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REVIEW AND DEVELOPMENT OF ELECTRONIC COOLING TECHNOLOGY AND APPLICATION GUIDE[1]

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ABSTRACT

The cooling load required to cool power electronics in modern combat vehicles is continuously increasing due to the rise of power consumption and the high thermal load of current theaters of operation. Advances in semiconductor technology have led to increased power dissipation from electronic chips while reducing their size. This has resulted in increased demand to remove the heat from these chips in order to prevent them from overheating leading to failure. In many circumstances, electronics cooling is provided through enhanced ventilation or air-handling units of the vehicle interior. However, the military has unique requirements for achieving thermal management of electronic devices such as Line Replaceable Units (LRUs). Some of these requirements include low weight, high efficiency, and reliability. Therefore, it is important that critical electronics be cooled effectively using conventional and/or advanced cooling technologies.

The primary objective of this work is to develop a Line Replaceable Unit Cooling Technology (LRUCT) summary database and application guide of current and future cooling technologies, and to assess readiness level of each technology, location/situation to be used, and characteristics. The guide will allow rapid development of LRU cooling concepts and to assist in the evaluation of the different cooling methods that best fit a specific application; thus, supporting system and subsystem level selection and LRU designs.

INTRODUCTION

The utilization of power electronics in military and combat vehicles is continuously increasing due to the demands of modern warfare. High heat dissipation associated with power electronics is imposing higher demand for cooling and driving the development of advanced cooling techniques to suit different applications. Failures resulting from high chip temperature include mechanical stresses, thermal fracture, and thermal de-bonding [1]. In addition to mechanical failure, chip performance is also reduced when specified junction temperatures are not met. Cooling performance, therefore, becomes critical to survivability and mission success. Performance, reliability, size, weight, and power consumption are the key elements dictating the selection of suitable cooling techniques in order to match specific power electronics applications.

LRUCT SUMMARY DATABASE AND APPLICATION GUIDE

The LRUCT guide is a compilation of descriptions of the different electronics cooling methods currently employed in products or being researched. The following cooling methods are broken up into seven categories which include:

- Air Cooling
- Liquid Cooling
- Heat Pipe Cooling
- Refrigeration Cooling
- Thermoelectric Cooling
- Phase Change Material Cooling
- Hybrid Cooling

Information about each individual method is divided into nine sections labeled as follows:

1. Status
2. Application
3. How it works
4. Advantages
5. Disadvantages
6. Figures
7. Mathematical Models
8. Attributes
9. Research Referenced

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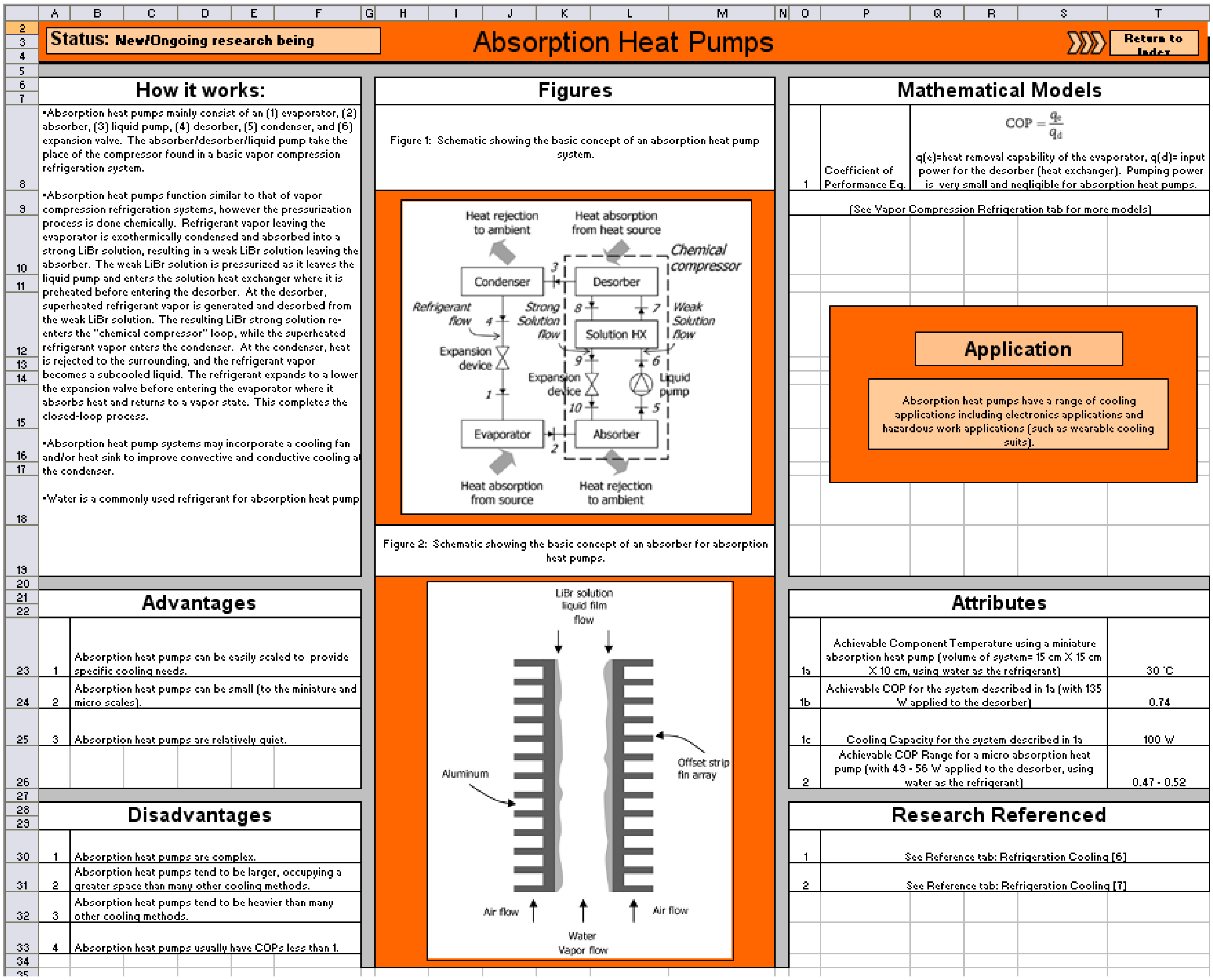

Status: New/Ongoing research being

Absorption Heat Pumps

How it works:

•Absorption heat pumps mainly consist of an (1) evaporator, (2) absorber, (3) liquid pump, (4) desorber, (5) condenser, and (6) expansion valve. The absorber/desorber/liquid pump take the place of the compressor found in a basic vapor compression refrigeration system.

