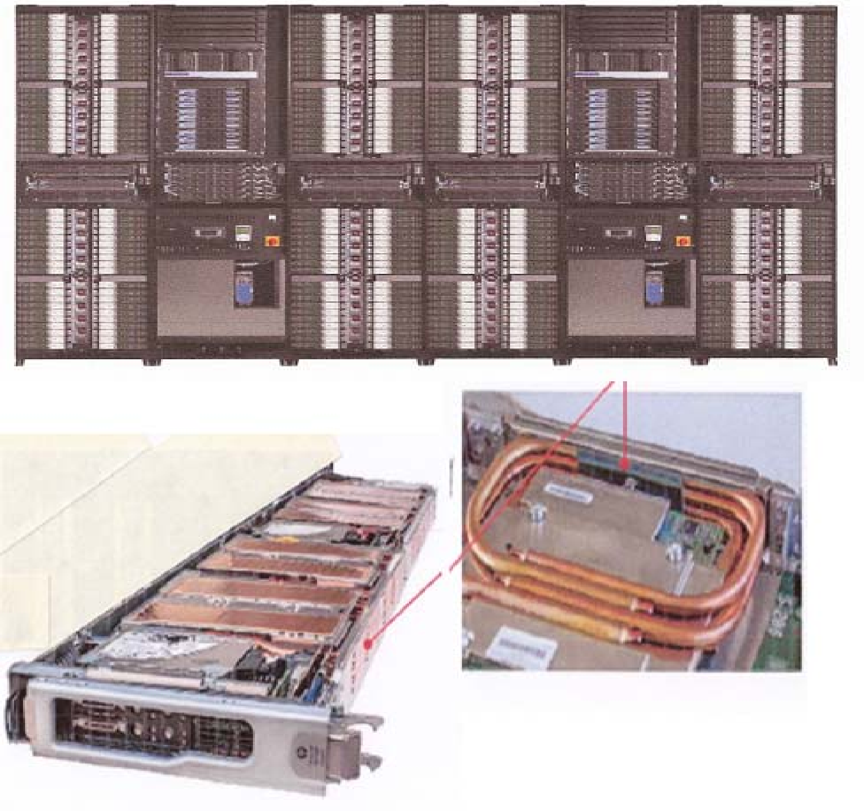


Figure 12 HP Apollo 8000 Super Computer with Heat Pipes

The Fujitsu high-end server GS8900 as shown in Figure 13 was released in 1999 [13]. The system employs a hybrid cooling solution which consists of indirect liquid cooling for high power components such as processor ships and forced air direct cooling for low power components such as other supporting components. The system includes up to totally ten cooling plates mounted on the system board for cooling of every Multiple Chip Modules (MCMs). The power from the MCMs varies from 20 to 300 watts, respectively.

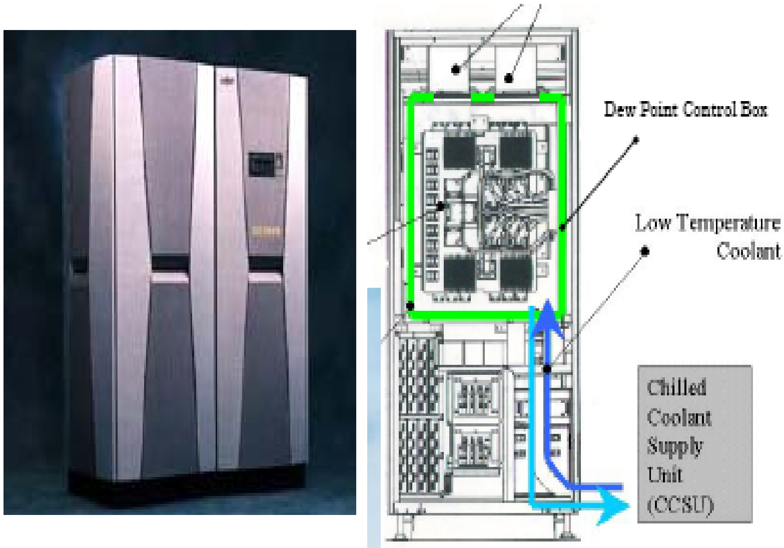


Figure 13 Schematic of Fujitsu Server GS8900 with Water Cooling system

The chilled water with a controlled inlet temperature near 0 ºC is delivered in a closed loop to all cooling modules while cooling redundancy is provided by N+1 refrigeration units and circulating pumps, respectively. Except for the MCMs, memory chips and power supply modules as well as other supporting electronics on the system board are cooled by the forced convection with air flow provided by two stirring fans inside of the dew point control box. The local air is also cooled by the cooling plates to the temperature about 10 ºC which provides an effective cooling to all air cooled components. The refrigeration capacity at the rack level is balanced to the overall heat dissipation inside the server.

