Chapter 4
Heat Flow Management in Portable Electronic Devices

Sagar Mane Deshmukh and Virendra Bhojwani

4.1 Introduction

The recent developments in the technologies help to reduce the size of the electronic devices. The electronic devices are very compact, which are prepared from assembly of more number of small components (dense arrangement). The devices mentioned come into the category of the portable electronics devices/components. The applications of which are mentioned as follows: (a) cassette players, (b) audio devices, (c) radios, (d) telephones, (e) mobile phones, (f) laptop computers, (g) pagers, (h) wrist watches with remind capabilities, (i) small toys, (j) switches and (k) resonators, etc. The power back up to the systems is generally provided by the batteries (Yeatman 2007) and or fuel cells (Ali et al. 2014). The power supplied to the different locations must be conditioned. The small components consuming the power in the electronic devices generate heat. Because of the space constraint dissipation of the heat from the devices becomes very difficult and hence heat flow management is key concern in the small electronic devices.

The maximum allowable temperature on the electronic component would be between 80 and 120 °C (Mjallal 2017). The hand-held devices should be maintained with temperature in the range of 42–45 °C. The conventional cooling techniques cannot be used at small scale because of different issues related to transfer of the heat, e.g. heat transferring media (air) has poor thermal conductivity, no space available for the movement of the heat-carrying media, placement-related issues, etc.

In case if the heat is not removed from the system, it may lead to following shortcomings (Mjallal 2017), (a) decreased life of the electronic components, (b) low voltage problems, (c) power conversion issues, power leakage issues and degradation

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S. M. Deshmukh (✉)
Department of Mechanical Engineering, Tolani Maritime Institute, Induri, Pune, India
e-mail: manedeshmukhsagar5@gmail.com

V. Bhojwani
Department of Mechanical Engineering, MIT ADT University, Loni, Pune, India

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of the chip life, (d) poor overall efficiency of the device, etc. It is very essential to maintain proper heat balance in the portable electronic devices.

In order to achieve a proper heat balance and/or to avoid the locally observed hotspots, diffusion of the heat should be done at fast rate and in large amounts. Heat flow management in the micro-electronic systems is based on cooling techniques used to remove the heat. This chapter explains the different cooling techniques used in the electronics cooling.

4.2 Recent Techniques Used to Get the Heat Flow Management in Electronics Systems (Cooling Technologies)

Following are the technologies used for heat flow management in the electronic systems,

- Heat Sinks
- Cold plates for the electronics cooling
- The natural air cooling
- Forced air cooling
- Use of the heat pipes
- Use of the Peltier effect for cooling
- Use of the synthetic jets for cooling
- Electrostatic fluid acceleration cooling
- Immersion cooling
- Use of the phase change materials.

All the above cooling technologies used to cool the micro-electronics systems are discussed in detail below.

4.2.1 Heat Sink Designs

Heat sink is a device often called as heat exchanger which is made up of metallic surfaces like copper or aluminium, etc. The simple heat sink with rectangular fins is shown in Fig. 4.1. It collects heat from the electronic device (location or platform where heat is generated) and transfers it to the transferring media (generally fluids like air, water, etc.). The main purpose of using the heat sinks in the electronic devices is to increase the area of surface for heat sharing. Sometimes the surface on which the heat sink is to be placed is not similar to the surface of the heat sink and heat spreaders are used. Heat spreaders are the connections between the heat sinks and the electronic device from which heat is to be removed.

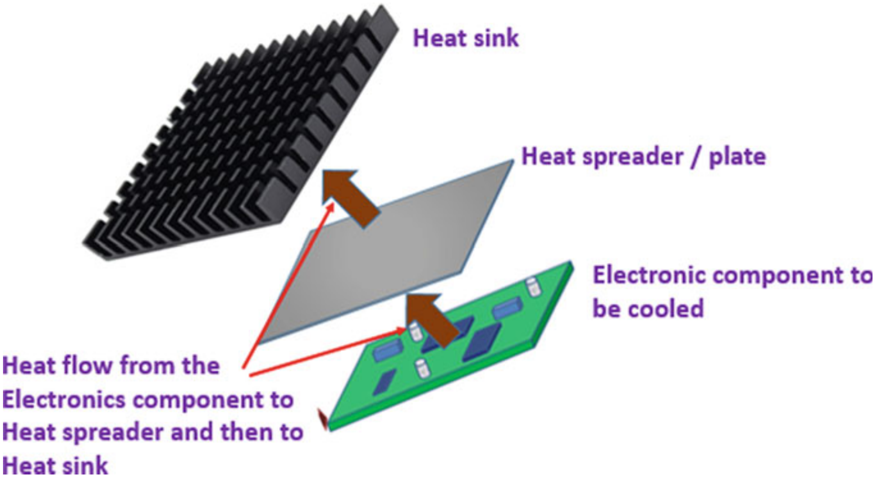


Fig. 4.1 Heat Sink with rectangular fins

Three types of heat transfers are generally involved in the process (as shown in Fig. 4.1) viz. (a) Conduction of the heat from electronic device to heat spreader and (b) conduction of the heat from heat spreader to surface of the heat sink and (c) convection and radiation from heat sink to cooling media.

4.2.1.1 Heat Conduction

The heat conduction is a phenomenon that occurs because of the energy sharing between the molecules with higher energy levels and lower energy levels. The energy transfer occurs from the higher energy level to lower energy level. Following equation can be used to calculate the heat by conduction:

$$q = -KA\frac{\mathrm{d}T}{\mathrm{d}X}$$

where,

q Heat transfer from electronic chip to the heat sink through heat spreader in ‘Watt’.
K Thermal conductivity of the heat spreader and heat sink (it varies from metal to metal), ‘W/mK’.
A Surface area used for heat transfer, ‘m^2’.
$\frac{\mathrm{d}T}{\mathrm{d}X}$ The temperature gradient existing along ‘X’ direction, ‘K/m’.

The general equation for heat conduction in all the three directions can be written as:

$q = -KA\nabla T,$

where,

$$\nabla T = i\frac{\delta}{\delta \mathrm{x}} + j\frac{\delta}{\delta \mathrm{y}} + k\frac{\delta}{\delta \mathrm{z}}$$

where,

i, j and k are the unit vectors along x, y and s directions.

4.2.1.2 Convection

The convection of heat occurs generally between solid surfaces (e.g. heat sink surface) to the fluids (e.g. air) which are in the motion. The equation used is as follows:

$$q = hA(T_{\mathrm{surface}} - T_{\mathrm{fluid}})$$

where,

h	Heat transfer coefficient for convection, W/m^{2}k,
T_{surface}	Temperature of the surface (e.g. Surface of heat sink), K
T_{fluid}	Temperature of the fluid in motion (e.g. Temperature of air), K,

4.2.1.3 Radiation

The energy transferred through the electromagnetic waves is called as radiation heat transfer.

$$q = \sigma\varepsilon\ \mathrm{A}\left(\mathrm{T}_{\mathrm{surface}}^4 - \mathrm{T}_{\mathrm{fluid}}^4\right)$$

where,

σ	Stefan Boltzmann constant,
ϵ	Emissivity.

4.2.2 *Cold Plates for Portable Electronic Cooling*

The method allows use of the metal plate (cold plate) between electronic component (source of the heat) and the working fluid which collects the heat from metal plate. The method is used to cool the micro-electronic circuits require higher thermal conductivity and higher heat flux carrying capacity. The liquids have a higher capacity to carry heat compared to the air. The method which facilitates to use liquids in cooling of the electronic systems is use of cold plates. The simple sketch of the cold plates used in the cooling applications is shown in Fig. 4.2. The cold plates are very simple in construction which includes cold plate surface/s (either on one side or both side), which are mounted on the hot zones created by the system (e.g. Electronic components generating heat) from which heat is to be removed. The heat collected by the surface of the cold plate is supplied to the working fluid flowing through the passages by convection mainly. Depending on the nature of the working fluid, the temperature is increasing or it is converted into the vapour phase. Figure 4.2 shows following locations, entry for the cold working fluid, front side and back side surfaces for collecting heat from system and outlet for the hot working fluid. The collected heat by working fluid can then be rejected at a required place. The working fluids used in the cold plates are single-phase or two-phase substances. The single-phase working fluids are oil-based fluids. The two-phase working fluids are mainly dielectric fluids and different refrigerant series.

The different arrangements of the cold plates are shown in Figs. 4.3, 4.4, 4.5 and 4.6. Figure 4.4 shows the arrangement of batteries combined together without addition of the cold plates in between them.

Figure 4.5 gives the clear picture of how cold plates are arranged between the batteries. It also shows the holding supports required in the arrangement.

This arrangement includes the use of cold plates between the batteries and fans placed on both the sides of the module. The performance of this system is better than the first module because it includes the heat collection from the hot battery surfaces by working fluid in the cold plate and the air circulation by the fan. The air used in

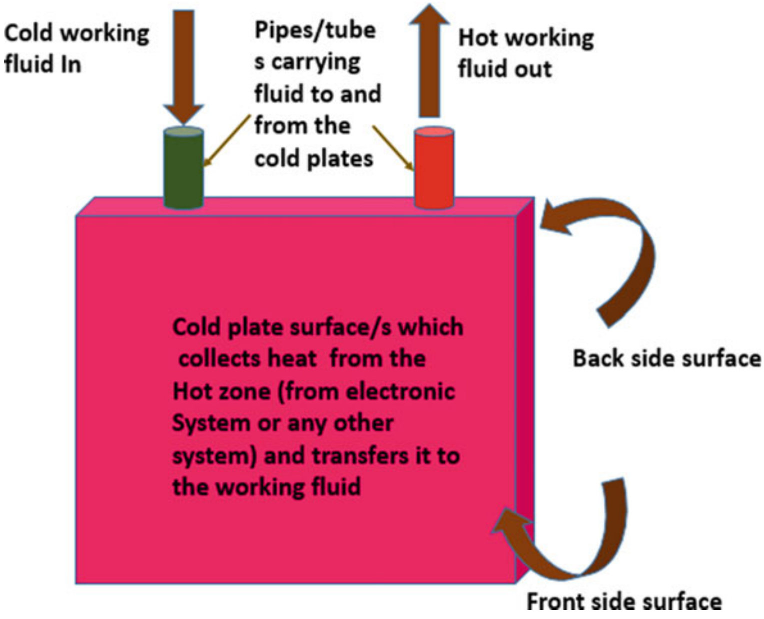


Fig. 4.2 Simple cold plates used in the cooling applications

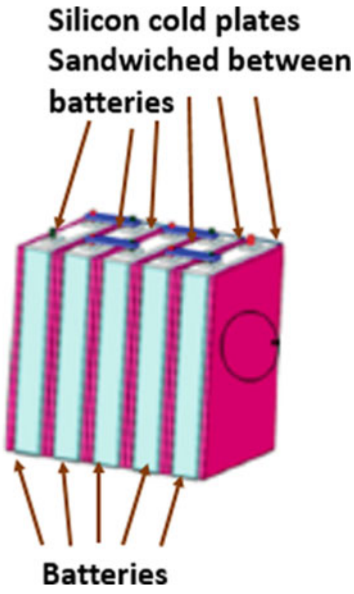


Fig. 4.3 Silicon cold plates sandwiched between the batteries (Li et al. 2019)

