20. Cooling Techniques for High Density Electronics (2)

20.1 Direct Impingement Cooling

In this method, components are cooled directly by blowing the coolant (such air). Flow channels are developed in the equipment design exposing heat generated components to the moving cooling air mass, Figure 20.1 This heat removal method develops low component-to-air temperature differences since the components are directly exposed to the thermal sink.

Component spacing and distribution become a prime design factor in order to assure proper cooling of all components in the flow channel. Coolant routing and the flow channel configuration must asst that sufficient cooling is directed and distributed over high heat generating devices. A flow system of this nature usually develops large flow losses due to viscous drag, and turbulence. This condition necessitates balancing of the pressure losses in different flow branches to assure adequate cooling throughout the equipment.

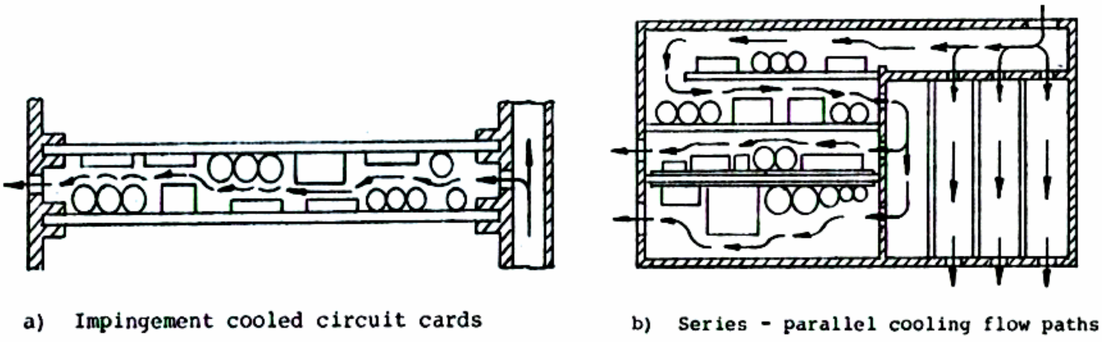


Figure 20.1 Direct impingement cooling

Hot spots on component boards or other assemblies due to concentrations of heat generating sources result in an uneven distribution of heat which increases the difficulty of obtaining effective cooling. Variations in component size and shape add an additional degree of complexity; Figure 20.1 In general, smaller parts experience lower case-to-coolant temperature differences due to end effects which increase its conductance. When determining on conductance as a result of flow directly over components, one should include the actual surface area of the parts.

Coolant temperature must also be accounted for. Variations in coolant temperature along surfaces of heat producing parts are a consequence of the duct configuration and component spacing at the location of interest. For this reason, hot spots within a given flow configuration determine the flow requirements for that branch. This approach generally results in conservative operating temperatures for low-heat generating components on the same assembly.

Airborne applications require consideration of varying air densities and flow losses due to changes in altitude. Air that cools airborne equipment can become moisture laden and m transport vehicle-associated contaminants which can cause intermittent performance or short-circuit printed circuit boards and connector interfaces. Exposed surfaces and components should be protectively coated to minimize the effects of moisture and other airborne contaminants.

<u>The process of developing impingement cooled equipment requires</u>

- Determination and description of heat generating components.
- Definition of the allowable maximum temperature for different classes of circuits or components used.
- Selection of candidate flow paths accounting for equipment configuration, interfaces and assembly arrangement in terms of generated heat distribution, coolant temperature rise and allowable component temperatures.
- Determination of low rates and pressure losses along each flow path
- Determination of component operating temperatures and equipment cooling requirements, e.g. inlet air temperature, flow rate and flow loss.