This hybrid cooling technology is further extended to the "K-computer", Japan's Next Generation Supercomputer jointly developed by Riken and Fujitsu, as given in Figure 14a [13]. The system includes 24 CPU system boards and 6 I/O systems boards which are densely packaged into 1U form factor in the rack. The schematic of the water cooling loops is illustrated in Figure 14b. As can be seen from the figure, the chilled water is delivered from the rack level supplying manifold to each modular liquid cooled unit (LCU) in parallel and hot water is then collected downstream in a rack level returning manifold. The LCU is attached to high power components of each system board and is connected by the non-spill fluid couplers to the manifolds through flexible hoses so that any system board can be easily removed from the rack without adversely effects on operation of the remaining system.

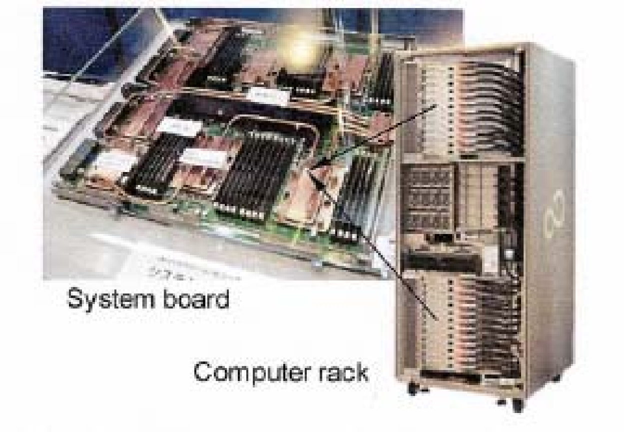


Figure 14a System Board and Computer Rack of K-Supercomputer

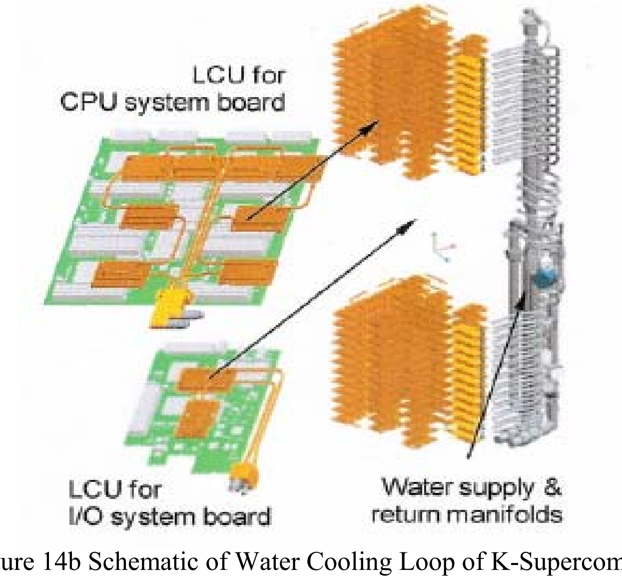


Figure 14b Schematic of Water Cooling Loop of K-Supercomputer

The complete system of the K-Supercomputer consists of 864 racks with the total heat load of 16 MW (18.5 kW per rack). The flow rate to each rack is 40 l/min with corresponding pressure drop of 50 kPa (7.3 psi). The coolant inlet temperature is kept below 18 ºC.

Combining high performance, scalability, and reliability along with superior energy efficiency, Fujitsu supercomputer PRIMEHPC FX-100 [14] as shown in Figure 15 which was released in 2014 further improves Fujitsu's supercomputer technology employed in the K-computer and PRIMEHPC FX-10. The core of the PRIMEHPC FX-100 is the SPARC64 Xlfx processor which can deliver over 1 teraflops peak performance. With the novel 20nm semiconductor process technology, 32 compute cores and 2 assistant cores are integrated into a single processor chip. In addition, the HMC

(Hybrid Memory Cube) is able to expand the memory bandwidth to 480GB/s per node and the one-processor-per-node technology further maximizes memory performance.