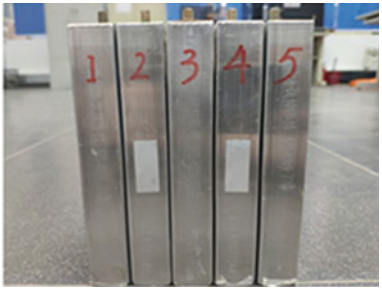


Fig. 4.4 Normal module (without cold plates) (Li et al. 2019)

Fig. 4.5 Cold plates of silicon material are placed in between batteries (Li et al. 2019)

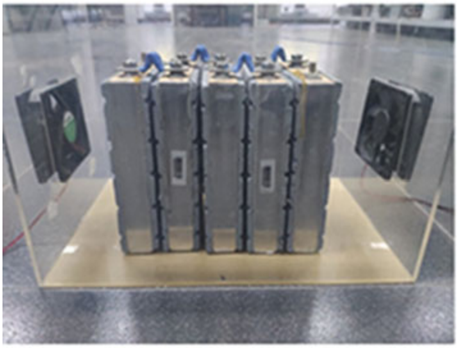


Fig. 4.6 Cold plates of silicon material and air flow circulation over it by fans (Li et al. 2019)

the system has a low thermal conductivity and hence the heat dissipation rates can be decreased.

Figure 4.7 shows the module in which the cold plates made from silicon are connected to the copper tubes. The performance of the system is improved because of the higher heat dissipation by copper tubes. Table 4.1 presents the data related to different types of the cold plate designs and related data.

The working fluids used in the cold plates should have following properties:

(a) Higher thermal conductivity (required to carry maximum possible heat from the hot zones)
(b) Higher specific heat (required to raise the temperature of the working fluid at the fast rate and to ensure the collection of the heat is performed at faster possible rates.
(c) Lower viscosity (This property is important for the faster fluid movement and to allow the lowest possible size of the tubes used for cold plates)
(d) Freezing point should be as low as possible (to avoid its freezing on the inner surface of the pipes)
(e) Higher flash point (to avoid explosions in the system)
(f) Low toxicity
(g) Low corrosion

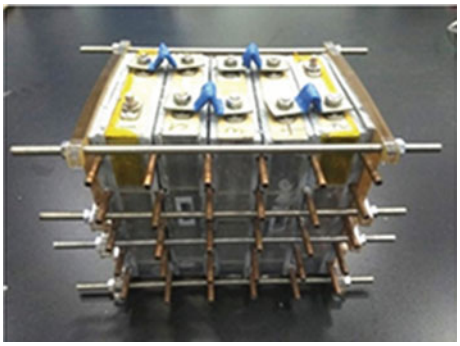
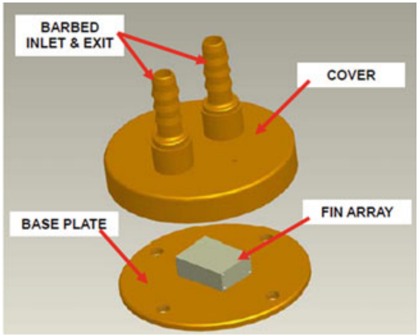
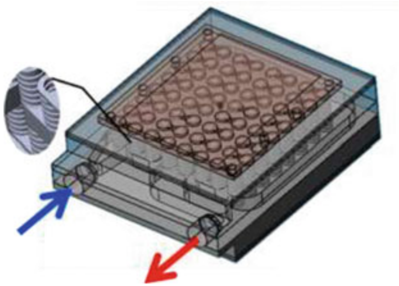


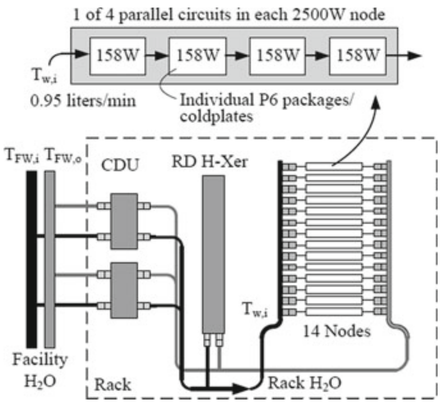
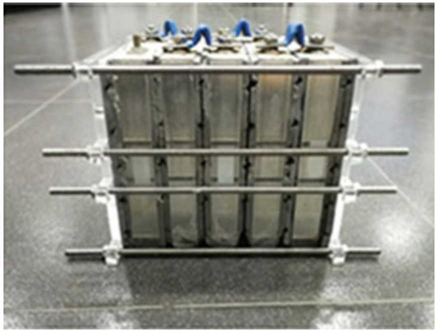
Fig. 4.7 Cold plates of silicon material connected to the copper tubes (Li et al. 2019)

Table 4.1 The different cold plate designs

Sr. No.	Authors	Design of the cold plate	Material used	Applications
1	Sukhvinder Kang et al. (2007)		Copper disc-shaped and water-based fluid	CPU cooling and GPU cooling
2	Sukhvinder S. Kang (2012)		Vortex liquid plate design and water glycol coolant	IGBT cooling

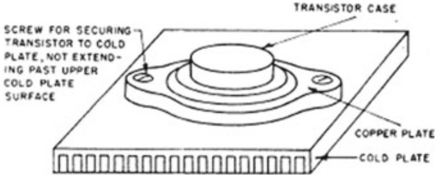
(continued)

Table 4.1 (continued)

Sr. No.	Authors	Design of the cold plate	Material used	Applications
3	Levi Campbell (2012)		Water-cooled cold plates	CPU cooling for IBM p575 supercomputer
4	Li et al. (2019)		Silicon cold plates with water flowing through the tubes	Used for thermal management of the batteries

(continued)

Table 4.1 (continued)

Sr. No.	Authors	Design of the cold plate	Material used	Applications
5	Mark (1958)		Aluminium cold plates used air as working fluid	Transistor cooling

(h) Higher thermal stability (to maintain the required properties in the fluid)
(i) Higher chemical stability
(j) Low cost
(k) Easily available.

The commonly used working fluids in the cold plates are as follows:

(a) Water
(b) Deionized water
(c) Inhibited Glycol and water solutions
(d) Dielectric fluid.

Some of the commonly used working fluids in cold plates along with their properties have mentioned in Table 4.2.

Advantages

(a) Simple in construction
(b) This method does not require the additional power to cool the system
(c) The additional surface area needed to enhance the heat transfer is not required (e.g. in case of heat sinks it is required)
(d) It can be directly connected to the electronic components
(e) Localized cooling of the electronic components is possible
(f) The heat transfer capacity is higher compared to the air cooling system
(g) Because of number of cold plate materials available in the market, weight of the system can be reduced by proper selection of the material
(h) Less space is required for its installation
(i) Can be operated in any orientation by setting the required flow direction
(j) No moving parts and hence less maintenance is required
(k) No noise and vibrations are generated in the system.

Disadvantages

(a) Because of more number of connected parts, chances of failure increases
(b) It needs working fluid to carry away heat from the electronic system (water cannot be used all the time)
(c) This system needs the micro channels for the flow of liquid which are to be fabricated by precise techniques and hence cost increases
(d) Pressure drop in the micro channels is main trouble (maintaining required flow rate is problematic).

Applications

(a) Cooling of the computer CPU
(b) Cooling of the micro-electronics (IGBT)
(c) Cooling of transistor

Table 4.2 Common working fluids suitable to use in cold plates and their properties (Rowe 1995, Thermal systems manual)

Working fluid in cold plate	Freezing point in °C	Flash point in °C	Viscosity in kg/ms	Thermal conductivity In W/m K	Specific heat, J/kg K	Density, kg/cu. m
Aromatic (DEB)	< -80	57	0.001	0.14	1700	880
Silicate ester (Coolanol 25 R)	< -50	>175	0.009	0.132	1750	900
Aliphatic (PAO)	< -50	>175	0.009	0.137	2150	770
Silicon	< -110	46	0.0014	0.11	1600	850
Fluorocarbon	< -100	None	0.0011	0.06	1100	1800
EG/Water (50% EG by volume and 50% water by volume)	−37.8	None	0.0038	0.37	3285	1087
PG/Water (50% EG by volume and 50% water by volume)	−35	None	0.0064	0.36	3400	1062
Methanol/water (40% methanol by wt. and 60% water by wt.)	−40	29	0.002	0.4	3560	935
Ethanol/water (44% by wt. Ethanol and 56% by wt. water)	−32	27	0.003	0.38	3500	927
Potassium format/water (Potassium 40% by wt. and Water 60% by wt.)	−35	None	0.0022	0.53	3200	1250
Ga–ln–Sn	−10	None	0.0022	39	365	6363

(d) Cooling of the battery
(e) Cooling of higher power lasers
(f) Cooling of fuel cells
(g) Cooling of medical equipments
(h) Cooling of motor drives.

4.2.3 Convective Air Cooling

This is the old and simple method used to cool the electronic systems. In this method, the naturally available air is used to cool the electronic systems. This method utilizes the concept of density difference to carry away heat from the systems. The cold air (with more density) is supplied to the system (to be cooled), it absorbs heat and becomes hot (with less density). The buoyancy effect pushes the less dense air upward and the fresh air can again be supplied at the bottom or the side of the system. This process of supplying the air at the bottom and its removal at the top or side of the system will be continued constantly to remove heat. Looking at the requirement of the system vents are provided at the top or the side of the electronic systems (for outgoing air) and at the bottom or side (for incoming fresh air). The heat flux carried in this method depends on the amount air supplied and the space which is available to carry the heat flux from the system. The distribution of temperatures on IC chips was analyzed using the ANSYS FLUENT in mixed convection mode (Mathew et. al. 2018).