•Absorption heat pumps function similar to that of vapor compression refrigeration systems, however the pressurization process is done chemically. Refrigerant vapor leaving the evaporator is exothermically condensed and absorbed into a strong LiBr solution, resulting in a weak LiBr solution leaving the absorber. The weak LiBr solution is pressurized as it leaves the liquid pump and enters the solution heat exchanger where it is preheated before entering the desorber. At the desorber, superheated refrigerant vapor is generated and desorbed from the weak LiBr solution. The resulting LiBr strong solution re-enters the "chemical compressor" loop, while the superheated refrigerant vapor enters the condenser. At the condenser, heat is rejected to the surrounding, and the refrigerant vapor becomes a subcooled liquid. The refrigerant expands to a lower the expansion valve before entering the evaporator where it absorbs heat and returns to a vapor state. This completes the closed-loop process.

•Absorption heat pump systems may incorporate a cooling fan and/or heat sink to improve convective and conductive cooling a the condenser.

•Water is a commonly used refrigerant for absorption heat pump

Figures

Figure 1: Schematic showing the basic concept of an absorption heat pump system.

Figure 2: Schematic showing the basic concept of an absorber for absorption heat pumps.

Mathematical Models

1	Coefficient of Performance Eq.	$COP = \frac{q_e}{q_d}$ q(e)=heat removal capability of the evaporator, q(d)= input power for the desorber (heat exchanger). Pumping power is very small and negligible for absorption heat pumps.

(See Vapor Compression Refrigeration tab for more models)

Application

Absorption heat pumps have a range of cooling applications including electronics applications and hazardous work applications (such as wearable cooling suits).

Advantages

1	Absorption heat pumps can be easily scaled to provide specific cooling needs.
2	Absorption heat pumps can be small (to the miniature and micro scales).
3	Absorption heat pumps are relatively quiet.

Disadvantages

1	Absorption heat pumps are complex.
2	Absorption heat pumps tend to be larger, occupying a greater space than many other cooling methods.
3	Absorption heat pumps tend to be heavier than many other cooling methods.
4	Absorption heat pumps usually have COPs less than 1.

Attributes

1a	Achievable Component Temperature using a miniature absorption heat pump (volume of system= 15 cm X 15 cm X 10 cm, using water as the refrigerant)	30 °C
1b	Achievable COP for the system described in 1a (with 135 W applied to the desorber)	0.74
1c	Cooling Capacity for the system described in 1a	100 W
2	Achievable COP Range for a micro absorption heat pump (with 49 - 56 W applied to the desorber, using water as the refrigerant)	0.47 - 0.52

Research Referenced

1	See Reference tab: Refrigeration Cooling [6]
2	See Reference tab: Refrigeration Cooling [7]

Figure 1: Screenshot from the original project excel file showing the structured layout for each of the individual method. Displayed is the absorption heat pump worksheet.

This guide was developed in Microsoft Excel®, making use of its grid formatting and worksheet sectioning to structure the guide and organize the different methods. Each category was designated a color and an abbreviation, making the file organized and easy to navigate. Information for each individual method is comprised in a single worksheet.

When the file is first opened, the "Cooling Method Index" worksheet is viewed which contains a list of each of the cooling methods, divided into their respective categories. A few details concerning the status and application are given about each of the methods, and a hyperlink button is available to quickly move back and forth between the index and the various cooling method worksheets of interest.

Information for each cooling method is presented in the format shown in Figure 1. From the index worksheet, details regarding the status and application of the method are presented again for completeness. The Status bar contains information about the maturity of the cooling method with its relation to electronics cooling, and information regarding research being performed involving the cooling method. The maturity of the method is classified by either "Mature" or "New." Research involving the method is classified as either "Ongoing" or "Limited." In the Application section, information about the use of the cooling method in current products or intended uses in future products is given.

The remaining sections provide more specific knowledge of how the method functions as well as additional modes of comparison to be used to distinguish and evaluate which cooling method is appropriate for a given application. In the "How it Works" section are details about the operation of the cooling method and the means by which it dissipates heat. Additionally, it may include remarks about the components, manufacturing methods, modifications, design considerations, and common materials/fluids used for the cooling method. The Advantages and Disadvantages sections incorporate information about the positive and negative aspects of the cooling method. This may consist of remarks about the size of the system, heat dissipation capabilities, environmental concerns, etc. Shown in the Figures section are schematics, graphs, pictures, or diagrams pertaining to the operation, design, or application of the cooling method. The Mathematical Models section includes sample equations relevant to the cooling method. Contained in the Attributes section is data indicating the capabilities of the cooling method. Lastly, the Research Referenced section includes identification numbers corresponding to the research papers and books used to pervade each of the method worksheets. These numbers refer to the individual papers and books which can be found by going to the "References" worksheet in the file.

The following chapters contain specific information regarding each of the cooling categories and individual cooling methods, of which is analogous to what is found in the LRUCT guide project file.

AIR COOLING

Air cooling methods primarily utilize conductive and convective heat transfer means to dissipate heat to the surrounding air. These methods mainly consist of heat sinks and fans.

Heat sinks function by transporting heat conductively through their solid structure, and then convectively to the ambient fluid. A large percentage of the heat transferred by heat sinks is also due to radiation [2,3]. Heat sinks improve heat dissipation through their composition of highly conductive materials such as copper, and through their geometry by employing a large surface area. Commonly, heat sinks are combined with many other cooling methods to improve the overall efficiency of a cooling system, and can function in many different fluid mediums. This section focuses on heat sinks making use of natural or forced convection, with the ambient fluid being air. Fin array, pin-fin array, microchannel, and foam heat sinks are covered in the project.

Fans enhance heat dissipation by generating bulk fluid motion which increases convective heat transfer. The two types of fans covered in the project are piezoelectric fans and axial fans.

Sample attributes obtained from specific research for the individual air cooling methods are listed in Table 1[*]. Details for each of the individual air cooling methods are provided in the following sections.

1.1 Fin Array Heat Sinks

Fin array heat sinks are commonly used in many cooling applications. Electronic applications include computers, audio equipment, and portable electronics. The status of this cooling method is "mature", with limited ongoing research being performed on fin arrays alone.

Fin array heat sinks consist of thin longitudinal fins in array formats which are sometimes covered with shrouds to confine and improve the flow of fluid across the fin array [4].

Advantages of fin arrays include their small, compact size, and low mass. In addition, numerous studies on fin arrays are available that indicate optimal design parameters, and fin arrays have been proven in commercial applications. A disadvantage of fin arrays includes their performance ability reaching peak limits with conduction and natural convection alone due to the continually increasing power of computer chips.

Pin-Fin Array Heat Sinks

Pin-Fin array heat sinks are used in a variety of cooling applications including computers and portable electronics. The status of this cooling method is "mature", with limited research being performed exclusively on pin-fins.

Pin-Fin array heat sinks consist of numerous pins in an array format. Many different pin styles have been experimented with including circular, square, elliptical, lancet, dropform, and NACA styles [5].

Pin-Fin arrays share the same advantages of fin arrays including having a small, compact size (and low mass), having numerous studies available that indicate optimal design parameters, and being a proven cooling method that is used in commercial applications. Likewise, their drawback consists of their performance ability reaching peak limits with conduction and natural convection alone due to the continually increasing power of computer chips.