The cooling scheme is still based on the hybrid with air and water cooling technology as employed in Fujitsu GS8900 and K-computer. However, FX-100 adopts the so-called "open-loop to facility cooling". In other words, the system utilized the chilled water from the facility for cooling

Figure 15 Fujitsu PRIMEHPC FX-100Supercomputer

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7.3 Other Types of Systems

Bland, Niggemann and Parekh [15] developed a compact high intensity cooler (CHIC) to cool 50 W/cm^2 device for space applications. Therefore, the coolant must not freeze in the system and should also have a low pressure drop to reduce the required pumping power. In addition, the cooler must also be lightweight and compact. The geometry (cross section) of this heat exchanger can not larger than 1 cm x 1 cm square area. The primary coolant in the system is Freon 11. The cooler consists of a stack of thin copper orifice plates and spacers which are bonded together and arranged to provide liquid jet impingement heat transfer on successive plates as shown in Figure 16. There are cutouts on the spacers in the region of the orifices. The hole pattern on alternate orifice plates is offset by half the hole pitch so that jets from orifices are targeted at locations midway between holes on the next orifice plate. This stack is bonded to the base plate which directs the liquid to the drain channels and provides the means by which the heat exchanger is attached to the heat source or device to be cooled.

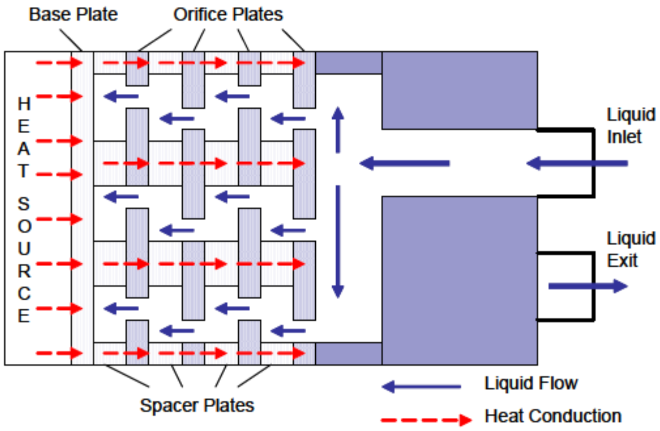


Figure 16 CHIC Heat Exchanger Design Concept

Figure 16 shows the fluid entering through an inlet tube into an inlet plenum where it separates into three streams and passes through orifices in the top plate. The liquid jets impinge on the next orifice plate to remove heat conducted through the spacer plates from the heat sources. Heat is first conducted to the base plate of the cooler and then is conducted through contacting areas between the orifice plates and the space plates and is finally transferred to the coolant from the orifice plates. Heat transfer path is shown by the dashed-line arrows while the flow path is represented by the solid arrows.The liquid from impinging jets then flows transversely into the nearby orifices and impinges on the next orifice plate again. The process is continued until the jets impinge on the base plate of the drain channels. The coolant then flows laterally through the narrow gap inside the outer shell into the drainage slot and out through the fluid outlet tube.

Thermal tests on the wafer thin coolers [16] were performed for the heat flux ranging from 5 to 125 W/cm^2. The primary application of these liquid cooled devices is to remove heat from compact gallium arsenide (GaAs) diode wafers used in laser communications as shown in Figure 17. The tested wafer thin coolers are a double pass microchnnel cooler, two types of single pass microchannel coolers, and two versions of jet impingement coolers such as CHIC mentioned above. In a typical application, GaAs diode wafers are fabricated including 40 to 400 individual diode emitters. For maximum efficiency, all diodes must operate below or near 25 °C with the maximum temperature gradient less than 1 °C

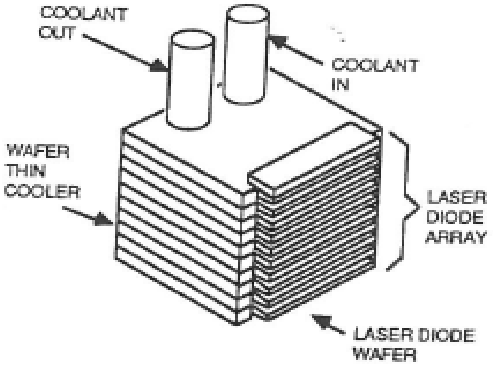


Figure 17 Laser Diode/Cooler Stack

The cooling demands of a semiconductor laser are extreme, particularly for the continuous wave (CW) condition. Some of high power lasers can generate the heat flux exceeding 3000 W/cm^2 even with the laser operating at only 50% efficiency. In addition, both reliability and performance also decrease significantly as the temperature of the devices increases, e.g., operating at elevated temperatures. Mundinger, et al. [17] develop a high performance silicon microchannel heat sink for alser diode array cooling with water as coolant as shown in Figure 18. A thermal resistance of 0.04 ºC cm^2 / W was obtained for a single linear bar. The design utilizes efficient, edge-emitting laser diode arrays in a rack and stack architecture combined with the high performance microchannel heat sink to allow the CW operation. This architecture can be scaled up to large areas with the projected thermal resistance of 0.09 ºC cm^2 / W for close-packed two dimensional array on this device.