The Newton's law of cooling can be used to find out how much heat flux is carried by air. The following is the equation to find out the heat flux (Incropera 2007 Edition)

$$Q = hA(Ts - Ta)^b$$

where,

Q	Heat carried away by the air, W
h	Heat transfer coefficient, W/m^{2}K
A	Cross-sectional area of the surface, m^2
Ts	Temperature of the source of heat or electronic surface, K
Ta	Temperature of the air, K
b	scaling exponent

Advantages

(a) Easy air availability and
(b) No power required to run this cooling system.

Disadvantages

1. The heat-carrying capacity depends on the natural air movement
2. It cannot be used when large amount of heat is to be carried
3. It cannot be used in micro-electronic systems because of space constraints.

Applications

(a) Electronic board cooling (comparatively large size)
(b) Condenser cooling in absence of the forced air draught.

4.2.4 Forced Air Cooling

This method includes creation of the forced draught of the air through external agency (e.g. Fans or blowers). This is very common method used to cool the electronic systems. The air is used as media to remove the heat from the electronic components.

Advantages

(a) The heat flux carrying capacity is more compared to natural type air cooling
(b) The size of the system can be reduced for the same heat flux carrying capacity
(c) The air supply and removal vents location can be changed based on orientation and space availability
(d) Easy air availability.

Disadvantages

(a) It needs power to drive the fans or blowers, etc.
(b) Cost increases because of the additional accessories
(c) The amount of heat carried is less compared to other recently developed cooling techniques which use the liquid coolants.

Applications

(a) Computer CPU cooling
(b) Laptop battery cooling
(c) Cooling of an electronic chip
(d) Cooling of the LEDs
(e) Cooling of the Inverters.

4.2.5 Heat Pipes

Heat pipes have found to be the best method for portable electronic cooling devices. The heat pipe technology is used because of its simple structure, high efficiency, cost-effective and flexibility. The heat pipe uses the working fluids whose phase change can be used to collect the heat from one location and to transfer it to the another location. It is effectively used in the portable electronic devices for cooling purposes because of its capacity to handle the heat is more than the generally used heat sinks of higher thermal conductivity (e.g. Copper or Aluminium). The heat pipe facilitates large amount of heat transfer with minimum temperature drop.

4.2.5.1 Principle of Operation of the Heat Pipe

The operation of the heat pipes depends on collection of the heat at the evaporator's location (Working fluid collects the heat from the electronic device which is heated) and discharging the heat at the condenser's location (working fluid rejects the heat in the cooling media or to the environment). The simple construction of the heat pipe is shown in Fig. 4.8. In the construction of the heat pipe following components play a significant role (a) Evaporator—The heat transfer takes place from the electronic device (hot spot) to the heat pipe and then it's given to the working fluid which helps in the evaporation of the fluid (Heat collection process).

(b) The working fluid in the vapor form is transferred from the evaporator to the condenser by pressure drop in the fluid.

(c) Condenser—The working fluid reaching in the vapour form is converted into liquid form (Heat rejection process).

(d) Wick –The working fluid in the liquid form returns from condenser to the evaporator through wick by the influence of the capillary action and pressure drop.

The main condition to get the movement of the working fluid in the heat pipes is

$$\Delta P_{\text{capillary}} > \Delta P_{\text{liquid}} + \Delta P_{\text{vapour}} + \Delta P_{\text{gravity}}$$

where,

$\Delta P_{\text{capillary}}$	The maximum capillary force inside the wick or structure
ΔP_{liquid}	Pressure drop required to transfer the fluid from condenser to evaporator
ΔP_{vapour}	Pressure drop required to transfer the fluid from evaporator to condenser

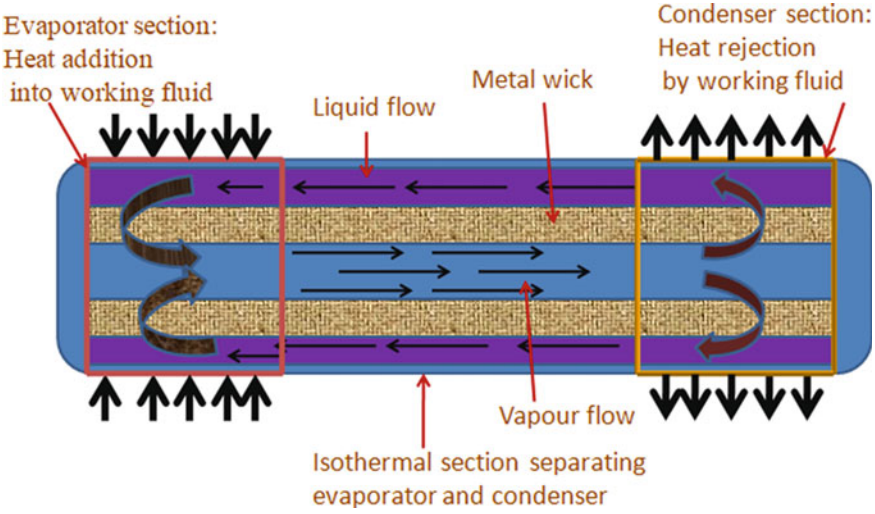


Fig. 4.8 Principle of operation of the heat pipe

$\Delta P_{\text{gravity}}$	Pressure drop because of the gravity force (it depends on the orientation of the heat pipe)

$$\Delta P_{\text{liquid}} = \frac{\mu_{\text{liquid}}\, L Q}{\rho_{\text{liquid}} K A w h f g}$$

where,

μ_{liquid}	Viscosity of the working fluid in the liquid form
L	Effective length used for the transfer of the fluid in heat pipe,
Q	Fluid flow rate
ρ_{liquid}	Density of the working fluid
K	Permeability of the wick structure
Aw	Wick cross-sectional area
hfg	Latent heat of vaporization of the liquid.

The vapour pressure drop can be calculated from the following formulae

$$\Delta P_{\text{vapour}} = \frac{16\mu_{\text{vapour}} L_{\text{effective}}\, Q}{2\frac{D_{\text{vapour}}^{2}}{4} A_{\text{vapour}} \rho_{\text{vapour}} h_{fg}}$$

where,

μ_{vapour}	Viscosity of the vapour phase of the working fluid
$L_{\text{effective}}$	Effective length
A_{vapour}	Cross-sectional area of the vapour chamber
ρ_{vapour}	Density of the vapour
h_{fg}	Latent heat
Q	Fluid flow rate
D_{vapour}	Distance of the vapour chamber

The maximum pressure drop in capillary is calculated as follows

$$\Delta P_{\text{capillary}} = \frac{2\sigma_{\text{liquid}}}{r_{\text{effective}}}$$

where,

$\Delta P_{\text{capillary}}$	Maximum pressure drop in the capillary
σ_{liquid}	Surface tension
$r_{\text{effective}}$	Effective radius of the wick pores

The maximum allowable heat transfer is

$$Q_{\max} = \left(\frac{\rho_{\text{liquid}} \sigma_{\text{liquid}} h_{fg}}{\mu_{\text{liquid}}}\right)\left(\frac{A_w K}{L_{\text{effective}}}\right)\left(\frac{2}{r_{\text{effective}}} - \frac{\rho_{\text{liquid}} g L_{\text{effective}} \sin \emptyset}{\sigma_{\text{liquid}}}\right)$$

where,

Ø The angle between heat pipe axis and horizontal (This is considered to be positive when the evaporator is installed above the condenser and it is negative for opposite case)

If, Ø = 0,
Then the equation is modified as follows,

$$Q_{\max} = \left(\frac{\rho_{\text{liquid}}\sigma_{\text{liquid}}h_{fg}}{\mu_{\text{liquid}}}\right)\left(\frac{A_w K}{L_{\text{effective}}}\right)\left(\frac{2}{r_{\text{effective}}}\right)$$

4.2.5.2 Heat Pipe Structural Details

The structure of the heat pipe includes three parts which are, (a) The container used in the pipe, (b) wick structure used and (c) working fluid used for handling the heat (may be heat collection or heat rejection).

The Container Used in the Heat Pipe

The container of the heat pipe is a metallic body that allows flow of heat through its structure from and to working fluid. Generally, it is selected based on following parameters,

(a) High thermal conductivity
(b) Good wettability
(c) Good machinability
(d) Ability to get welded easily
(e) High strength to weight ratio
(f) Good compatibility with the surrounding
(g) Good compatibility with the working fluid
(h) Less porous
(i) Ability to maintain minimum temperature difference between wick structure and the heat source.

Wick Structure Used

This is very important part of the heat pipe which helps to transfer the fluid from condenser to the evaporator by capillary action in any required orientation/position of the heat pipe.

Fig. 4.9 Wick with sintered structure (Elnaggar 2016)

The wick structures are observed in following types.

(a) Wick with sintered structure
(b) Wick with grooves
(c) Wick with screen mesh.

All these wicks are discussed in detail below,

(a) Wick with sintered structure

Figure 4.9 shows wick with sintered structure. In this type of wick, very small pore size increases capillarity force generated in the process, which is essential during the antigravity applications. The permeability is low. This type of wick helps to maintain the very small temperature differences between condenser and the evaporator. The lower thermal resistance in the arrangement leads to improve the thermal conductivity of the heat pipe. The cylindrical wicks are shown in Fig. 4.9 The Permeability values of the rectangular heat pipes were similar to the cylindrical ones. The copper powder can be sintered at a temperature of 800–1000 °C.

(b) Wick with grooves

Figure 4.10 shows the wick picture with grooves fabricated on the internal surface of the channel carrying the working fluids. This can be used in any orientation but with low capillary force used to drive the fluids. It's used for the small-capacity power applications. The different parameters which are important while designing this type of wick is size of the grooves and its material.

(c) Screen mesh wick

The screen mesh wick is shown in Fig. 4.11. This wick shows very good characteristics when more power is to be handled at any random orientation. In this type of

Fig. 4.10 Wick with grooves (Elnaggar 2016)

Fig. 4.11 Screen mesh wick (Elnaggar 2016)

the wick structure major role is played by the wick thickness, number of layers of fiber, material of the fiber used and type of the fluid used.