Microchannel Heat Sinks

Microchannel heat sink cooling applications primarily consist of computer chip cooling. The status of this cooling method is "mature", with ongoing research being performed that utilizes microchannel heat sinks.

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[*] Units for select metrics in Table 1 are defined as follows: 1. Fin Array Heat Sink (W/m): the m refers to the length of the fins. 2. Pin-Fin Array and Carbon Foam Heat Sinks (W/m²): the m² refers to the base area of the heat sink.

Air Cooling Attributes			
Cooling Method	**Metric**	**Value**	**Reference**
Fin Array Heat Sink	Range of Heat Dissipation with Forced Convection	50 - 470 W/m	[16]
Pin-Fin Array Heat Sink	Range of Heat Dissipation with Forced Convection	5000 - 54000 W/m²	[5]
Microchannel Heat Sink	Maximum Heat Dissipation Enhancement Compared to Conventional Fin Array with Forced Convection	62%	[6]
Metal Foam Heat Sink	Range of Thermal Conductivity with Natural Convection	0.5 - 1 W/m-K	[17]
Carbon Foam Heat Sink	Heat Transfer Coefficient of Carbon Foam Block with Forced Convection	2600 W/m²	[9]
Piezoelectric Fan	Maximum Heat Transfer Coefficient Enhancement Compared to Natural Convection	375%	[13]
Centrifugal Fan	Max Sound Pressure Level Produced by Fan	34.7 dBA	[18]

Table 1: Sample air cooling attributes from specified research.

Microchannel heat sinks consist of numerous small enclosed channels (dimensions of which are measured on the scale of µm) [6, 7]. Advantages of microchannels include their compact size and low mass. However, to function effectively microchannels need to be coupled with a method of forced convection. This creates the disadvantage of having a more complex cooling system.

Foam Heat Sinks

Foam heat sink electronics cooling applications include computers and power converters. The status of this method is "new," with ongoing research being performed that employs foam heat sinks.

Foam heat sinks consist of a porous structure composed of metal (commonly aluminum) or carbon [8,9]. Figure 2 shows the pore structure of aluminum foam.

Advantages of foam heat sinks include their ability to be lightweight, and their proven effectiveness at providing cooling capabilities beyond that of fin and pin-fin arrays [6, 8-10]. Some disadvantages of foam heat sinks are their low mechanical strength, and the capacity of the foam pores to be blocked by particles which can reduce their performance [10].

Piezoelectric Fans

Piezoelectric fans have been experimentally applied to a range of electronics with emphasis on portable electronics including PDAs, cell phones, and notebook PCs [11-14]. The status of piezoelectric fans is "new," with ongoing research being performed utilizing this type of fan.

Piezoelectric fans consist of a thin elastic beam, disk, or plate with a piezoelectric material bonded to a portion of the beam. When an alternating current is applied to the piezoelectric material, it causes the material to expand and contract lengthwise at the frequency of the input. This expanding and contracting motion applies bending moments at the ends of the patch causing the thin elastic beam to oscillate, and in turn generates air flow [11,12,14]. Figure 3 shows a typical piezoelectric fan setup.

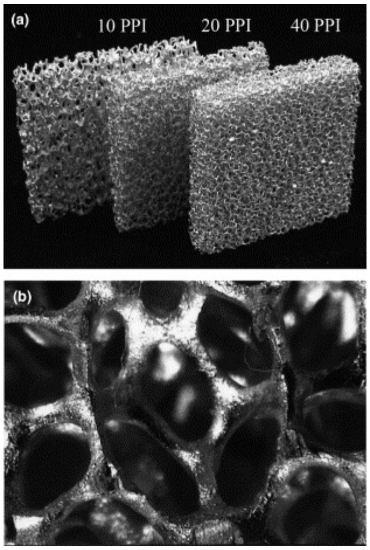

Figure 2: (a) Varying pore configurations for aluminum open-cell foams and (b) typical pore structure of an open-cell metal foam [8].

Some advantages of piezoelectric fans are their ability to be small and lightweight, consume very little power, and produce very little audible noise depending on their operating frequency [11,13,14]. Disadvantages include their unproven performance in commercial products, and the limited availability of studies indicating optimum design parameters [13].

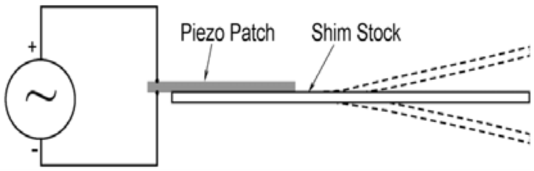

Figure 3: Piezoelectric fan oscillating under an applied alternating voltage [12].

Axial Fans

Axial fans are commonly used in many cooling applications and are one of the primary cooling methods used for desktop and notebook computers. The status of this method is "mature," with limited research being performed on axial cooling fans alone.

Axial fans consist of fins rotating on an axis which generates fluid flow parallel to the axis of rotation. Advantages of axial fans consist of their proven performance in commercial electronics, as well their ability to be small and lightweight. However, as computer chips are continually becoming more powerful, the number of axial fans needed for a system and the power applied to them is increasing, creating the disadvantages of increased noise levels and power consumption [15].

LIQUID COOLING

Liquid cooling methods primarily utilize convective heat transfer, as well as pool boiling to dissipate heat [1]. These methods can be separated into direct and indirect liquid cooling.

Direct liquid cooling methods involve either the electronic equipment being fully immersed in a liquid fluid medium, or having the liquid fluid sprayed directly onto the electronic equipment. Latent heat is removed from the heat source convectively by the liquid fluid and as the liquid undergoes a phase change to vapor [1, 19-21]. Dielectric and non-dielectric fluids can be used and include FC-72, FC-86, HFE-7100, R-134a and water. When using non-dielectric fluids, the electronic components must be properly sealed to avoid short circuits [19-21]. This project covers the direct liquid cooling methods of direct immersion, liquid jet impingement, and spray cooling.

With indirect cooling systems, the working fluid does not come in contact with the heat source. The heat source is usually mounted directly onto a cold plate which is made up of a thermally conductive material. Heat from the heat source is dissipated conductively through the cold plate, and then convectively to the working fluid being pumped through channels within the cold plate. Once the fluid has passed through the cold plate, it travels to a heat exchanger where the absorbed heat is released to the surroundings. The fluid is then pumped back to the cold plate, forming a closed loop process. Water is frequently used as the working fluid for these systems [1, 29]. To improve their overall effectiveness, liquid cooling systems commonly incorporate fans and heat sinks.

Sample attributes obtained from specific research for the individual liquid cooling methods are listed in Table 2[†]. Details for each of the individual liquid cooling methods are indicated in the following sections.

Direct Immersion

Direct immersion cooling electronics applications include the cooling of CPUs and other microelectronics. The status of this method is "mature", with ongoing research being performed utilizing direct immersion.

Direct immersion cooling for electronics involves the electronic components (circuit boards, computer chips, etc.) being immersed in a dielectric fluid that is either stagnant or flowing. These systems are mainly composed of a container, fluid reservoir, and pressure relief valve [1, 19, 21].