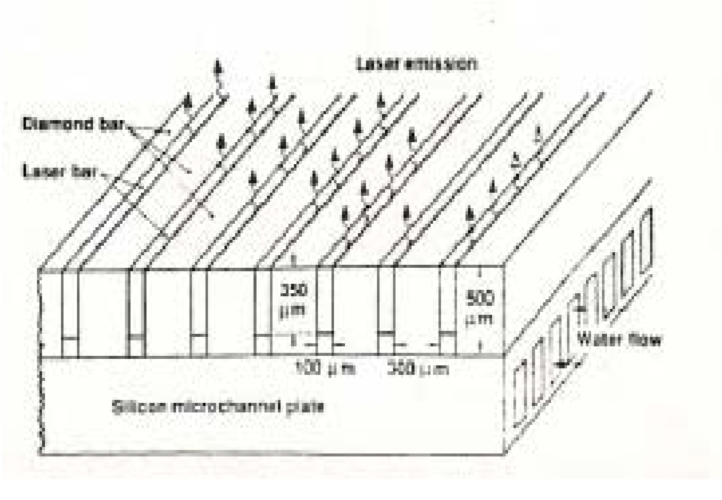


Figure 18 conceptual Design for a Compact high Performance 2D array

Palm and Tengblad [18] adopts a two phase thermosyphon to cool electronics mounted on a vertical PCB in a sub-rack as illustrated in Figure 19. The thermosyphon loop consists of a condenser and three evaporators connected in series by two 3 mm i.d. tubes. The evaporators are made from small rectangular copper blocks with about 2 cm^2 frontal area, and forced convection flow boiling takes place in narrow circular channels (1.1 – 3.5 mm i.d) inside the copper blocks that achieves extremely high heat transfer coefficients (up to 45000 W/m^2- ºC). The condenser is made from a 4 mm thick copper sheet with the size of a PCB (151 x 265 mm). The top section of this copper sheet includes an array of vertical parallel flow channels with square cross section of 2 mm x 2 mm. The measured heat transfer coefficients are higher than the calculated values based on the Nusselt theory. The possible reason for this is the reduction of the condensate film thickness by capillary forces induced by the sharp edges in the corners of channels. The copper sheet is glued to an aluminum heat sink so that the heat generated from components can finally be dumped into the ambient by radiation and free convection

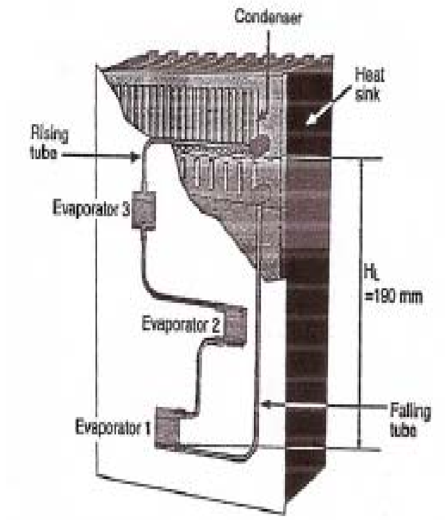
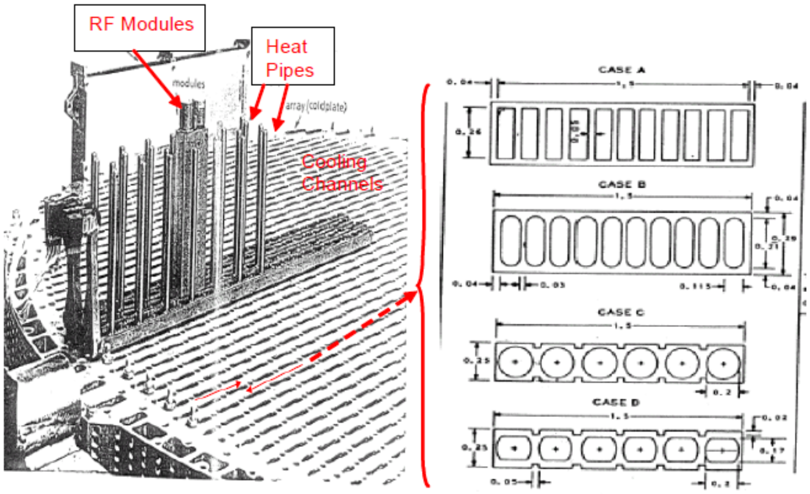