Characteristics of the working fluids used in the heat pipes.

The working fluid which is circulated in the flow channels plays a very important role in heat pipes. It has to carry heat from one location and drop it to the other location. The working fluid must have following characteristics.

1. It must not react with the wick structure and materials of the walls
2. Lower viscosities
3. It should have higher thermal conductivity
4. It should have higher latent heat

Table 4.3 Properties of the working fluids used in the heat pipe (Elnaggar 2016)

Working fluid	Boiling points (°C)	Melting points (°C)	Useful working range (°C)
Helium	−261	−271	−271 to−269
Nitrogen	−196	−210	−203 to−160
Ammonia	−33	−78	−60 to 100
Acetone	57	−95	0–120
Methanol	64	−98	10–130
Flutec PP2	76	−50	10–160
Ethanol	78	−112	0–130
Water	100	0	30–200
Toluene	110	−95	50–200
Mercury	361	−39	250–650

5. It should possess good wet ability with the wick structure and material of the wall
6. It should be thermally stable
7. It should have good surface tension.

The properties of the working fluids used in the heat pips are presented in Table 4.3. The distilled water is used as a working fluid normally but many scientists have conducted trials by adding the nano-particles in the water to check the performance. Other fluids listed in the table have been also used for electronic cooling.

4.2.5.3 Types of the Heat Pipes

Cylindrical Heat Pipe

In this type of the heat pipe, the arrangement to circulate the working fluid is provided in the structure (through wicks). This is one of the old types of the heat pipe and it is simple in construction.

Figure 4.12 shows the cylindrical heat pipe which involves three sections mainly (a) evaporator section, (b) middle section (adiabatic zone) and (c) condenser section.

The studies conducted earlier show that design of the cylindrical heat pipe with very less heat loss at the middle section is possible. The cylindrical copper heat pipe with working fluid water was tested. The two layers of the wicks were used with 150 meshes. The temperature drops of less than 5 K were observed in their studies. The steady-state value of the temperature of the vapour was found to be increasing with either increasing the heat input or decreasing the water flow rate.

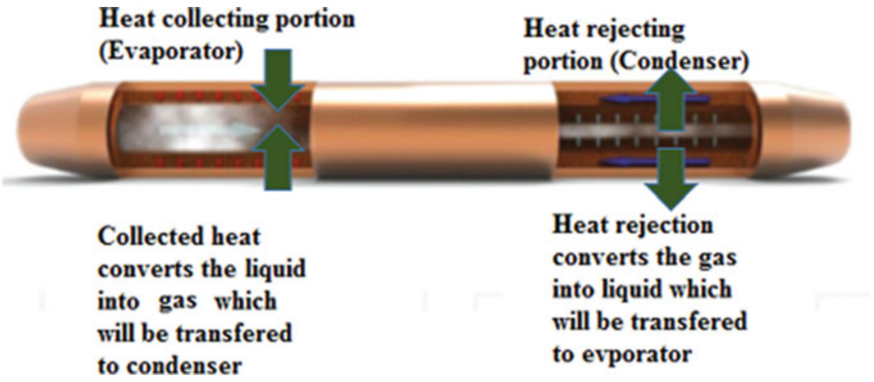


Fig. 4.12 Cylindrical heat pipe (Elnaggar 2016)

Flat Heat Pipe

The flat heat pipe consists of the evaporator section and the condenser section which is rectangular in shape. One section of the evaporator can be maintained at the middle of the device and remaining three sections of condenser placed surrounding the evaporator section. Figure 4.13 shows the flat type of the heat pipe. The model in the figure was prepared by the Wang and Vafai (2000). Temperature difference was found to be uniform on the surfaces. The coefficient of the heat transfer was calculated and it was 12.4 W/m^2 °C and the fluxes was varying between 425 and 1780 W/m^2.

Micro Heat Pipe

Figure 4.14 shows the micro heat pipes. Micro heat pipes have fabricated as wick with groove of sharp edges. The sharp edges provided improve the capillary pressure to force the liquid. Figure shows the different shapes of the micro heat pipe which were fabricated and tested by (Hung and Seng 2011). Micro heat pipes with different designs were fabricated square star (4 corners), hexagonal star (6 corners), octagonal star (8 corners) grooves and corners with width ‘w’ were tested. The configuration included apex angles which were varied between 20° and 60°. The following important parameters play very important role in the design of the micro heat pipe, which were total length, area of the cross-section, shape of the cross-section, number of corners and acuteness in the angles at corners.

Oscillating/Pulsating Heat Pipe

The schematic diagram of the oscillating heat pipe is shown in Fig. 4.15. The construction of this type of the heat pipe does not include the wick structure to

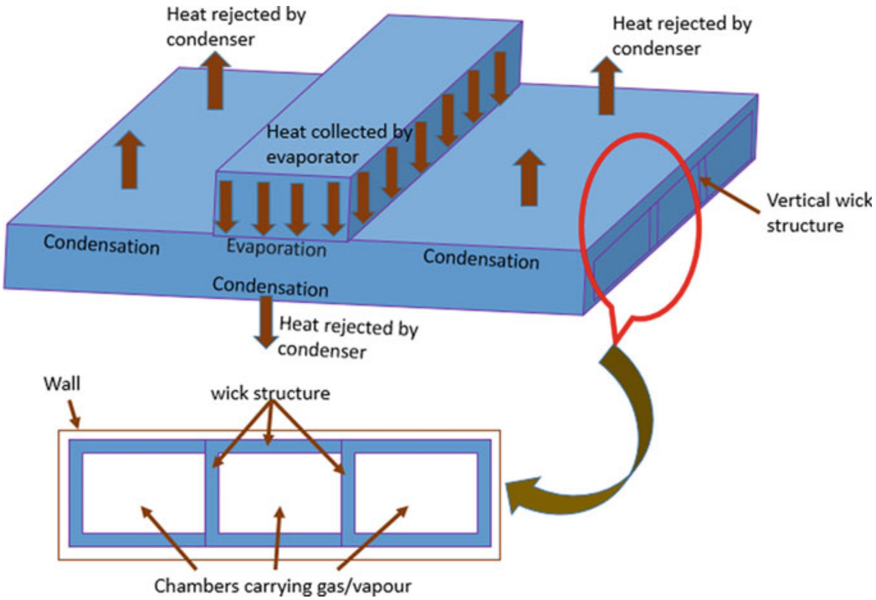
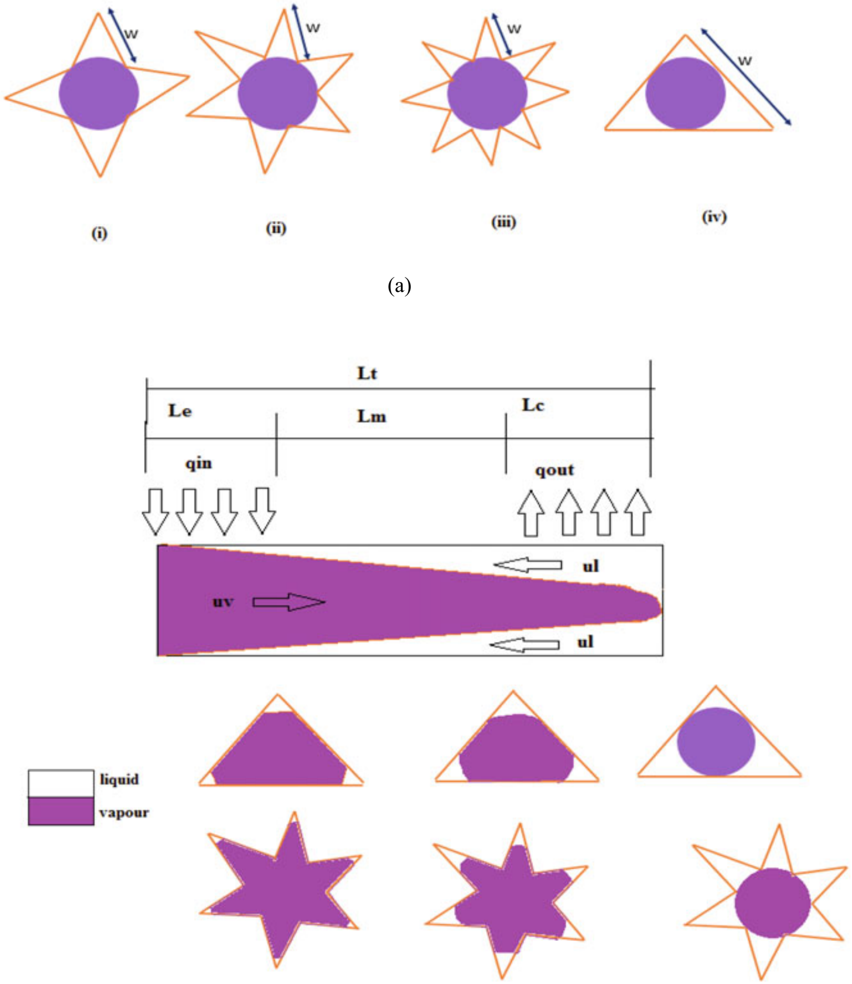


Fig. 4.13 Flat heat pipe (Elnaggar 2016)

transport the condensate back to heating section and hence there is no scope for countercurrent movement of liquid and vapour in pipeline. The fluctuation of the pressure waves drives the self-exciting oscillation inside the channels/passages, the oscillation creator accelerates the heat transfer from end to end. The heat transfer is enhanced with the oscillating mechanism in this type of the heat pipe. The changes in the pressure results into the increasing the volume and the contraction during the change of phase from vapour to liquid results into thermally excited oscillating motion of the liquid plugs and vapour bubbles between evaporator section and condenser section. This was a result of the flow of both liquid and vapour in the same direction. The important parameters which control the performance of this type of the heat pipe are diameter of the tube, number of turns provided, filling ratio, nano fluids, etc.

4.2.5.4 General Design Consideration for Heat Pipes

The analytical and numerical methods can be used for designing the heat pipes. The measurement of the pressure and the velocity inside the heat pipe is not possible because of its smaller size. The calculations by analytical approach give an idea about these parameters. The numerical approach is very useful in understanding the thermal resistances and the heat flow conditions in the heat pipes by knowing the temperature profiles generated at various locations. The successful running of the cooling systems used in the electronic devices depends on the characteristics of the flowing fluid in the system.