20.2 Jet Impingement Cooling

Jet impingement and microchannel cooling are two methods presently under investigation. Jet impingement cooling of microelectronic chips is accomplished by passing a coolant through a capillary tube or orifice aimed at the surface to be cooled. A typical arrangement is shown in Figure 20.2. A liquid under pressure in the chamber is allowed to pass through an orifice plate and directly onto the microchip component. Shown in the figure is a leadless chip carrier attached to a substrate through a series of solder bump joints. The dielectric coolant strikes the chip and absorbs its heat dissipation. The development model shown is not representative of a system in production. However, in addition to microchip cooling, there are applications in electronics which utilize spray cooling or direct impingement cooling of component surfaces. One such application is a variable- speed constant-frequency (VSCF) generator for use aboard commercial and military air craft. The dielectric coolant in this case passes through small-orifice jets aimed directly at high heat dissipators, mostly diodes, and power transistor assemblies located within a partially filled liquid reservoir. Since these units are exposed to wide temperature extremes, the coolant flow at low temperature through the nozzles is much reduced, and this reduction must be taken into account in the thermal design. The oil that cools the electronic components also cools the generator and stator. There are two modes of operation possible with liquid jet impingement single-phase and two-phase cooling. In addition, the jet can be free or submerged.

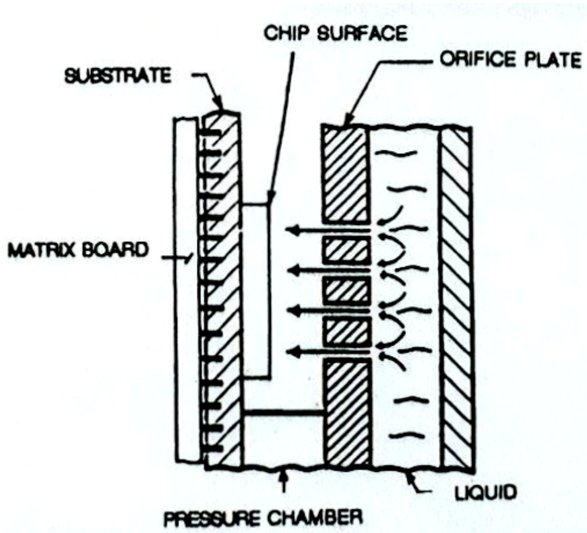


Figure 20.2 Jet impingement configurations

In the submerged case the cavity is filled with the coolant while in the free mode, as shown in Figure 20.2, the liquid jet is exposed to a gaseous environment. The most efficient heat transfer takes place in the free liquid impingement case when the cooling mode is a combination of boiling and free convection. Ma and Berg have reported experiments with Freon R- 113 where up to 100 W/cm^2 over a small chip surface (0.2 by 0.2 in) was cooled using jet impingement boiling.

These experiments and others have found that significant improvements in heat transfer are possible with jet impingement above that normally encountered in the boiling mode alone for immersed components. The combination of loca1 boiling and forced convection leads to an extension of the critical heat flux for Freon R-l 13 beyond the 20- to 40-W/cm^2 free zone to 70 W/cm^2 with jet impingement under saturated liquid conditions, to as high as 100 W/cm^2 when the liquid is subcooled. As in boiling alone, the surface condition and coolant in contact are important parameters in determining the heat transfer. The advancement of wafer scale integration (WSI) with its packaging and electrical advantages may well result in the initial development of novel jet impingement techniques for IC cooling implementation into hardware.

The design of this type of system must take into account the ultimate heat- sink or boiling-point temperature of the jet coolant and the heat-path resistance from chip to sink. Goodling et al. report on the use of Freon-12 and Freon-22 operating below room temperature with jet impingement on the backside of 4.0-in water. Their tests reveal flux densities of 100 W/cm^2 and higher as the critical heat flux. However, despite this and other reported progress, future implementation into a production system using ICs will require compatibility tests to verify the coolant stability in contact with the electronic enclosure and the chip surface overlong periods. These same experimenters found that th temperature overshoot in boiling could be much reduced using jet impingement as com pared to the normal free saturation boiling mode. In the jet impingement experiments reported to date small high-velocity jets of fewer than 50 ft/s are directed to the backside of chip surfaces for local heat removal; present experimentation has been done mostly with dielectric liquid fluorocarbons and with freons and water. The options in this type of cooling include free jet versus submerged jet, type of coolant, spacing of the jets, and the distribution of liquid to large array surfaces.