Figure 19 Three Evaporators Thermosyphon for Cooling of Electronics

4. Aerospace and Space Systems

Yeh [19] employed counter flow cooling scheme with dielectric liquid (coolanol-25) to cool microwave modules with a large cold plate as given in Figure 20. Heat generated from modules was transferred by heat pipes to the cold plate consisting of 53 aluminum extruded slats (channels) with fluid flowing in opposite direction in alternating channels. In other words, the heated walls are sandwiched by the fluids flowing in opposite directions. Each heat pipe serves a pair of modules. The total system power is 7.4 KW. The coolant is supplied to the cold plate at 7 gallons per minute (GPM) with pressure of 70 PSIG and a maximum temperature of 46 °C.



Section of Cold Plate with 53 Counter Flow Channels

Subchannels Inside A Single Channel

Figure 20 Liquid Cooled Clod Plate for RF Systems

Once coolant enters supply manifolds, the fluid flows in opposite directions through the adjacent fluid channels and is collected in the discharge manifolds as it leaves the system. The counter flow scheme is selected to reduce the maximum cold plate temperature and also to minimize the temperature difference of the cold plate. Each cold plate slat which is made by the extrusion process includes several subchannels in order to enhance the liquid convection heat transfer of the cold plate by increasing the heat transfer surface. The final solid cold plate which is made by vacuum blaze together of 53 individual cold plate slats is complicated and costly. As presented in Figure 20, various shapes of subchannels in each case (from top, Case A to bottom, Case D) are investigated to meet the following requirements : (1) thermal performance, (2) weight, (3) producibility, (4) structural integrity and (5) cost. The initial design of 10 rectangular subchannels (Case A) is not acceptable because the sharp, square subchannels are not feasible in the extrusion process and Cases B and C are rejected because the wall thickness is too thin. The case with six circle subchannels with diametrically opposite flat sides (top and bottom) is chosen because it meets not only thermal and structure but also manufacturing and weight requirements.

The choice of this particular thermal design scheme is to meet maintenance/service requirement that calls for individual microwave modules to be repaired or replaced onsite in the field. Once the front cover of the array is removed, the heat pipe can be unscrewed from the cold plate and then the module in question can easily be repaired or replaced. Therefore, any thermal solution must take into consideration of maintenance and service requirements.

Yeh [20] employs a different thermal solution to the system which microwave modules are directly mounted to the individual cold plate slats for the similar RF system as mentioned previously. A fully populated system includes a large number of microwave modules that are arranged in 88 columns in an oval shaped enclosure. Each column of modules is cooled and supported by a vacuum brazed aluminum cold plate slat as given Figure 21a through which Coolanol-25 is flowing. Because of a near oval configuration of the array, the number of modules mounted to each cold plate slat varies across the array. An off-set rectangular fin stock with height of 0.04 in is bonded to the channel. The longest and shortest cold plate slats contain 25 and six modules, respectively. All cold plate slats are connected to the supply (inlet) and discharge (outlet) manifolds in the flow distribution headers (FDHs)

The total system power for a fully populated array is 19.43 kW with each module dissipating 11.242 watts. The coolant (Coolanol – 25R) with a flow rate of 4.6 lbm/kW-min (0.55 gal/kW-min) is supplied at 65 psig and 15 ºC to the system. In order to achieve the symmetrical temperature profile over the entire array, a U-shaped flow pattern in every cold plate slat as shown in Figure 21b is adopted. The coolant enters a cold plate slat from the inlet manifold of the FDH flowing to the midpoint of the slat, and then turns 180 degrees forming a U-shaped flow pattern. The returned fluid is collected at the outlet manifold of the FDH. At the interface between the slat and the outlet manifold, an orifice is installed within the slat flange to regulate the flow rates to individual slats, and O-rings are used to provide a fluid seal between the slat and manifold. An offset fin (15 fins per inch) with a height of 0.04 in is bonded to the channel in order to enhance heat transfer.