(a)

(b)

Fig. 4.14 micro heat pipes (Elnaggar 2016). (a) Different cross-sectional areas of the heat pipes (i) square star grooves, (ii) hexagonal star groove, (iii) Octagonal star groove, (iv) equilateral triangle. (b) Optimally charged equilateral triangle and star groove micro heat pipes (Lt-total length, Le-Evaporator length, Lc-Condenser section length, Lm-length of the middle section, qin-heat in the system, qout-heat out from the system, ul-liquid velocity, uv-vapour velocity)

Considerations While Designing the Heat Pipe Systems

(a) The fluid used in the system is incompressible, it is at steady state, 2D analysis is accurate and flow is laminar.
(b) The working fluid is ideal gas
(c) Phase change does not lead to heat generation

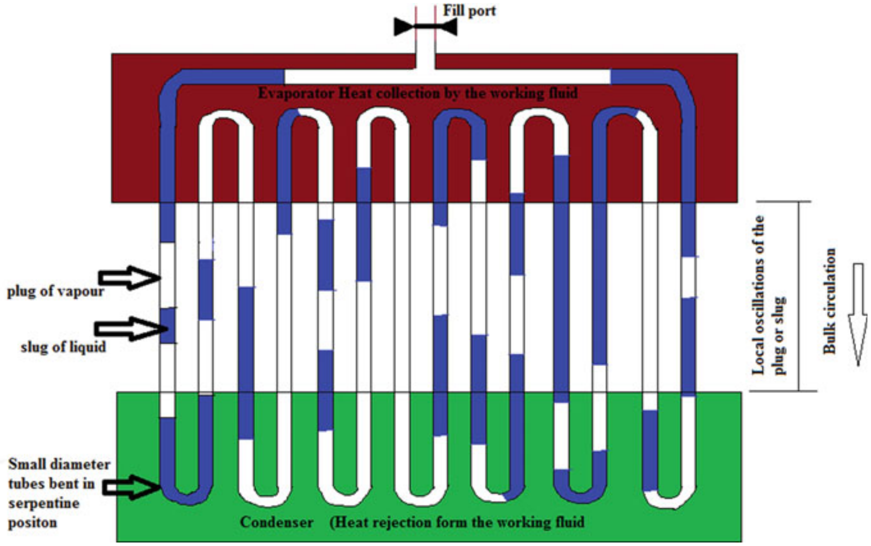


Fig. 4.15 Oscillating heat pipe (Elnaggar 2016)

(d) No chemical reaction
(e) Physical properties are supposed to be constant
(f) Proper coupling between liquid–vapour, liquid-surface and vapour surface interfaces.

Advantages

(a) Ability to transfer large amount of heat at very small temperature difference between the condenser and evaporator section, because of very high thermal conductivity (cycle operated on two-phase cycle)
(b) No moving components and hence its maintenance-free, noise-free, vibrations free and more life
(c) Size of the heat pipe can be very small and easily installed in the portable electronic devices
(d) The device can be operated at any orientation and hence can be used in portable electronic devices.
(e) It can be fitted at a location where conventional fans can't be placed
(f) The sizes of the condenser and evaporator could be different with controlled evaporation and condensation rates. It helps to accommodate the heat pipes in available space.

Disadvantages

(a) Less suitable for the applications with less space availability
(b) The configurations of the heat pipes with multiple pipe design need more space and it is costlier
(c) Not suitable for high-power micro-electronic systems
(d) Less flexibility compared to the vapour chambers (cannot be placed in the systems which have uneven platforms).

Applications
The heat pipes have been used in the following applications mainly:

(a) Refrigerator systems for cooling purposes
(b) Air conditioning systems for cooling purposes
(c) Heat exchanger systems for heat collection and rejection
(d) Capacitor cooling
(e) Transistor cooling
(f) Desktop cooling
(g) Laptop cooling.

4.2.5.5 Heat Pipes for Computer Applications

The biggest benefit of higher thermal conductivity of the heat pipes leads to increases its applications in electronic cooling systems. In heat pipes, heat transfer rate is very fast. The scientists have suggested a perfect match of heat pipes in electronic cooling systems, notebooks, personal computers, etc. The systems which include integration of the fins and the heat pipes to cool the high power and high-temperature systems were developed by Ligierski and Wiecek (2001). The heat pipe system used to cool the desktop PC is shown in Fig. 4.16.

The simple cooling systems with due modifications (heat pipes with cooling fins) were compared with the basic systems by Kim et al (2003). The system showed reduced noise levels and increased cooling effect.

The systems proposed by the Yu and Harvey (2000) designed heat pipe for the Pentium II machine and found that the performance of the machine in terms of the mechanical and thermal management systems was improved.

The system of heat pipes with heat sink was fabricated to reduce the noise level in cooling system of the PC CPU which includes heat sink with fan.

The design (as shown in Fig. 4.17) which includes the close-end oscillating heat pipes which were used for cooling of the CPU of the of PC, fabricated by Wang et al. (2007).

The diagram included the evaporator Sect. (0.05 m) and the condenser Sects. (0.16 m) with vertical orientation. The working fluid used was R134a. The model was developed to take a load of 70 W. The system performance was improved

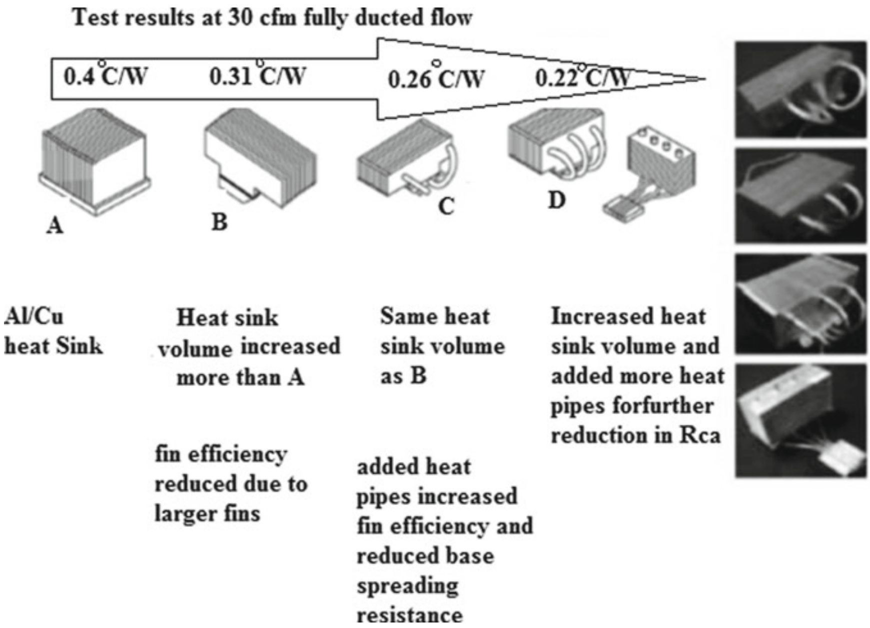
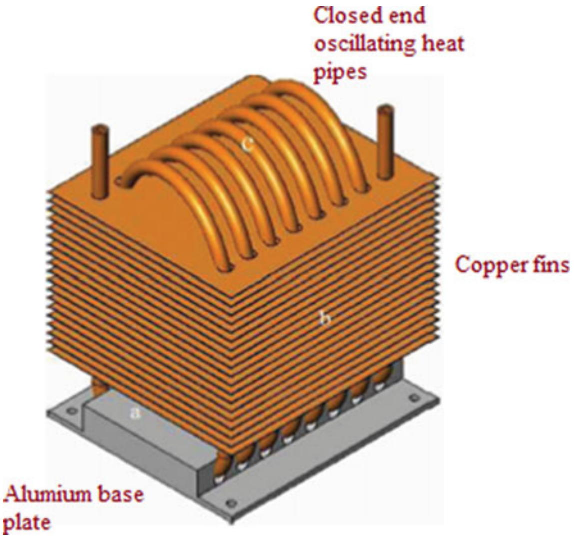


Fig. 4.16 Cooling systems (heat sinks with heat pipes) used to cool the desktop PCs (Elnaggar 2016)

Fig. 4.17 Cooling system to take load on PC CPU (Elnaggar 2016)



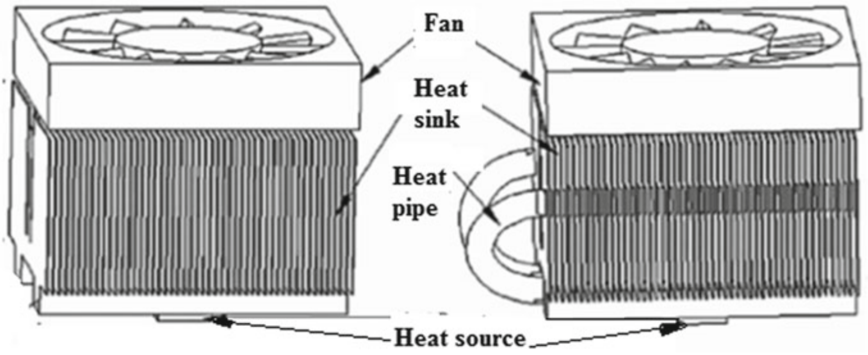


Fig. 4.18 Heat sink with and without heat pipe integration (Elnaggar 2016)

compared to the conventional heat sink system. The design of heat sink with and without heat pipe integration is shown in Fig. 4.18.

The heat pipe with U shape fitted in the fins (as shown in Fig. 4.19) was developed to cool the high-frequency processors (Intel core 2 duo, Intel core 2 Quad, AMD Athlon 64 series, AMD phenomenon series). This system included the phenomenon of transfer of the heat from the CPU to the flat base plate and then to the heat sinks and heat pipes. The calculation of the thermal resistance was the main target in the study conducted by Wang (2008). The lowest thermal resistance value of 0.27 °C/W was observed during their studies.