20.3 Impingement Cooling Thermal Analysis

Single-phase free jet impingement cooling is influenced by many variables, such as jet diameter d, velocity V, number of jets n ,per source, jet-to-source distance x, jet configuration, size of heat source area $\ell \times \ell$ and coolant properties. Based on the single-phase free jet tests, the correlation data for FC-77 and water were found to agree well with following Equation 20.1, for jet distances to the heat source falling within the limits of 3 <x/d<15.

$$\bar{N}_u = 3.84 R_e^{0.5} P_r^{0.33}\left(0.008\frac{\ell}{d_h} + 1\right) \qquad (20.1)$$

Their tests were for nozzle diameters d_h of 0.020 to 0.040 in and jet velocities of under 50 ft/s. The foregoing Equation 20.1 holds true for small surface dimensions of $\ell < 0.5$ in, which in most cases is typical of microelectronic devices. Larger surfaces with multijet impingement can also be analyzed provided the number of jets per unit heat source area is comparable with the test conditions specified.

A large increase in heat transfer is possible with jet impingement boiling where the dependence on surface condition and fluid in contact is most important. In the case of submerged jet cooling on small surfaces, Ma and Bergles report significant increases in the critical heat flux or burnout as compared to the same surfaces when exposed to immersion boiling alone. They found that the pool boiling curve is coincident with the jet boiling curve and can in fact be extrapolated to values of critical heat flux for jet impingement boiling on the order of five times the pool boiling values. Not all experimenters report similar results. At the present time there are no generalized equations defining jet boiling for either submerged or free conditions. In the case of non boiling jet impingement in a submerged liquid, the stagnation-point Nusselt number within the potential core correlatable to within 10 percent is in accordance with the following equation

$$N_u = 1.29 R_e^{0.5} P_r^{0.4} \qquad (20.2)$$

A comparison of the submerged Nusselt number at stagnation (Equation 20.2) with the free jet Nusselt number (Equation 20.1) for average conditions on small areas indicates a 3:1 improvement in these single-phase heat transfer cases.

20.4 Hybrid Cooling

This simply implies a combination of liquid and air cooling for high power dissipation electronics, while minimizing contact resistance throughout the system. In this process, the avionics industry has made great strides and produced cooling systems capable of removing high heat fluxes. Figure 20.3 shows one such system.

Figure 20.3a, on the lift shows a rack/card guide system where the liquid is flowing through the card rack. The heat that is generated within the PCB is conduction through the solid core to the rack where the liquid is used as the transport vehicle to remove it from the system. The illustration on the right in Figure 20.3a shows a thru-card scheme where the PCB core is chambered for fluid passage. Thus the conduction heat transfer from the PCB to the rack, as shown in the figure on the right, is eliminated.