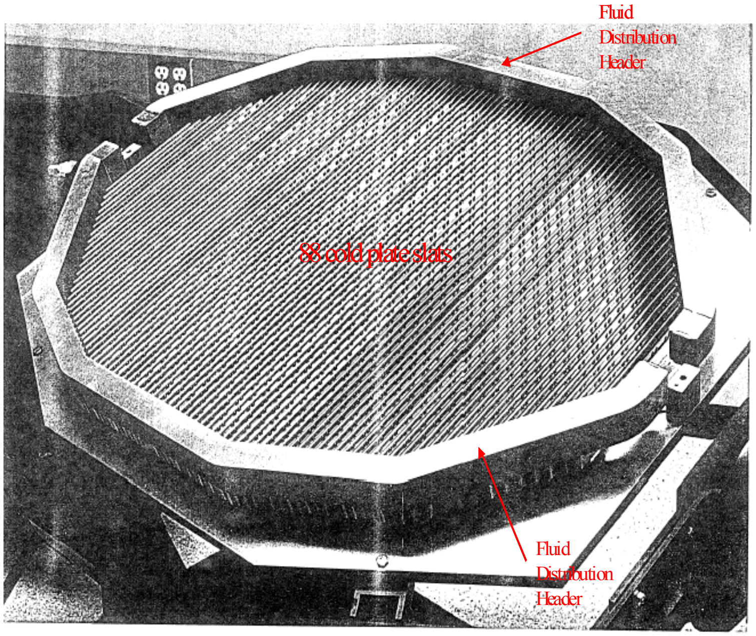


Figure 21a System Thermal Control Unit with 88 Individual Cold Plate Slats

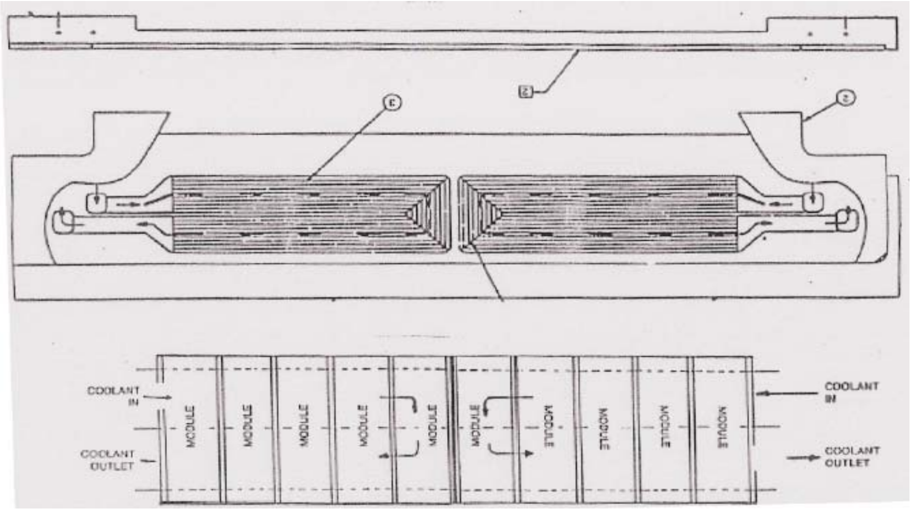


Figure 21b Flow Pattern within Individual Cold Plate Slats

This cooling scheme is much effective as compared with the previous one as shown in Figure 20 in Reference 19 because components are directly mounted on the cold plate slats which significantly reduce the length of thermal path from the component (heat source) to the coolant. However, this cooling method will not allow repairing or replacing any individual module on site in the field as the previous system does. These two examples clearly reveal that the maintenance and repair requirements for any large and complicated system may determine what type of thermal solution is needed.

Porter [21] employs two phase thermosyphon to cool a phased array radar antenna which includes a array of phasers (heat generated components) and 25 embedded tubes within the plate filled with Freon-11 oriented vertically to provide a gravitational liquid return condensate. Each phaser generates a heat flux of 5 W/in^2 to the cold plate. Figure 22 illustrates the system thermal control unit. Due to heating from the phasers, liquid Freon-11 becomes vapor which rises in the evaporator cold plate flowing to the liquid cooled condenser as shown in Figure 22. By the gravity, the liquid condensate flowing inside the tubes is returned to the evaporator cold plate and the cycle is repeated again