Advantages of this method and using dielectric fluids include the provision of temperature stability over a surface area (eliminating the development of hot spots), and the environmental friendliness and low boiling point of the dielectric fluids, allowing the use of plastic containers. A disadvantage of dielectric fluids includes their low surface tension, which allows the fluid to easily seep into crevices, causing an initial delay in heat dissipation. This also requires the immersion container to be tightly sealed [19-21].

Liquid Jet Impingement

Liquid jet impingement cooling systems have a range of cooling applications. Intended electronic cooling applications include high-power electronics such as IGBT based inverters for hybrid vehicles [22]. The status of this method is "mature", with ongoing research being performed utilizing liquid jet impingement cooling.

[†] Units for select metrics in Table 2 are defined as follows:
1. Direct Immersion and Jet Impingement (W/cm²): the cm² refers to the component surface area, and impacted area, respectfully.

Liquid Cooling Attributes			
Cooling Method	**Metric**	**Value**	**Reference**
Direct Immersion	Maximum Heat Dissipation From a Copper Surface Using HFE-7100	24.5 W/cm²	[21]
Jet Impingement	Maximum Heat Dissipation	1127 W/cm²	[23]
Spray Cooling	Chip Junction Temperature Reduction when compared to a similar Air Cooling System	33 °C	[25]
Indirect Cooling	Maximum Temperature Reduction at Chip Junction	10.3 °C	[29]

Table 2: Sample liquid cooling attributes from specified research.

Liquid jet impingement cooling consists of a single jet or multiple jets of liquid being directed at a heat source. These cooling systems are classified as either free surface, submerged, or confined. For free surface impingement, the liquid jet discharges into the ambient gas before contacting the heated surface, shown in Figure 4. With submerged jet impingement, the liquid jet discharges into a region comprised of the same liquid. Confined jet impingement consists of the liquid jet being confined and channeled across the heat source. Confined jet impingement cooling systems commonly utilize microchannel heat sinks as a means of channeling the liquid jet. These systems are mainly comprised of nozzles, a pump, and drainage reservoir [1, 23, 24].

Advantages of these systems consist of the ability to obtain high heat transfer coefficients, as well as the methods effectiveness resulting in the possible elimination of thermal interface materials. Disadvantages of using this kind of system include the requirement of a power input, and the larger space needed to be allocated in order to hold the required components [1, 23, 24].

Spray Cooling

Spray cooling systems have a wide range of cooling applications including high-speed electronics and high power lasers [25-28]. The status of this method is “mature”, with ongoing research being performed.

Spray cooling systems function by forcing the coolant through an orifice, causing the liquid to break up into droplets which then impact the heated surface. Various nozzle types, creating different spray features, exist for spray cooling. Types of sprays include hollow-cones, full-cones, and fan sprays. Gas-atomizers are frequently incorporated to inject air into the liquid stream, further breaking up the liquid droplets and enhancing evaporation due to a reduction in vapor partial pressure. Spray Cooling systems mainly consist of a nozzle or an array of nozzles, drainage reservoir, and pump [1, 25, 28].

These systems offer the advantages of low liquid droplet impact velocity and higher heat transfer rates above that of pool boiling techniques due to the minimized resistance of vapor droplets [25, 28]. The disadvantages are similar to that of liquid jet impingement cooling method, consisting of the need for a power input and the allocation of space to hold the required components for the cooling system.

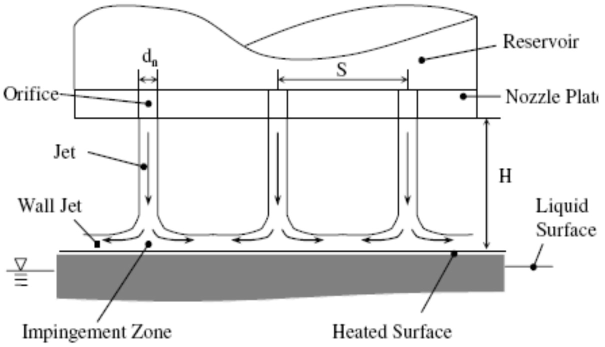

Figure 4: Schematic showing the basic concept of free surface liquid jet impingement cooling with multiple jets [24].

Indirect Cooling

Indirect cooling system applications for electronics include high-power computers, IGBT modules, and LEDs [29, 30]. The status of this method is “mature”, with ongoing research being performed.

Indirect cooling systems mainly consist of a cold plate, pump, reservoir, and heat exchanger [1, 29]. Advantages of indirect cooling systems include their ability to produce little noise, to offer localized cooling, and to transfer heat far from the heat source [29]. A disadvantage to using these systems involves allocating the required space needed to mount the components.

HEAT PIPE COOLING

Heat pipe cooling methods utilize multiple mechanisms to dissipate heat. They generally consist of three main sections which include the evaporator, adiabatic, and condenser sections. As heat is applied to the evaporator section, the fluid inside the heat pipe vaporizes and is driven through the adiabatic section to the condenser section due to the pressure difference that is generated. At the condenser section, latent heat is released as the vapor condenses back to a fluid. The fluid is then transferred back to the evaporator section due to capillary forces created by the wick structure, forming a closed loop process [1, 31-33}. This process is illustrated by Figure 5.

Heat pipes usually contain the basic elements of a wick structure, working fluid, and conductive container. Common working fluids include water, acetone, methanol, and ammonia, with newer research utilizing nanofluids [1, 31-34]. Common materials used include copper for the container, and various metallic sintered powders and wire meshes for the wick [1, 32-34].

Heat pipe cooling systems commonly incorporate fans and heat sinks to improve the overall effectiveness of the system. The individual methods covered by this project are cylindrical heat pipes, flat heat pipes, micro heat pipe arrays, loop heat pipes, and bellows heat pipes.

Sample attributes obtained from specific research for the individual heat pipe cooling methods are listed in Table 3. Details for each of these methods are indicated in the following sections.

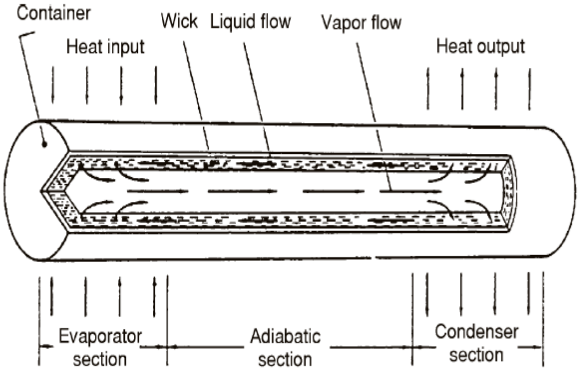

Figure 5: Schematic of a cylindrical heat pipe showing the concept of heat pipe cooling [1].

Cylindrical Heat Pipes

Cylindrical heat pipes have a range of cooling applications, with electronics cooling applications including computers. The status of this method is "mature," with ongoing research being performed using cylindrical heat pipes.

In a cooling system application, multiple cylindrical heat pipes are frequently used as opposed to just one heat pipe. Certain designs involve arrays of cylindrical heat pipes similar to that of pin-fin arrays [32].