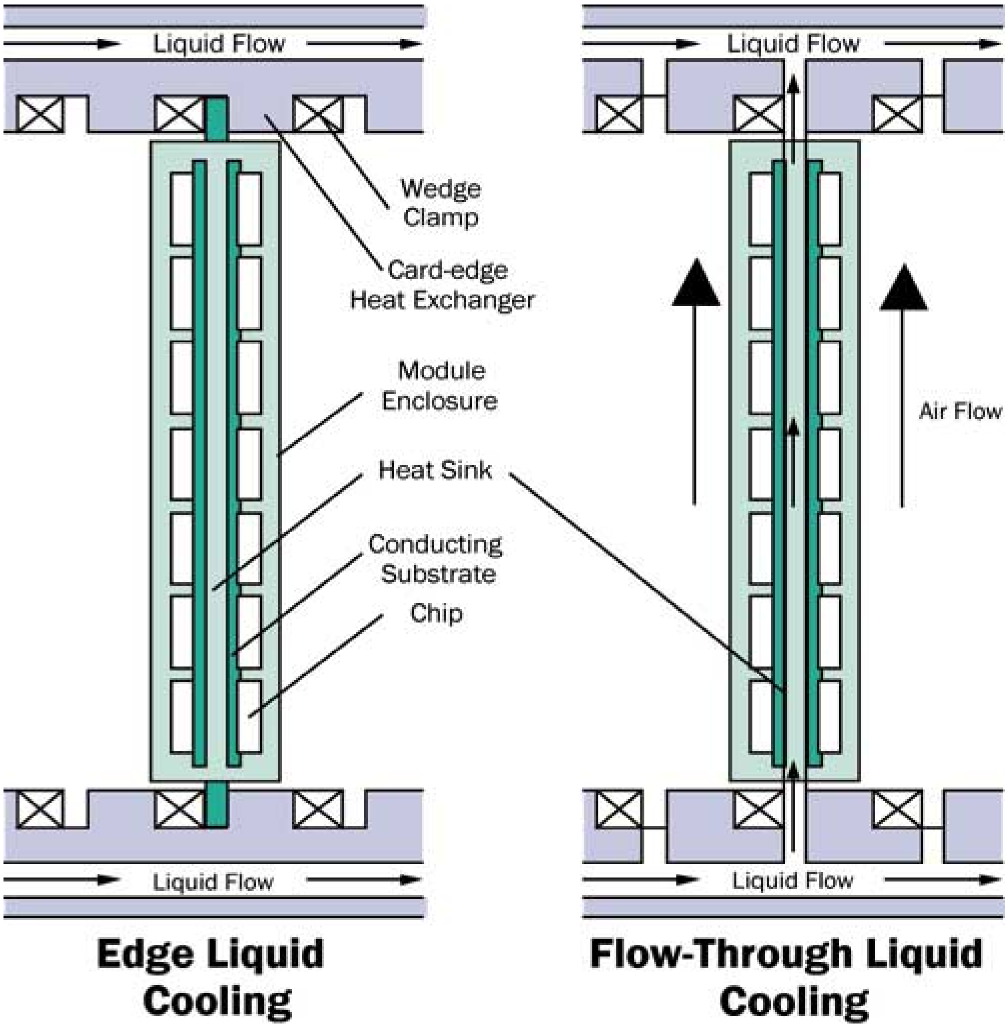


Figure 20.3a.Two hybrid systems for an avionics application: On the left, edge liquid cooling; on the right, thru-card liquid cooling

Figure 20.3b shows the extensive packaging required to make such systems happen. Tightly sealed joints and mechanical contacts with least resistance are required to attain the level of thermal performance required for such a cooling option.

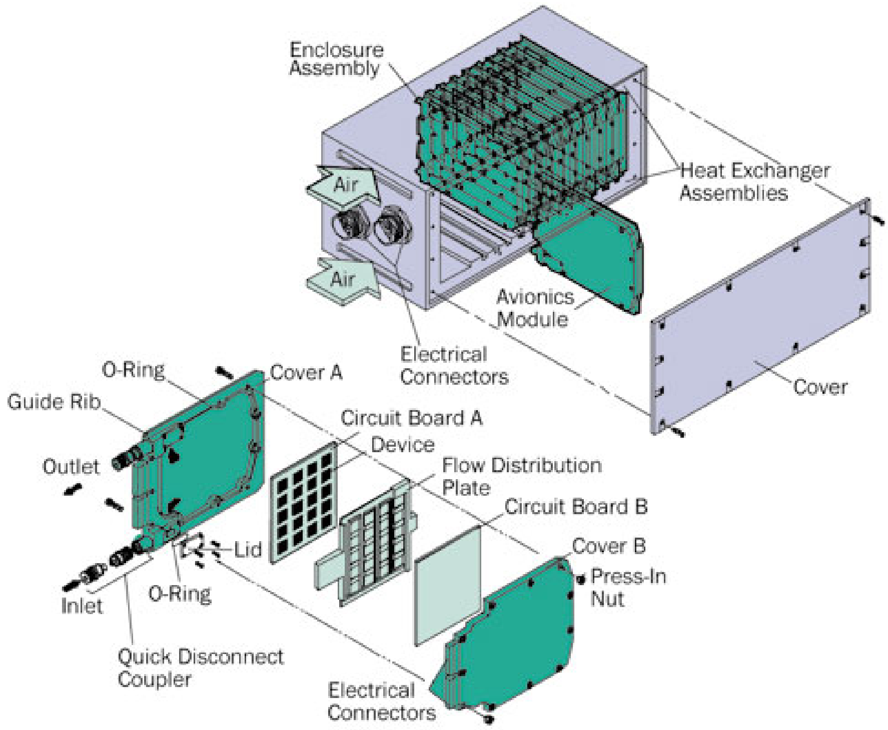


Figure20.3b Card and rack level packaging required for hybrid cooling

Although I have purposefully avoided the discussion of cooling capacity, the exception to the path may be merited here since these systems are not commonly encountered nor discussed in the open literature. Therefore, Figure 20.4 shows the removal capabilities of the hybrid systems for different cooling arrangements.