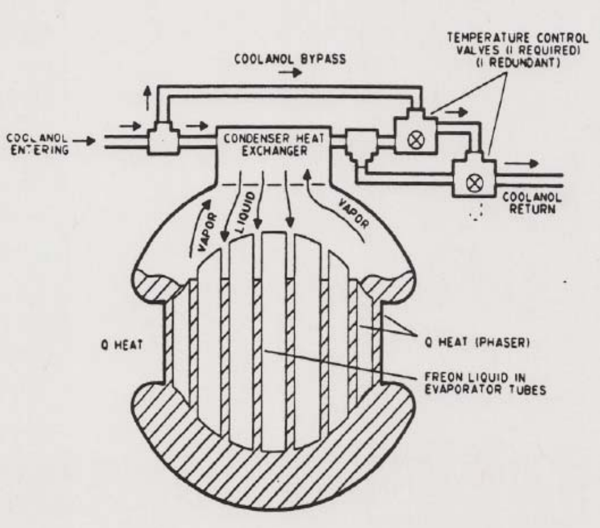


Figure 22 Antenna Temperature Control System

Terminal guidance of hypervelocity interceptors with infrared (IR) seeker, including IR window is often employed to successfully hit the target. A shroud covers the window until the terminal phase of the intercept so that the window is subjected to aerodynamic heating only for a very short time, typically less than 10 seconds. Exposure to an uncooled IR window to high heat flux (up to 500+ W/cm^2) due to aerodynamic heating from hypersonic flights (velocity up to 4 km/sec) results in a rapid increase in temperature. One possible solution to the above problem is to adopt an actively cooling for the IR window. Wojciechowski, et al. {22} utilize integrated internal microchannels with water to cool the diamond film/silicon window as shown in Figure 23. The window is mounted on the interceptor forebody of blunted cone with apex half angle from 5 to 15 degrees. The maximum heat flux on the window is 500 W/cm^2 at unshrouded conditions of 4 km/sec and 25 km altitude. The maximum water flow rate available is 0.4 kg at 305 ºK. Because the single phase unidirectional flow, a significant temperature gradient in the axial direction is generated. The estimated maximum surface temperature and temperature gradient of the window are 415 and 35 ºC, respectively. The large temperature gradient leads to optical aberrations which may exceed the acceptable limits.

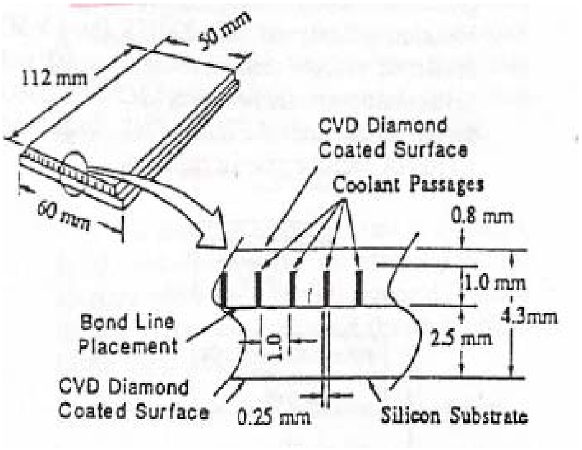


Figure 23 Microchannel Internally Cooled Window

To overcome the axial window temperature gradient as described above, a new actively cooled IR window concept as shown in Figure 24 with two phase convective flow boiling of liquid ammonia is proposed by Burzlaff et al [23]. The two phase flow boiling with liquid ammonia has several advantages : (a) high latent heat of vaporization (greater than 1 kJ/g) yields high cooling capacity with small flow rates), (b) low boiling temperature (lower than 240 ºK at the operation pressure keeps window temperature low and uniform, and (c) low triple point (less than 200 ºK) and reasonable saturation pressure (smaller than 300 psia) simplifies storage and dispensing over the range of environmental temperatures. The coolant is confined to narrow longitudinal channels to minimize obscuration. In addition, pre-cooling of the window prior to shroud deployment insures a uniform low temperature which maximizes thermal conductivity and minimizes IR absorption.