Distinguishing cylindrical heat pipes from other forms of heat pipes is the cylindrical shape of their containers. Although this form is works well with regards to the amount of active surface area, it does create a disadvantage due to the cylindrical shape being inconsistent with the shapes of electrical components. This limits the ability to directly place electronic components onto the heat pipe [1]. However advantages of these heat pipes include their adaptability to fit in a range of enclosures and be very small, there ability to dissipate heat over substantial distances and there ability to transport heat with small temperature drops along the heat pipe [31, 33].

Flat Heat Pipes

Flat heat pipes are intended for electronics cooling at the computer chip level [34]. The status of this method is "new," with ongoing research being performed utilizing this type of heat pipe.

For flat heat pipes, the container is in the form of a flat (circular or rectangular) plate. This creates the advantage of having low thermal contact resistance between electronic components due to the similarity of their shapes [1]. Other advantages include the ability to be small (to the miniature and micro levels), and to dissipate heat over substantial distances at low temperature drops [35, 36]. However, flat heat pipes alone would not be a sufficient cooling system for an electronic device, and should be combined with another cooling method such as a type of forced convection.

Many flat heat pipes incorporate heat sinks at the condenser section to further enhance a systems overall heat transfer capability [34]. Figure 6 shows a schematic of a flat heat pipe.

Micro Heat Pipe Arrays

Micro heat pipe arrays are generally designated for use in electronic component cooling with placement in circuit board substrates [38]. This is a newer method, with ongoing research being performed incorporating micro heat pipes.

Micro heat pipe arrays consist of numerous micro heat pipes (in an array format) which contain only two of the three basic elements of heat pipes which includes the working fluid and container. Instead of utilizing a wick, the varying curvature in the evaporator and condenser section creates a pressure difference that drives the working fluid

Heat Pipe Cooling Attributes			
Cooling Method	**Metric**	**Value**	**Reference**
Cylindrical Heat Pipe	Maximum Increase in Heat Dissipation using Nanofluids as the Working Fluid	26%	[31]
Flat Micro Heat Pipe	Range of Heat Dissipation	50-128 W	[37]
Micro Heat Pipe Array	Maximum Substrate Temperature	60 °C	[40]
Loop Heat Pipe	Maximum Heat Dissipation	70 W	[43]
Bellows Heat Pipe	Maximum Temperature Drop	65 °C	[47]

Table 3: Sample heat pipe cooling attributes from specified research.

back to the evaporator section, forming a closed loop process. For micro heat pipe arrays, the container is extremely small and measured using the µm scale [39, 40]. One method of creating micro heat pipe arrays is by etching microchannels into a silicon wafer, filling the channels with the working fluid, and then sealing off the top of the microchannels (usually by placing another silicon wafer on top) [38].

Advantages of micro heat pipes include their small size which allows numerous heat pipes to be placed on a single silicon wafer, and also their low fabrication cost. Disadvantages include their sensitivity to the presence of non-condensable gases in the vapor channel, and the occurrence of dry-out effects with liquid accumulation in the vapor channel [38-40].

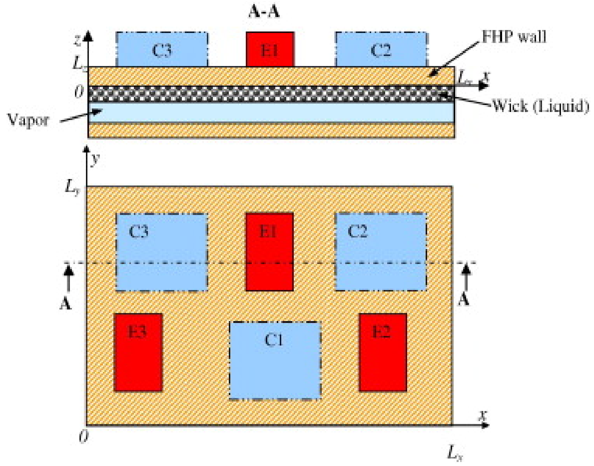

Figure 6: Schematic of a flat heat pipe showing an arrangement of electronic components and condensers on the top [36].

Loop Heat Pipes

Loop heat pipes have a range of electronic cooling applications with newer applications being in notebook PCs [45]. The status of this method is “mature,” with ongoing research being performed.

Loop heat pipes (LHP) differ from other heat pipes due to the condenser and evaporator sections being separated, and therefore having to be connected by tubing or piping (see Figure 7) [41, 42]. Variations of LHP include ramified LHP which contain multiple condensers and evaporators, and reversible LHP which can function with a heat flux applied to either end of it (each end has a condenser/evaporator combination, and can act as either of the two) [42]. This cooling method has an advantage of the ability to be very small and flexible, allowing them to fit in a variety of enclosures [41-44]. Other advantages include their low sensitivity to orientation and their heat dissipation capabilities beyond that of conventional single container heat pipes, such as higher performance and transportation of heat over greater distances [42-44]. A disadvantage of loop heat pipes is their requirement of more space than conventional single container heat pipes due to the separation of the evaporator and condenser sections and additional tubing/piping.

This cooling method has an advantage of the ability to be very small and flexible, allowing them to fit in a variety of enclosures [41-44]. Other advantages include their low sensitivity to orientation and their heat dissipation capabilities beyond that of conventional single container heat pipes, such as higher performance and transportation of heat over greater distances [42-44]. A disadvantage of loop heat pipes is their requirement of more space than conventional single container heat pipes due to the separation of the evaporator and condenser sections and additional tubing/piping.

Bellows Heat Pipes

Bellows heat pipes have a range of applications as thermal switches for electronics cooling [46]. The status of this method is "mature," with limited research being performed that utilizes this type of heat pipe.

With bellows heat pipes, the evaporator section is contained in a bellows vessel which allows the heat pipe to move longitudinally depending on the pressure inside of the heat pipe. As pressure increases within the heat pipe, the retarding spring forces of the bellows vessel will be overcome and the heat pipe will begin to extend [46]. This feature allows this type of heat pipe to be used as a thermal switch.

Advantages of this cooling method include its insensitivity to vibrations, and the flexibility of the bellows structure which compensates for any misalignment between the electronic component and the heat pipe evaporator, reducing thermal contact resistance [46, 47]. One disadvantage of bellows heat pipes is the limited amount of research available specifying optimum design parameters.

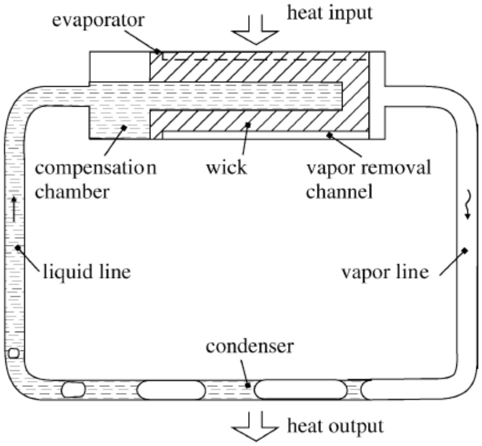

Figure 7: Schematic of a loop heat pipe [42].