The data depicted in Figure 20.4 clearly show the advantage of, say, subcooled jet impingement and a conventional cooled system, approximately a factor of 13 However, one cannot overlook the packaging requirements to deliver such a cooling solution, as shown in Figure 20.3b. The cost of these requirements and the attainment of a high reliability cooling system may not make these systems suitable for typical commercially available electronics.

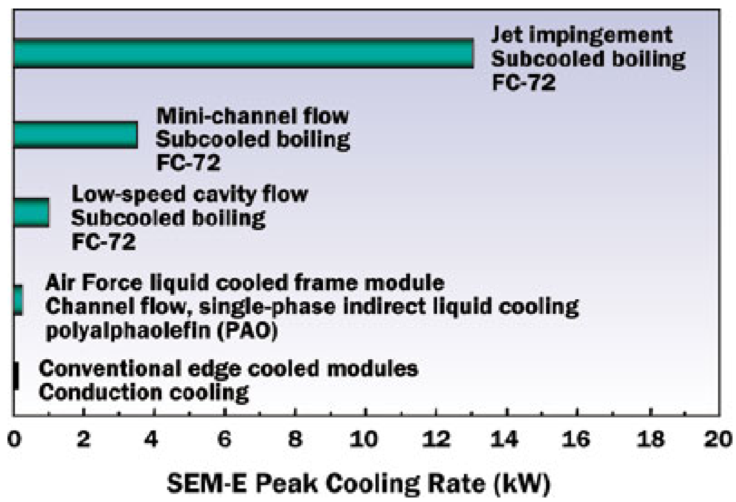


Figure 20.4 Heat removal capacity for different hybrid system as compared with a convection cooled system

20.5 Vapor Compression Cooling for High Performance Applications

Introduction

This is a relative newcomer to the electronics industry. Vapor compression refrigeration is being adapted to cool computer and telecommunications equipment in a limited number of high performance applications. Vapor compression can lift large heat loads and can heat sink at below ambient temperatures. Cold plates can offset high case-to-junction temperature gradients to keep high power integrated circuits from overheating and/or can lower junction temperatures for enhanced integrated circuit performance.

As a method of enhancing computer performance, below ambient cooling has been actively researched since the 1960's. Today's mainstream semiconductor technology, CMOS, has been repeatedly characterized at low temperatures. Multiple performance enhancing reasons exist to cool CMOS (complementary metal oxide semiconductor) devices to very low temperatures. The challenge is to do so reliably and cost-effectively.

Although early (1960-1980) cold electronics development programs targeted 77K or lower temperatures, a moderate approach to low temperature computing has gained momentum in recent years. Vapor compression cooling technology is employed to chill components to a minimum temperature of 233K (-40 ^{o}C) for two good reasons.

First, reliable, relatively inexpensive vapor compression systems can lift high heat loads at this temperature. Second, 233K presents less significant electronic packaging problems to be overcome than does operation at 77K.

Mechanically Assisted Cooling Benefits

High power electronic systems are testing the limits of traditional cooling methods. Effective heat removal is required to keep silicon junction temperatures below critical temperatures at which devices will fail to operate correctly. Natural convection or forced air cooling is proving to be insufficient in an increasing number of applications. Mechanically assisted cooling can meet these needs, but must do so at acceptable costs. Vapor compression cooling of specific, high performance applications can provide favorable cost/benefit ratios.

Mechanically assisted cooling subsystems are said to provide "active cooling" since they require energy. Some mechanically assisted cooling subsystems reduce the heat sink surface temperature below ambient air temperature. It is convenient to refer to a heat sink that operates at below ambient temperatures as a cold plate.

Key attributes of the cooling subsystem include its efficiency, its operating temperature and its cooling capacity. The subsystem's efficiency can be specified as its Coefficient of Performance (COP), or the amount of heat it can move divided by the power the subsystem consumes to move that heat.