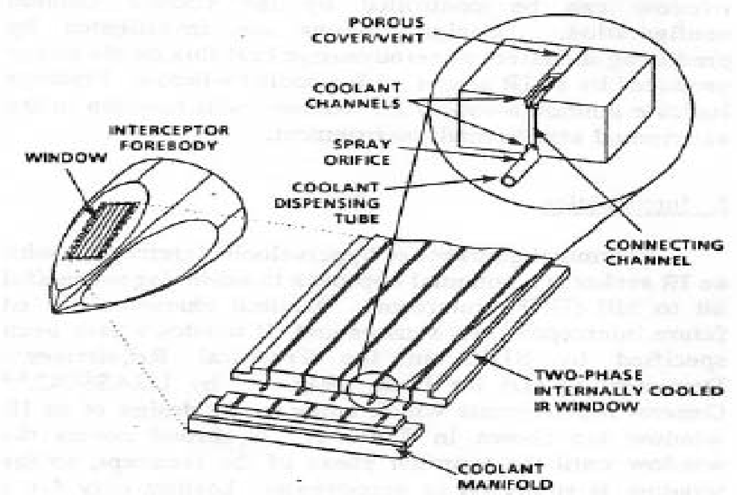


Figure 24 Two Phase Flow Cooled IR Window for a Hypersonic Interceptor

Liquid ammonia at 244 ºK (corresponding to the saturation temperature of 18 psia) is delivered at high pressure to tubes in the lower cooling channels is uniformly dispensed by an array of orifices in the tube as given in Figure 25. These submerged jets impinge at the bottom of the window and also produces turbulent flow to cool the window. Fins within the channels further enhance the heat transfer. The mixture of the vapor and liquid ammonia then flows through the connecting tubes to the identical cooling channels in the upper section of the window. Finally, the vapor and excessive liquid are then exhausted through a porous cover in the upper cooling channels to the ambient. The heat transfer mechanism is the forced convective flow boiling which is so effective that it not only reduces the temperature but also maintains a relatively uniform temperature over the window.

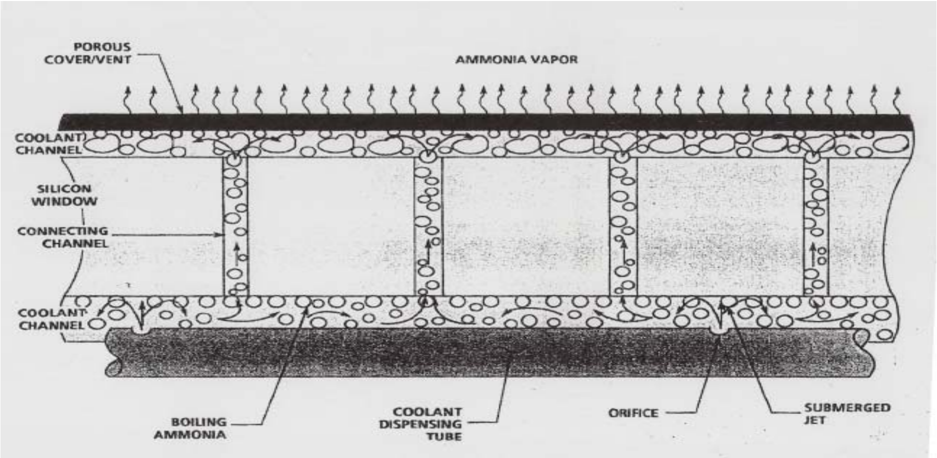


Figure 25 Cross Section View of Flow Patterns for Window Coolant Channels

Summary and Conclusion

The purpose of this work is to provide an in-depth review of trends of employing the existing liquid cooling technologies to the commercially available systems in various types of industries. For any forced convection system, the pressure drop is as important as the heat transfer. A high pressure drop system will require a large pump which not only consumes more power but also is heavy and costly. Generally high heat transfer coefficient always accompanies by the high pressure drop. In addition, the general system thermal design guidelines for liquid cooled equipment are presented as follows:

1. A good system design must have a good balance between the heat transfer and the pressure drop. Therefore, the goal of system thermal design is to maximize heat transfer and to minimize pressure drop.
2. Because of its superior thermal properties, water has long been the best working fluid for the computing systems, including the most of advanced supercomputers. However, water can not be used in a direct immersion cooling and nor for outdoor applications. The former is due to its poor dielectric properties and the later is because of its high freezing point. Water also must be properly treated for anti-corrosive and anti-fungal prior to being used in any cooling systems. For material compatibility, copper must be used for the entire liquid loop if water is adopted as the coolant. On the other hand, aluminum can be employed for all dielectric fluids. De-ionized water which is often used as coolant is compatible with stainless steel. All above three types of materials (copper, aluminum, and stainless steel) are compatible with Ethylene Glycols. In short, the coolants must be chemically compatible with the materials which they will contact within the entire coolant loop and from leakage.
3. The hybrid cooling scheme which employs liquid cooling to high power components while using air cooling for the rest of components on the board is pretty much standard cooling method for the today super computers. The possibility of condensation in the system becomes a major concern in the industry. Therefore, this issue must be resolved in the system design.
4. While the primary attention in the design of any liquid cooled electronic systems is focusing at the cooling areas, consideration must also be given to the practical design aspects that include the maintenance and service requirements of the equipment. Generally, system designs should be as simple as possible with easy access to the internal parts of the system. In addition, another requirement is that system should minimize the needs to drain the coolant in a large scale during the service. Furthermore, as illustrated in Figures 20 and 21, the thermal solutions must take into consideration of the maintenance and service requirements of the system, especially for those complex systems.

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