REFRIGERATION COOLING

Two refrigeration cooling systems were covered in this project, which includes vapor compression refrigeration and absorption heat pumps.

The basic operation cycle of a vapor compression refrigeration system involves the working fluid (refrigerant) entering the evaporator, where it absorbs energy from the component being cooled, causing it to transform from a fluid to a superheated vapor. This superheated vapor enters the compressor, where its pressure is then raised so that its saturation temperature is slightly above the cooling medium used in the condenser. As the vapor enters the condenser (which functions as a heat exchanger), energy is released and the vapor returns to a subcooled liquid. This subcooled liquid passes through the expansion valve, where it expands to a lower pressure and is now ready to re-enter the evaporator, completing the closed-loop cycle [48].

Absorption heat pumps function similar to that of vapor compression refrigeration systems, however the pressurization process is done chemically. Refrigerant vapor leaving the evaporator is exothermically condensed and absorbed into a strong LiBr solution, resulting in a weak LiBr solution leaving the absorber. The weak LiBr solution is pressurized as it leaves the liquid pump and enters the solution heat exchanger where it is preheated before entering the desorber. At the desorber, superheated refrigerant vapor is generated and desorbed from the weak LiBr solution. The resulting LiBr strong solution re-enters the "chemical compressor" loop, while the superheated refrigerant vapor enters the condenser. At the condenser, heat is rejected to the surrounding, and the refrigerant vapor becomes a subcooled liquid. The refrigerant expands to a lower pressure in the expansion valve before entering the evaporator where it absorbs heat and returns to a vapor state. This completes the closed-loop process [49].

Many refrigeration systems incorporate a cooling fan and heat sink to improve convective and conductive cooling at the condenser. Sample attributes obtained from specific research for the individual cooling methods are listed in Table 4. Details for each of the individual refrigeration cooling methods are indicated in the following sections.

Vapor Compression Refrigeration

Vapor compression refrigeration (VCR) system applications include high power electronics such as telecommunication equipment and high performance computers [50, 51]. The status of this method is "mature," with ongoing research being performed focusing on vapor compression refrigeration.

These systems consist of four main components which includes a (1) compressor, (2) condenser, (3) expansion valve/throttling device, and (4) evaporator [48]. Common refrigerants used by VCR units are R134a and R22 [50-52].

Advantages of using VCR systems include their ability to cool below ambient temperatures and to reject heat far from the heat source [50, 51]. In addition, VCR coefficient of performance values tend to be greater than one [51]. A disadvantage of these systems is the possible development of condensation due to their cooling power which could damage the electronic components [50]. Other disadvantages include the size of VCR systems, which are generally larger than other cooling method systems, as well as their complexity [52].

Refrigeration Cooling Attributes			
Cooling Method	**Metric**	**Value**	**Reference**
Vapor Compression Refrigeration	Cooling Capacity	300 W	[51]
Absorption Heat Pump	COP Range	0.47-0.52	[53]

Table 4: Sample refrigeration cooling attributes from specified research.

Absorption Heat Pumps

Absorption heat pumps have a range of cooling applications including electronics applications and hazardous work applications (such as wearable cooling suits) [49, 53]. The status of this method is "new," with ongoing research being performed utilizing this method.

Absorption heat pumps mainly consist of an (1) evaporator, (2) absorber, (3) liquid pump, (4) desorber, (5) condenser, and (6) expansion valve. The absorber, desorber, and liquid pump take the place of the compressor found in basic vapor compression refrigeration systems. For these systems, water is used as the refrigerant, and LiBr as the absorbent [49].

The advantages of this cooling method include its ability to be easily scaled to provide specific cooling needs, and its ability to operate quietly. Disadvantages include its complexity, as well as its tendency to have coefficient of performance values of less than one [49, 53].

THERMOELECTRIC COOLING

Thermoelectric cooling involves solid state electrically driven heat exchangers that pump heat in a direction dependent on the polarity of the applied voltage [54]. These systems operate by means of the Peltier Effect, where a temperature difference is induced when an electrical current flows through a junction of dissimilar materials [54, 55].

Thermoelectric cooler (TEC) modules contain two semiconductors which are commonly made up of Bismuth Telluride (Bi2Te3) [55, 56]. A negative type (n-type) semiconductor contains a small excess of Telluride having more electrons, and a positive type (p-type) semiconductor has a small Telluride deficiency having fewer electrons. When electrical power is applied to the semiconductors, electrons move from the low level energy p-type semiconductor to the high level energy n-type semiconductor [55]. This causes heat to be absorbed at the cold surface which is then transferred to a heat sink at the hot surface where it can be dissipated [54, 55]. This process is shown by Figure 8.

Conventional thermoelectric coolers as well as micro thermoelectric coolers are covered in this project. Sample attributes obtained from specific research for the individual cooling methods are listed in Table 5. Details for each of the individual methods are contained in the following sections.

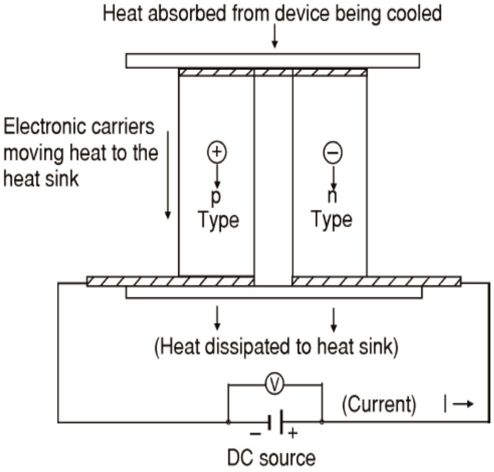

Figure 8: Schematic showing the concept of thermoelectric cooling [1].

Thermoelectric Coolers

Thermoelectric coolers have a wide range of cooling applications including car seats, portable medical coolers, optoelectronic devices, and semiconductor lasers [1, 54, 55, 57]. The status of this method is "mature," with ongoing research being performed.

Most TECs contain multiple modules composed of the n-type and p-type semiconductors in an array format, as opposed to one single module. Other semiconductor materials consider for use in TECs include Skutterudite and Zn4Sb3 [56].

TECs have the advantages of being a reliable, quiet cooling method, and having the ability to cool below ambient temperatures [1, 54, 56, 58]. Some drawbacks to using TECs include their inefficiency (having coefficient of performance values of less than one), and their low cooling capacity [56].

Thermoelectric Cooling Attributes			
Cooling Method	**Metric**	**Value**	**Reference**
Thermoelectric Cooler	Maximum Heat Dissipation	207 W	[58]
Micro Thermoelectric Cooler	Range of Achievable Temperature Differences Between the Hot and Cold Surfaces	0.7-32.2 K	[59]

Table 5: Sample thermoelectric cooling attributes from specified research.

Micro Thermoelectric Coolers

Micro thermoelectric coolers are intended for microelectronic cooling applications which include power amplifiers, laser diodes, and microprocessors [59]. The status of this method is "new," with ongoing research being performed.