The most common cold plate technologies for high performance cooling are currently thermoelectric devices, chilled fluid loops and vapor compression refrigeration.

Vapor Compression Refrigeration

Vapor compression refrigeration offers several important advantages. These include low mass flow rate, high COP, low cold plate temperatures and the ability to transport heat away from its source. The following is a more detailed look at vapor compression refrigeration of high performance electronics.

Figure 20.5 is a schematic representation of the vapor compression cycle. At the top of the loop, heat is introduced to the system by the device being cooled. This heat vaporizes liquid refrigerant in the evaporative cold plate. This vapor is subsequently carried through the suction tube to the compressor. Work is supplied to compress the warm vapor into a hot, high-pressure vapor that is passed to the condenser.

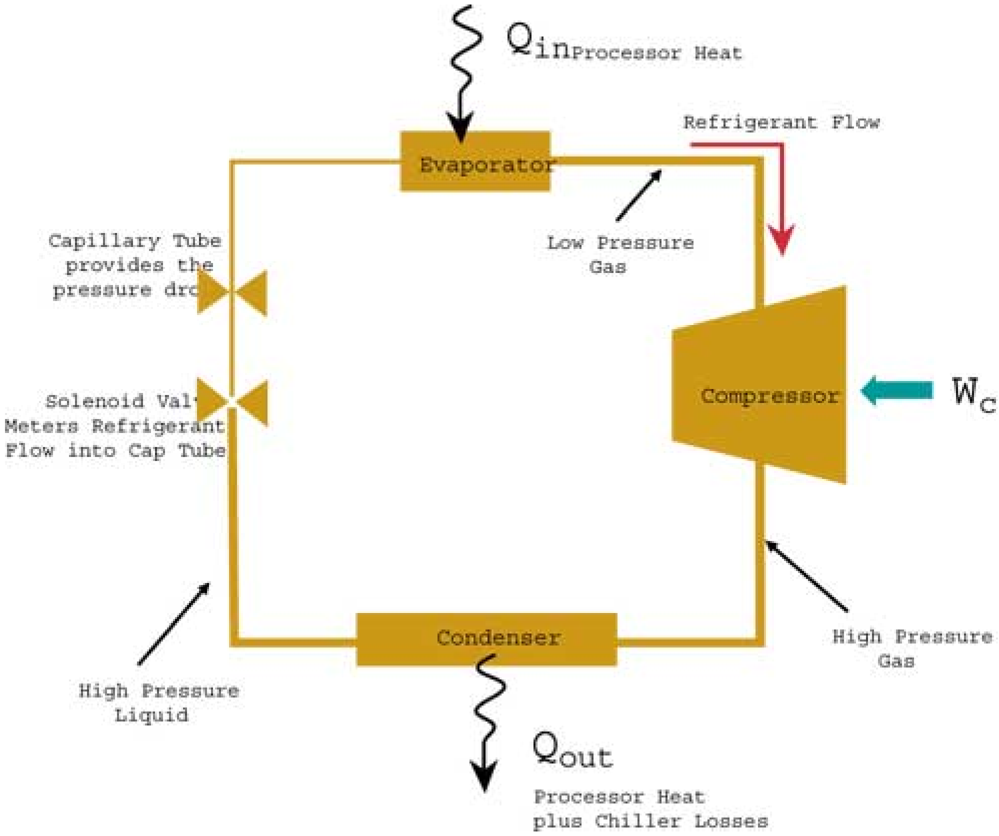


Figure 20.5 Refrigeration cycle schematic

The hot high-pressure vapor releases its heat to the air stream across the condenser fins as it condenses into a warm liquid. Warm liquid is pumped from the bottom of the condenser through an expansion device where its pressure and temperature drop significantly, creating the refrigeration effect. The cycle completes as the cold fluid passes to the cold plate.

The cycle depicted in Figure 20.5 offers several advantages for electronic cooling applications. Vapor compression systems can reject heat far from the source by separating the evaporator and condenser in a so-called "split system". Vapor compression refrigeration transports large quantities of heat with a small mass of circulating fluid.