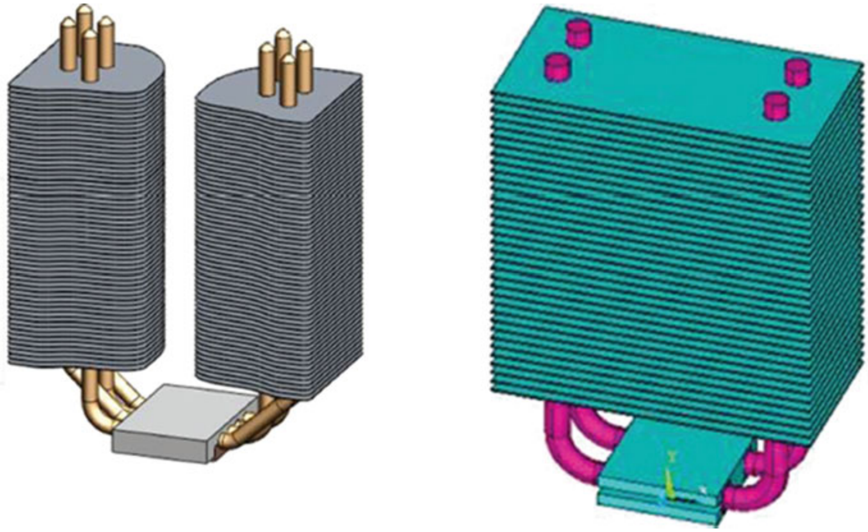


Fig. 4.19 U-shaped heat pipes used in cooling system of desktop **a** Multiple heat pipes and, **b** Twin heat pipes (Elnaggar 2016)

Table 4.4 Different heat pipe designs (Elnaggar 2016)

Sr. No	Type of the heat pipe	Number of heat pipes used in the system	Arrangement of the heat pipe	The total thermal resistance obtained	Authors
01	L-type	3	Horizontal	0.475 °C/W	Kim et al. (2003)
02	U-type	2	Horizontal	0.27 °C/W	Wang et al. (2007)
03	U-type	2 and 4	Horizontal	0.24 °C/W	Wang (2008)
04	U-type	1	Horizontal	0.5 °C/W	Liang and Hung, (2010)
05	L-type	6	Vertical	0.22 °C/W	Wang (2011)
06	U-type	4	Vertical	0.181 °C/W	Elnaggar et al (2011a, b)
07	U-type	2	Vertical	0.2 °C/W	Elnaggar et al (2011a, b)

The velocity and heat input played a significant role in controlling the thermal resistance in the cooling systems designed above. The cooling system performance of the vertical arrangement was found to be superior to the horizontal arrangement. The lowest value of the thermal resistance was observed to be 0.181 °C/W for heat load equal to 24 W and velocity of coolant equal to 3 m/s. The second cooling system was designed to increase the effective thermal conductivity to improve the performance of the system. The data related to the different types of the heat pipes is presented in Table 4.4.

Important Points

(a) The heat sinks with heat pipes are more efficient systems compared to conventional systems.
(b) The orientation of the system plays a significant role in deciding the performance of the cooling system.
(c) Vertical orientation is superior in performance compared to the horizontal one
(d) Multi-heat pipe’s performance is better than the single heat pipes.

The system which uses heat pipes to cool the laptop system is shown in Fig. 4.20. Elnaggar et al. (2013) developed system which was implemented to cool the processor (size 10 mm X 10 mm) of the laptop. In the system, the heat pipe was fixed on the processor surface where heat is picked up by the evaporator section and transferred to the condenser section where it is rejected by conventional methods.

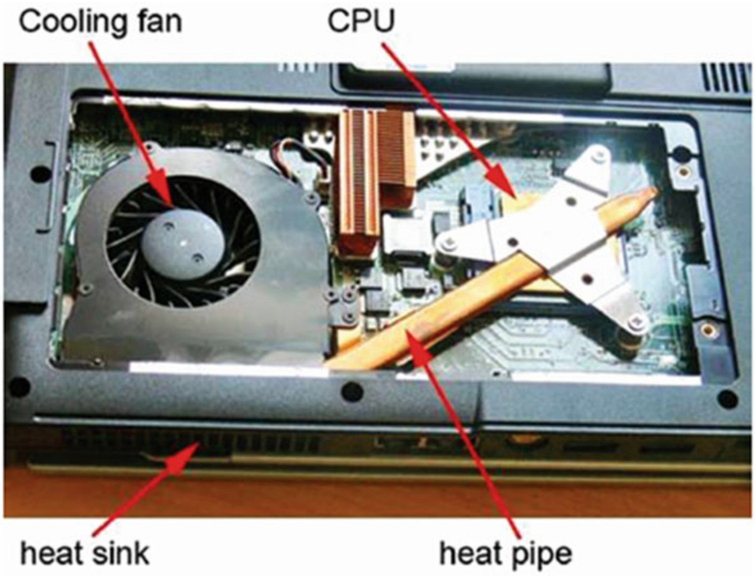


Fig. 4.20 Laptop cooling through the heat pipe system (Elnaggar 2016)

4.2.6 Peltier Cooling Devices

The Peltier cooling devices work on the principle of the Peltier effect. The Peltier effect was first introduced in the market in 1834. As per this effect when two dissimilar metals are connected together to form the junctions and if DC current is applied at these junctions, this causes a temperature difference across these junctions. The Peltier effect is also called as thermoelectric effect. The device which produces the Peltier effect is shown in Fig. 4.21. In this device the P- and N-type semiconductor material is sandwiched between these ceramic wafers. The ceramic material acts as a good electric insulator and increases the strength and rigidity of the system. The N-type semiconductor material has excess of the electrons and the P-type semiconductor material has deficit of it. The couple formed by N- and P-type semiconductors is shown in Fig. 4.21. The thermoelectric system used in cooling applications may have several hundreds of the couples working to generate cooling effect. The electrons from the P-type semiconductor material move to the N-type semiconductor material through the electric wires/connectors and the electrons attain the high energy absorbing state which is used to collect the heat from heat source (e.g. Electronic component). The electrons will continue its flow through the lattice structure and move from the N-type semiconductor material to the P-type semiconductor material and lower the energy level by dropping the heat at heat sink (location where heat is to be rejected).

The performance of the Peltier cooling device depends mainly on the temperature of the heat source (electronic component to be cooled), temperature of the heat sink

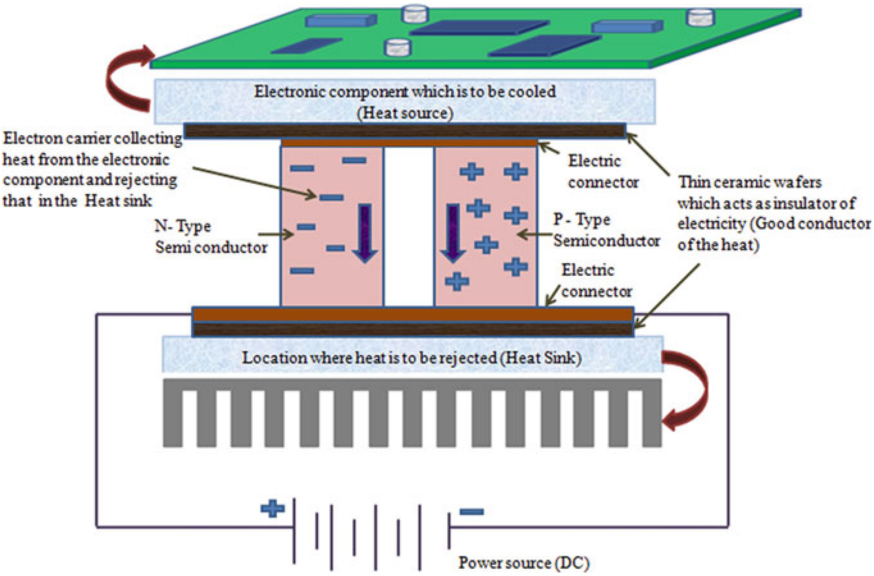


Fig. 4.21 Basic working principle of the Peltier cooling device

(location of the heat rejection) and amount of heat that is to be transferred/handled by the cooling system. The temperature and heat of the location (heat sink) where heat is to be rejected is calculated by using following mathematical Eqs. (4.1) and (4.2)

$$T_{\text{hot,side}} = T_{\text{ambient}} + R_{\text{thermal}} Q_{\text{hot,side}} \tag{4.1}$$

$$Q_{\text{hot,side}} = Q_{\text{cold,side}} + P_{\text{input}} \tag{4.2}$$

The temperature difference across the Peltier cooling module is calculated by the following Eq. (3).

$$\Delta T_{\text{Peltier device}} = T_{\text{hot,side}} - T_{\text{cold,side}} \tag{4.3}$$

where,

$T_{\text{hot,side}}$	The temperature of the hot side or sink side, K
$T_{\text{cold,side}}$	The temperature of the cold side or electronic component side, K
T_{ambient}	The temperature of the surrounding, K
R_{thermal}	The thermal resistance offered by the heat exchanger, K/W.
$Q_{\text{hot,side}}$	The amount of the heat rejected by thermoelectric device at its hot side or sink side, W

Table 4.5 Allowable temperature rise above surrounding

Sr. No	Modes of heat transfer	Allowable temperature rise at heat sink °C
1	Natural convection	20–40
2	Forced convection	10–15
3	Cooling by liquids	2–5 (this rise is considered above the coolant temperature)

$Q_{\mathrm{cold,side}}$	The amount of the heat collected by thermoelectric device at its cold side or electronic component side, W
P_{input}	The input electrical power supplied to the Peltier cooling device, W
$\Delta T_{\mathrm{Peltier\ device}}$	The temperature difference across the Peltier cooling device, K

The heat sink temperature close to ambient temperature helps in retaining the performance of the Peltier cooling device and in maintaining the required temperature on the cold side of the cooling device. If the thermal resistance of the heat sink is increasing because of any reason in that case, following are the allowable rise in the temperatures of heat sink above surrounding for different modes of heat transfer. The data of the Allowable temperature rise above surrounding for different modes in presented in Table 4.5.

The total heat load on the device includes following

(a) Heat load from the electronic components, because of its power consumption
(b) Heat load generated because of chemical reaction at various locations
(c) Heat load because of two close electronic or other components with temperature difference because of radiation
(d) Heat load because of convection
(e) Heat load because of the insulation losses
(f) Heat load because of the conduction losses through the metallic components (accessories used for connecting the parts screws, nuts, bolts, etc.)
(g) Heat load because of the transient response of the system (accumulated load).

Advantages

(a) No moving parts involved in the cooling system
(b) Two-fold use (Can be used as heater or cooler)
(c) No noise
(d) No vibrations
(e) No cooling fluids used in the circuits
(f) Less maintenance
(g) More life
(h) Leak proof
(i) Can be produced easily with small size
(j) Very much flexible.