Micro TECs consist of multiple modules in an array format, which involves the semiconductor materials being deposited onto silicon wafers as thin films. The makeup of a micro TEC module is shown in Figure 9. Commonly used materials for the n-type and p-type semiconductors include Bi2Te3 and Sb2Te3, respectively [59-61]. Other possible semiconductor material combinations include SiGe/Si and InGaAs/InGaAsP [59].

Advantages of micro TECs are comparable to that of standard TECs, in addition to their small size [59, 61, 62]. Some disadvantages include their inefficiency (having coefficient of performance values of less than one), and their complicated and expensive fabrication process [59].

PHASE CHANGE MATERIAL COOLING

Phase change materials (PCMs) function by absorbing heat from the heat source and storing it, releasing it to the surroundings at a later time. PCMs are intended for periodic cooling applications, where the electronic device is being used intermittently [1, 63].

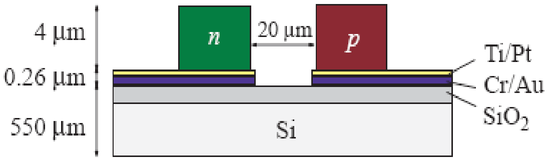

Figure 9: Schematic of a micro TEC module showing the various layers and semiconductors (missing the top cold surface) [60].

PCMs operate as a two-phase system (usually between solid and liquid states). As an electronic device is operating, heat is withdrawn and stored in the PCM, eventually causing the PCM to change phases (melting from a solid to a liquid). When the electronic device is not being operated, the heat stored in the PCM is released to the surrounding fluid as the PCM re-solidifies [1, 63-65].

Materials used in PCM applications include paraffin wax, Bi/Pb/Sn/In, and n-eicosane [64, 66, 67]. PCM cooling applications usually incorporate heat sinks, and frequently incorporate a method of forced convection as well.

Conventional phase change material applications as well as phase change material based heat sinks are covered in this project. Sample attributes obtained from specific research for the individual cooling methods are listed in Table 6. Details for each of the individual methods are contained in the following sections.

Phase Change Materials

Phase change material based heat sinks are intended for electronic applications including portable electronics such as mobile phones, personal computers, game consoles, and digital cameras [63, 65, 67, 68]. The status of this method is "new," with ongoing research being performed using PCM based heat sinks.

PCM based heat sinks consist of a heat sink coated with a phase change material. The amount of PCM coating on the heat sinks can vary from filling the entire heat sink cavity with PCM to just covering a small portion of the heat sink (shown by Figure 10). This cooling method incorporates the high surface area and high conductivity of heat sinks with the high energy absorption of PCMs [65, 67, 68].

An advantage of PCM based heat sinks, beyond that of conventional PCM applications, is its improved temperature control ability [65, 67, 68]. However, as with conventional PCM applications, PCM based heat sinks become less effective under a prolonged applied heat once the PCM is fully melted.

Phase Change Material Cooling Attributes

Cooling Method	Metric	Value	Reference
Phase Change Materials	Maximum Heat Dissipation	207 W	[58]
PCM Based Heat Sinks	Range of Achievable Temperature Differences Between the Hot and Cold Surfaces	0.7-32.2 K	[59]

Table 6: Sample phase change material cooling attributes from specified research.

Phase Change Material Based Heat Sinks

Phase change material based heat sinks are intended for electronic applications including portable electronics such as mobile phones, personal computers, game consoles, and digital cameras [63, 65, 67, 68]. The status of this method is "new," with ongoing research being performed using PCM based heat sinks.

PCM based heat sinks consist of a heat sink coated with a phase change material. The amount of PCM coating on the heat sinks can vary from filling the entire heat sink cavity with PCM to just covering a small portion of the heat sink (shown by Figure 10). This cooling method incorporates the high surface area and high conductivity of heat sinks with the high energy absorption of PCMs [65, 67, 68].

An advantage of PCM based heat sinks, beyond that of conventional PCM applications, is its improved temperature control ability [65, 67, 68]. However, as with conventional PCM applications, PCM based heat sinks become less effective under a prolonged applied heat once the PCM is fully melted.

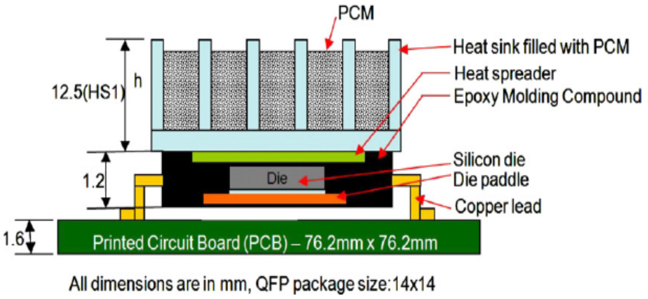

Figure 10: Schematic of a quad flat package (QFP) electronic device incorporating a PCM based heat sink consisting of a fin array filled with paraffin wax [67].

HYBRID COOLING

The hybrid cooling section contains information about cooling methods combining two or more of the six main cooling categories. These cooling methods highlight single experiments involving the combination of the different individual methods and categories. Hybrid methods combine the advantages of the different methods into one system, and often certain disadvantages as well.

Because air cooling methods are common in all cooling systems, many of the other categories with individual methods incorporating air cooling methods are not considered as hybrid cooling methods in this project. The hybrid methods highlighted by this project are all newer methods and include sorption heat pipes, thermoelectric prototypes, and a unique fan prototype.

Sample attributes obtained from specific research for the individual cooling methods are listed in Table 7[‡]. Details for each of these methods can be found in the following sections.

Sorption Heat Pipe

Sorption heat pipes (SHPs) are intended for high power electronics cooling such as electronics on spacecraft and IGBT modules for railway trains. They are a combination of heat pipes (usually loop heat pipes) and solid sorption cryo-coolers. SHPs consist of a sorbent system containing an adsorber/desorber and evaporator at one end, with the condenser and evaporator of a heat pipe at the other end. The SHP operates as a heat pipe until its cooling possibilities have been exhausted, at which time the sorption cooler begins to function [70, 71].

Sorption heat pipes have two phases of operation. Phase 1 involves heating the sorption canister to begin the desorb process, where the working fluid begins to filter from the porous media of the canister and condenses into the evaporator/condenser of the heat pipe. A portion of the liquid enters the evaporator of the heat pipe through a porous valve. The other portion of the liquid returns to the canister, due to capillary forces of the sorbent bed inside of it, and enhances the mass and heat transfer in the sorbent material. At this point, the heater is switched off, and the working fluid of the sorption cooler is accumulating in the evaporator as the sorbent bed is cooling. The porous valve is now fully

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[‡] Units for select metrics in Table 7 are defined as follows: 1. Sorption Heat Pipe (W/cm^2): the cm^2 refers to the component surface area.