Vapor compression operates at a COP approximately three times that of thermoelectric devices in a similar application. Vapor compression can produce -40 ^{o}C cold plate temperatures using common food storage and cooling refrigerants.

Refrigerant Fluids

The refrigerant physical properties and operating pressures determine its evaporating temperature and its capacity to transport heat. A wide variety of vapor compression refrigerant fluids are commercially available. Water, alcohol, butane, and ammonia are among the list of well studied refrigerant fluids.
Operating pressure range, heat capacity, atmospheric disruption potential, explosion hazard and corrosion potential make some fluids inappropriate for some applications. R-134a and R-404a are common refrigerants currently in use in high power electronics cooling applications.

Heat Capacity and Heat of Vaporization

When bounded systems of gases, liquids or solids absorb heat they must either increase in temperature or change their physical state. For example, the temperature of a gram of water will increase one degree centigrade when it absorbs one calorie of heat. Similarly, at a given pressure and temperature, one gram of water will absorb nearly 540 calories of heat without temperature increase as it changes from a liquid to a gaseous state.

This characteristic amount of heat absorbed during a state change is referred to as a material's heat of vaporization. Vapor compression refrigeration employs the refrigerating fluid's heat of vaporization. Practically this allows a small fluid mass to transport a relatively large amount of heat.

Temperature of Vaporization

Just as water turns to steam (water vapor) at 100 ^{o}C at atmospheric pressure, a given refrigerant will vaporize at a specific temperature at a given pressure. The pressure vs. temperature characteristic curve determines the lowest practical operating limit of a particular refrigerant. Figure 20.6 shows the pressure-temperature characteristic curves for the commercial refrigerant R-404a. Low cold plate temperatures can be used to offset the temperature rise that occurs at the interface between a cold plate and its load device or to lower the operating temperature of the load device.

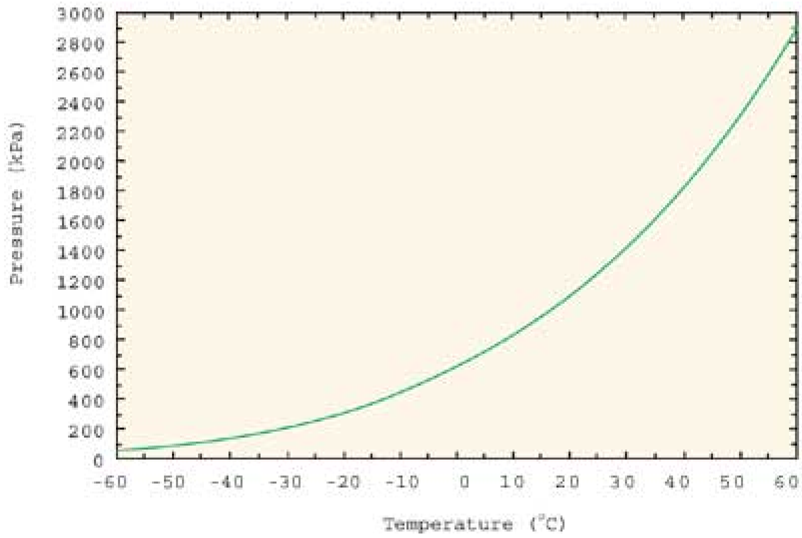


Figure 20.6 PT curve for R-404a

Benefits of Sub-Ambient Cooling

CMOS technology has scaled predictably since the early 1970's. Smaller features allow more circuit elements, such as transistors, to be interconnected on a single silicon chip. Smaller transistors switch on and off faster. As CMOS scales from generation to generation, faster and more functionally rich chips are produced.

Continued improvement in wafer and device fabrication has encouraged development of physically larger chips. Larger chips containing more transistors operating at higher frequencies dissipate more power. Large quantities of heat must be removed from the integrated circuit surface to ensure that junction temperatures remain below critical temperatures. High power chips may require below ambient cold plate temperatures to ensure that device junctions be maintained at below their critical temperatures. Sub-ambient cooling can also allow CMOS transistors to switch on and off faster.