Table 4.6 The materials used for preparing the Peltier device (Chanyoung et al. 2015)

Sr. No	Material of the Peltier device	Working temperature range, K
1	Bismuth telluride	Near to 300
2	Lead telluride	600–900
3	Silicon germanium	Up to 1300
4	Bismuth-antimony alloys	Near to 300

Disadvantage

(a) Costly for the same cooling capacities
(b) Lower cooling efficiency
(c) Needs power supply.

Applications of the Peltier Cooling Device
These devices are generally used for following purposes (a) heating, (b) cooling and (c) maintaining temperature.

(a) Cameras (Charge coupling devices also called as CCDs)
(b) The micro-processors used in electronic circuits
(c) The laser diodes
(d) The blood analyzing device
(e) The portable coolers used during picnics, etc.

The different materials used for fabricating the Peltier device and their working temperature ranges are mentioned in Table 4.6.

4.2.7 Synthetic Jet Air Cooling

The synthetic jet technology is well-proven technology in which flow of the air is generated with the help of the diaphragm (or actuator) movement in the cavity. The movement of the diaphragm is periodic and it is confined to one of the walls of the cavity. The simple sketch of the synthetic jet formation is shown in Fig. 4.22.

The different devices used for actuation are mentioned below,

Mechanical Drivers
Mainly pistons are widely used as an actuator under this category. This type of actuator can be used for producing the round synthetic jets. Important features of the mechanical drivers are as follows:

(a) These actuators are rigid and sturdy
(b) It cannot be used in small systems (limitation on size)
(c) Noise and vibrations is a big problem under fast running of the system
(d) Response time is more compared to other systems.

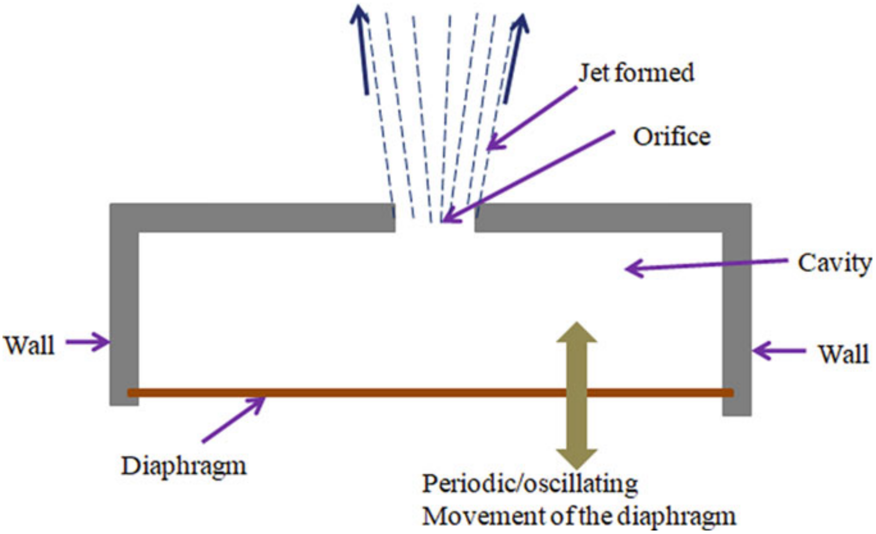


Fig. 4.22 Simple sketch of the synthetic jet actuator

Electromagnetic

The electromagnetic type of actuators is mainly solenoid actuators. Important features of electromagnetic type of actuators are as follows:

(a) Quick in response time
(b) Less vibrations and noise
(c) Flow control is easy
(d) Actuator movement control is precise
(e) More reliable.

Piezoelectric Actuator

The Bimorphs, thunder actuators, plasma actuators are the piezoelectric actuators used to generate the synthetic jets. The important features of the actuator are as follows:

(a) Quick response,
(b) Suitable for micro systems,
(c) Light in weight,
(d) Capability to get a very small displacement in given response time,
(e) Minimum energy consumption for the required output.

Acoustic Actuator

The best example of the acoustic actuator is the loudspeaker. This was used for underwater vehicle propulsion. Following are the important features of the acoustic actuator.

(a) Can be used in small systems
(b) The displacement of the actuator can be controlled easily
(c) Light in weight.

The most widely used diaphragms in this system are piezoelectric (preferred because of its less weight and power consumption abilities) and electromagnetic (preferred because of its reliability and low noise characteristics). The following main two strokes are performed to supply the required cooling air in this technique.

Compression Stroke

The upward movement of the diaphragm creates the compression stroke because of which the air collected in the cavity will be forced through the orifice present at the top of the system and vortices are generated in the downstream direction because of the boundary separation (Didden 1979). The vortices generated in the zones near to the orifice will be smaller in dimensions compared to the vortices in the zones away from the orifice. During this stroke, the vortices will vanish after some particular length in the downstream direction and continuous jet will be formed. The compression stroke working is shown in Fig. 4.23.

Suction Stroke

Figure 4.24 shows the suction stroke performed by the diaphragm. The downward movement of the diaphragm creates the suction of the air from ambient (zone near to the orifice) in the cavity. During this movement of the air the previously formed vortices during the compression stroke are pushed away from the orifice. If system is not running as per the design conditions, the vortex formed during the compression stroke is carried back to the orifice and required jet characteristics will not be obtained (Rampunggoon 2001).

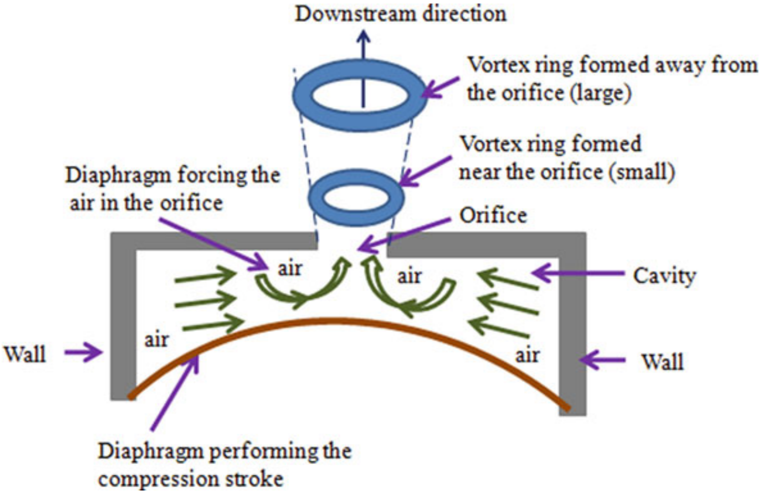


Fig. 4.23 Diaphragm performing the compression stroke

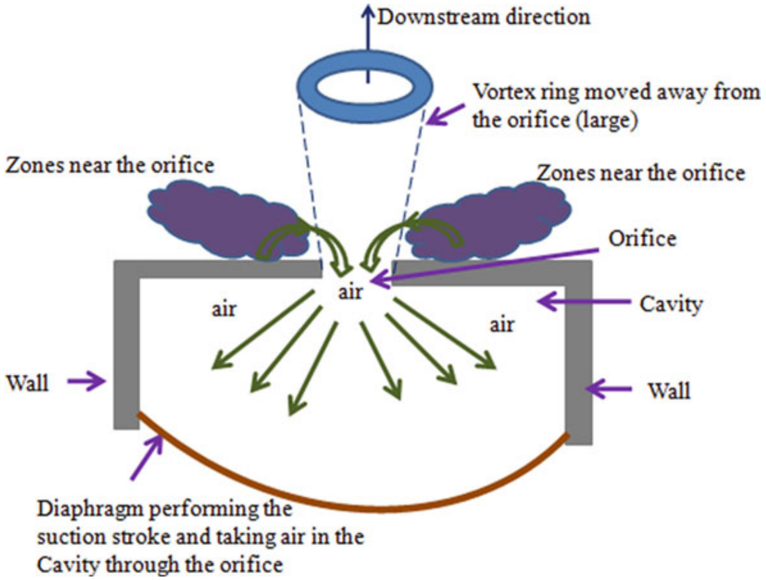


Fig. 4.24 Diaphragm performing the suction stroke

Advantages

(a) It has capacity to carry the higher heat flux from the electronics components even with the lower air flow rates
(b) The noise produced in this system is comparatively less
(c) High reliability of the system (Mahalingam et al. 2007)
(d) It can be connected to the electronic systems without the aid of any complicated fixtures (can be designed as per the requirement of the space)
(e) Construction costs are less
(f) Operated with less noise
(g) The size of the system is less compared to conventional cooling systems where natural convection is used
(h) More number of options available for the actuators
(i) It can be operated in any orientation (Cheung et al. 2009)
(j) Preparation of multiple orifices is easy to increase the flow rates.

Disadvantages

(a) The most of the actuators operated with electric power
(b) The cost increases when the synthetic jet cooling system is to be produced precisely in the small size as per the shape of the electronic system
(c) The cooling system with mechanical type of the actuators has less response
(d) The control of the flow rate increases the complexity of the design.

Applications

(a) Cooling of the electronic systems, e.g. Laptop, handheld PCs, controllers, etc.
(b) The transfer of the thermal energy (Gil and Wilk 2020; Arshad et al. 2020)
(c) Flow control (Gil 2019)
(d) For mixing of the fluids, e.g. automobile, medical, chemical, plastic industries (Le Van 2019).

4.2.8 Electrostatic Fluid Acceleration

The method involves the use of device called as electrostatic fluid accelerator to get the movement of the targeted fluid (e.g. air) in the required direction. This technique uses the Coulomb force to accelerate the electrically charged molecules of the fluid (e.g. air). There are mainly three steps that are important in order to get the movement of the fluid in this technique and these are mentioned below:

(a) Ionization of the working fluid particle
(b) Movement of the ionized and non-ionized working fluid particles in the downstream direction (through ion-ion or ion-neutral particle collisions)
(c) Deionization of the working fluid particle.

The air available is abundant and most of the times the working fluid used in the micro-electronic systems are air. Let us discuss the working principle with the help of air as a working fluid. The principle of the working of the electrostatic fluid accelerator is shown in Fig. 4.25.

(a) **Ionization of the working fluid particle**
In this step the air is ionized (also called as process of charging the air). The ions produced in these processes possess the effective/net electrical charge. The process used to ionize the air molecules is called as corona discharge. This process of corona discharge is very simple which does not require extreme conditions (e.g., high temperatures, low pressures, etc.).