Hybrid Cooling Attributes			
Cooling Method	**Metric**	**Value**	**Reference**
Sorption Heat Pipe	Heat Dissipation Capability	> 200 W/cm²	[71]
Thermoelectric Prototype I	Maximum Temperature Difference Between the Hot and Cold Surfaces	43 °C	[73]
Thermoelectric Prototype II	Maximum Effective Operating Heat Load	57 W	[74]
Fan Prototype	Semiconductor Chip Temperature	78.5 °C	[75]

Table 7: Sample hybrid cooling attributes from specified research.

open, allowing Phase 2 to begin. Liquid evaporation occurs in the evaporator. As the evaporation process finishes, the porous valve closes and the sorbent bed begins to cool to the ambient temperature, which is assisted by the heat pipe condenser [70, 71].

Advantages of this method includes its low sensitivity to a certain amount of acceleration and deceleration, its ability to function in harsh environments (ambient temperatures of 40 °C or more), and its considerable heat dissipating capability [70, 71]. A disadvantage to this system is its complexity.

Thermoelectric Prototype I

This thermoelectric prototype is intended for general cooling applications ranging from electronics to food-storage. The prototype device consists of a thermoelectric cooler, encapsulated phase change material (PCM), heat pipe-embedded fin array heat sink, and axial fan (see Figure 11) [72, 73].

This device combines the heat dissipation capabilities of several cooling methods: Heat from the heat source is absorbed by the PCM, stored and eventually transferred to the TEC. The heat dissipated by the PCM is absorbed at the cold side of the TEC and then transferred to the hot side of the TEC due to the Peltier Effect. Heat from the hot side of the TEC is then dissipated by the heat pipe-embedded fin array heat sink, which utilizes the high surface area and conductivity of the fin array with the effective phase change and distant heat transferring capabilities of heat pipes. Heat dissipation is further enhanced by the cooling fan [72, 73].

A modified version of this device includes a thermosyphon connecting the separated PCM and TEC. The thermosyphon acts as a thermal diode which only allows the transfer of heat in one direction, preventing the transfer of heat back to the heat source in situations where the power is turned off [73].

Advantages of this cooling system include enhanced temperature stability for the component being cooled and cooling below ambient temperatures. Disadvantages include its complexity, relatively large size, and low coefficient of performance value [72, 73].

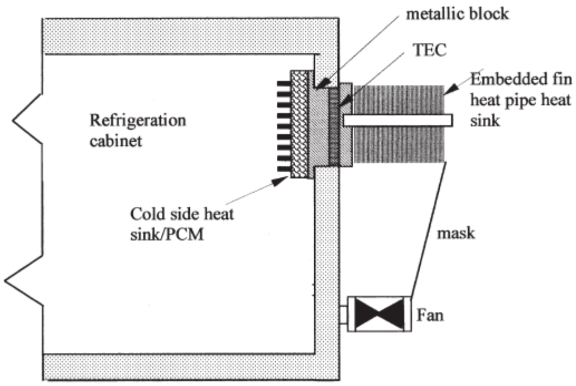

Figure 11: Schematic of a thermoelectric prototype device incorporating a thermoelectric cooler, phase change material, heat pipe-embedded heat sink, and cooling fan [72].

Thermoelectric Prototype II

This thermoelectric prototype is intended for the cooling of computer chips, and consists of a thermoelectric cooler, cold plate, pump, and heat exchanger with a cooling fan shown by Figure 12 [74].

Incorporated by this device are the cooling capabilities of TECs and indirect liquid cooling systems. Heat from the heat source is absorbed by the TEC at the cold side and transferred to the hot side of the TEC due to the Peltier Effect. The heat from the hot side of the TEC is absorbed by the cold plate, which is transferred conductively through the cold plate material, and then convectively to the working fluid flowing through the cold plate. The working fluid carries the heat to the heat exchanger where it is dissipated to the surroundings. From the heat exchanger, the working fluid is pumped back to the cold plate, completing the closed loop process of the indirect cooling system [74].

Advantages of this cooling system include the ability to cool below ambient temperatures and ability to dissipate heat far from the heat source [74]. Disadvantages include is relatively large size and complexity.

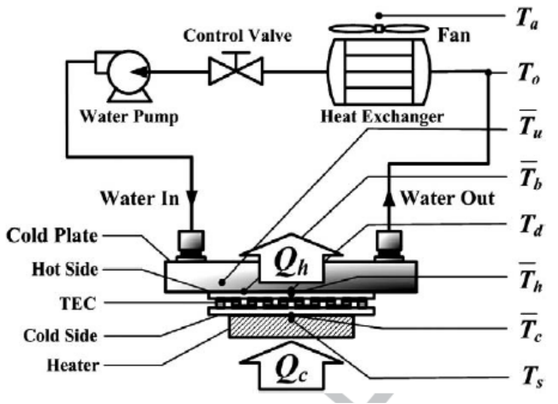

Figure 12: Schematic of the prototype device incorporating indirect liquid cooling with a thermoelectric cooler [74].

Fan Prototype

This fan prototype was designed to cool a semiconductor chip, and incorporates three centrifugal fans, a heat spreader, four heat pipes, and three sets of circular heat sinks (see Figure 13) [75].

The prototype combines the cooling methods of heat pipes, axial fans, and heat sinks. As heat is applied by the heat source it is transferred conductively to the evaporator section of each of the four heat pipes by the heat spreader. The heat absorbed at the evaporator vaporizes the working fluid inside the heat pipes which is driven to the condenser section due to the pressure difference generated. The heat is released at the condenser section of the heat pipes and transferred across the circular heat sinks and then convectively to the surroundings. The centrifugal fans improve convective cooling by pulling cool air up through the center of the prototype and pushing it across the circular heat sinks [75].

Some advantages of this prototype include enhanced temperature stability and heat removal far from the heat source [75]. A disadvantage is its relative noise level due to the use of three fans.

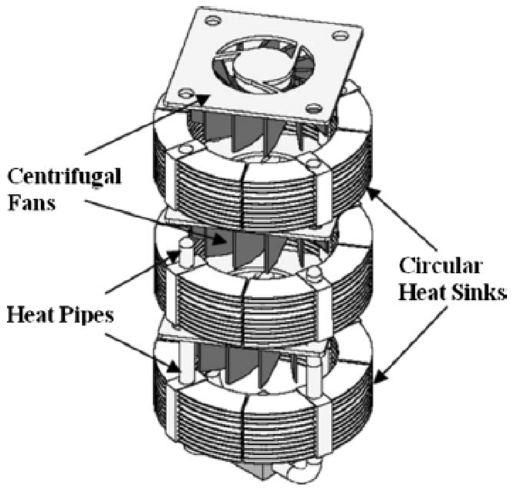

Figure 13: Schematic showing the fan prototype [75].

SUMMARY

Based on the review presented in this paper it can be summarized that traditional cooling methods have reached their peak capability of removing heat from high powered electronics and that the recently developed methods of electronics cooling have the potential to remove heat at higher rates than the traditional methods. However, more research is needed in areas such as metal foams, thermoelectric cooling, and phase change methods in order to improve their reliability, application, and reduce cost.

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