Vapor Compression Application Issues

Application of vapor compression to electronic cooling requires careful engineering. The cold plate must efficiently lift heat from the device being cooled. Cold surfaces cannot be allowed to collect condensate from the surrounding air. Refrigerant tubing must be incorporated into the physical design to supply and remove refrigerant. The compressor and condenser unit must be integrated into the physical design. The entire solution must be cost effective and reliable.

Cold plate design must assure efficient thermal transfer from the device being cooled to the refrigerant stream inside the cold plate. Flat and smooth interface surfaces are generally required. The cold plate is fabricated from a thermally conductive material with thin wall design to shorten the thermal path from the target to the refrigerant. The cold plate internal design optimizes heat transfer. Surface texture and refrigerant path length are increased within the limits of an acceptable pressure drop between the inlet and outlet of the evaporative cold plate.

Water, a hazard to electronic assemblies, condenses on exposed surfaces at or below dew point temperatures. This issue extends to all exposed cold area of the refrigerant path. Cold surfaces must be insulated from and sealed against moisture-laden air to avoid hazardous condensation.

Vapor compression applications are typically closed loop. Refrigerant is recirculated around the loop indefinitely. This requires that refrigerant tubing be routed within the electronic assembly to connect the evaporative cold plate to the compressor/condenser assembly. Clever design is required to minimize the impact of this particular "issue".

The "cooling engine" must be integrated into or otherwise accommodated in the physical design. Vapor compressors have not been designed for aesthetics. They are typically hidden in the bottom of refrigerators and water fountains. Industrial design or styling must be considered. Compressors are heavy, consume power and radiate noise. Table 20.1 provides size, weight and capacity information for typical modern compressors A and B along with parameters for a technically feasible but unavailable mini-compressor.

All of the application issues discussed must be considered during the physical design stage of a system if vapor compression cooling is to be effectively integrated. An example of such a system is shown in Figure 20.7.

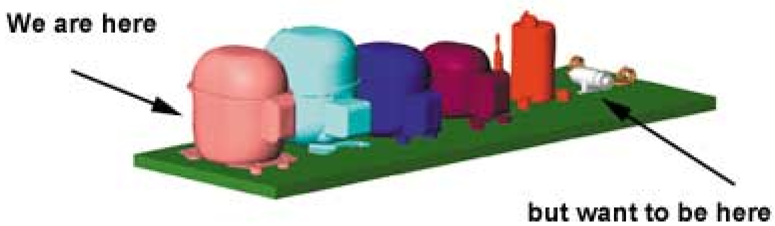
Figure20.7 Vapor compression cooling for Super G™ Computer

Reliability at 233K

Low temperature operation results in a blend of hazards and benefits. Hazards include electro-mechanical failure due to material or thermal coefficient of expansion mismatches or electronic failure due to hot carrier effects. Only materials and components that are known to maintain their physical integrity at -40 ^{o}C can be chilled.

Table20.1 Specifications for Typical Compressors

Compressor	Size	Weight	Capacity
A	6" x 6" x 8"	16 lbs	30 W @ -40°C
B	8" x 10" x 9"	25 lbs	150 W @ -40°C
Mini-Compressor	1.5" x 4"	2 lbs	200 W @ -40°C



Conclusion

Reliable vapor compression driven cooling subsystems can be designed and manufactured for use in high performance electronic applications. Vapor compression cooling can be used for thermal management and/or performance enhancement.

Today a small fraction of all computers are equipped with vapor compression coolers. Broader use of this powerful cooling technology depends on several factors. First, the cooling technology will evolve to become a better fit for computing and telecommunication applications. Programs are underway to reduce the size and weight of vapor compressors and to build-in capacity control features that can interface seamlessly with computing. The lower temperature limit of the commodity vapor compression technology of 233K is also being addressed. Vapor compression systems are operating at much lower temperatures in the laboratory now.

Mechanically assisted cooling is emerging as a practical solution to high performance electronic cooling problems. The adoption and refinement of vapor compression cooling to address these problems can unlock a new era of electronics. One in which electronic cooling-specific compressors allow the use of ultra-high performance semiconductor devices designed specifically for low temperature operation. Microprocessor frequencies will be both scaled up and cooled up.