(b) **The movement of the ionized particles in downstream direction**
The ionized particles will have a net charge because of which they will be repelled by the same charge electrode and attracted by the opposite electrode. The driving force is mainly created by creating the electric field across the electrodes. Out of all air molecules, some may not get ionized. So, when ionized particles are moving towards the oppositely charged electrodes, they travel to carry non-ionized particles with them. This process generates a thrust. The propelling of the ions from the electrode will bump these ions on neutral molecules and accelerate them. It is possible because of the electric field applied. The ions during this process supply the potent energy and generate kinetic energy in the molecules of the air (that is a process of accelerating the air molecules). Part of the energy is wasted to increase the air temperature or driving force is not created in the required direction.

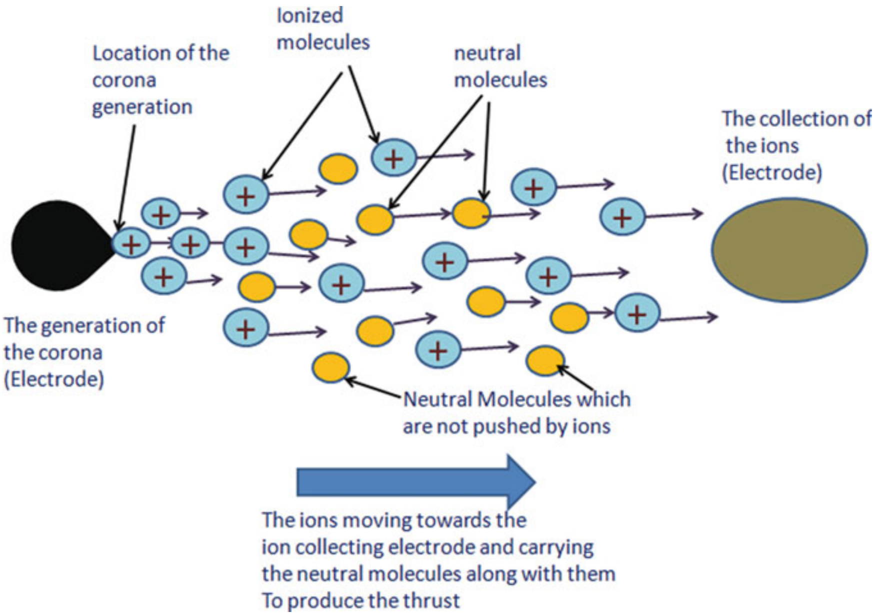


Fig. 4.25 The working principle of the electrostatic fluid accelerator

(c) **Losing the charge to electrode**
Once the ions reach to the electrode of opposite charge they will lose their charge by receiving the electrons from electrode. During this process, those ions which are not colliding with the electrode will be moving back upstream in towards the attracting electrode. In such situation addition electric field needs to be created to minimize this effect.

Advantages

(a) The generation of the near laminar profiles of the air with required control over flow velocity (Michael 2006)
(b) Flexibility in designing the system (very simple electrode geometry in solid-state)
(c) Manufacture is easy
(d) The amount of power consumption is low (Michael 2006)
(e) Benefit of carrying large amount of heat compared to conventional system and
(f) The ability to decrease the boundary layer formed between the solid–liquid interface within the closed structure (Michael 2006)
(g) No rotary parts and hence no vibrations and noise in the system
(h) The temperature of the working fluid (air) will be maintained.

Disadvantages

(a) Electric power consumption for ionization
(b) Limitations on the air flow rate because of the restriction on size of the device
(c) This system has the problem of the reverse air flow
(d) The chances of the sparking in the device are more if the electronic components (layers) are placed very near to each other
(e) The voltage supplied needs to be carefully controlled in order to get required corona strength.

Applications

(a) Cooling of the micro-electronics (e.g. micro-processor cooling **by thorn technologies**)
(b) Development of fluid flow pattern
(c) To filter the air (Michael 2006)
(d) To add the moisture content in the air (humidification) (Michael 2006)
(e) Audio speakers
(f) Propulsion of the small vehicles (Michael 2006).

4.2.9 Immersion Cooling Technology

The emersion cooling technology involves the use of liquids to collect the heat from the source (location where heat is generated). This technique is useful to remove more heat flux compared to the conventional method of removing heat with the help of heat sinks.

There are mainly two types available in this category; (a) Direct cooling and (b) Indirect cooling.

4.2.9.1 Direct Cooling

In this method, the liquid coolant supplied in the channels makes direct contact with the electronic component. The direct cooling arrangement is shown in Fig. 4.26. In this arrangement the cooling liquid is supplied at the bottom (right side) and it comes into contact with the heat-generating sources (e.g. chips, substrates, etc.) during its path in the upward direction (as shown Fig. 4.26) and the hot liquid exits at the top on the right side. Because of the direct contact of the liquid coolant and the heat sources, the thermal resistance offered in the direct contact type method is removed and the heat flux carrying capacity of this method increases. The liquid coolants used in this type should not be conductive type (e.g. Mineral oils should be used).

This method offers the temperature of the electronic component maintained always below the liquid coolant temperature because of the high heat transfer coefficient. The amount of heat collected by the liquid coolant depends upon the coolant

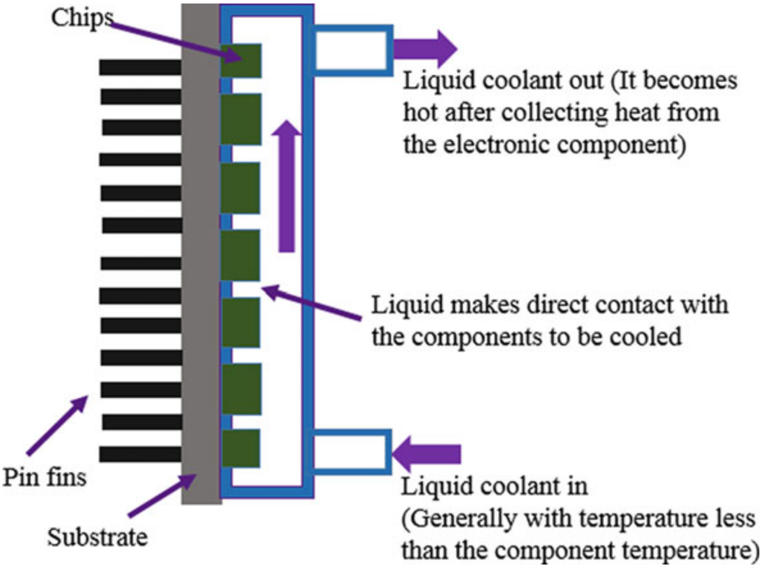


Fig. 4.26 Immersion cooling through direct contact of liquid coolant with the component to be cooled

type and the type of the heat transfer mode. The modes of the heat transfer are mainly forced convection, natural convection and boiling. The boiling mode always carries the highest heat through the liquid coolants because of its higher heat transfer coefficients. Figure 4.27 shows the comparison of the different modes of the heat transfer and their heat transfer coefficients.

The heat-carrying capacity of this method is more than the air cooling methods. The water cannot be used as liquid coolant in this method, because of its incompatibility with the hardware used in micro-electronic systems. The most widely used liquid coolants in direct type of the immersion cooling are the (a) FC–72, (b) FC–77 and (c) FC–86.

Important thermo-physical properties comparison for different liquid coolants is presented in Table 4.7. From Table 4.7 it is very much clear that the thermos-physical properties (mainly boiling point, specific heat, thermal conductivity and heat of vaporization) of water is superior compared to FC–72, FC–77 and FC–86. Because of their compatibility with the electronic components, these are used in the direct immersion cooling technology.

4.2.9.2 Indirect Cooling

This method involves the cooling of the electronic components with the indirect contact between liquid coolant and the electronic components. The principle of the working of indirect method of cooling of the electronic components is shown in Fig. 4.28. The liquid coolant is supplied through the channel at its one end (Fig. 4.28

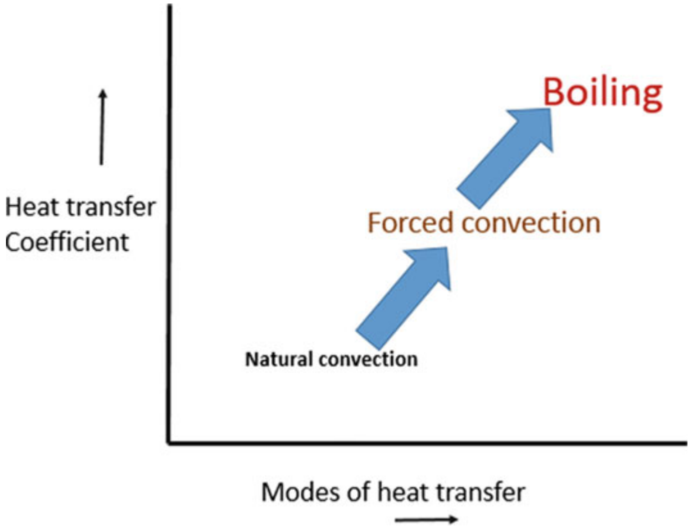


Fig. 4.27 Comparison of the different modes of the heat transfer and their heat transfer coefficients

Table 4.7 Thermo- physical properties of the liquid coolant (Danielson et al. 1987)

Thermo-physical property	H_2O	FC-77	FC-72	FC-87
Boling point in °C (at 1.013 bar)	100	97	56	30
Density (kg/m^3)	1000	1780	1680	1633
Specific Heat KJ/kg K)	4.179	1.172	1.088	1.088
Thermal Conductivity (w/m K)	0.613	0.057	0.0545	0.0551
Heat of vaporization × 10^{-4} (w s/kg)	243.8	8.37	8.79	8.79

at the bottom right side) and it moves through the channel to collect the heat from the cap/cover plate and exits from its other end of the channel (Fig. 4.28 at the top right side). The cap is receiving the heat from the various electronic components (e.g. chips, substrates, etc.). Because of the indirect contact between liquid coolant and the electronic components the thermal resistance increases and the heat-carrying capacity of this type is less than the direct type. Water can be used very easily as a liquid coolant because of its good thermo-physical properties.

4.2.9.3 Single-Phase Immersion Cooling

In this type of cooling the working fluid does not change its phase while collecting the heat from the electronic components/system and hence it is called single-phase immersion cooling. The simple working principle of the single-phase immersion

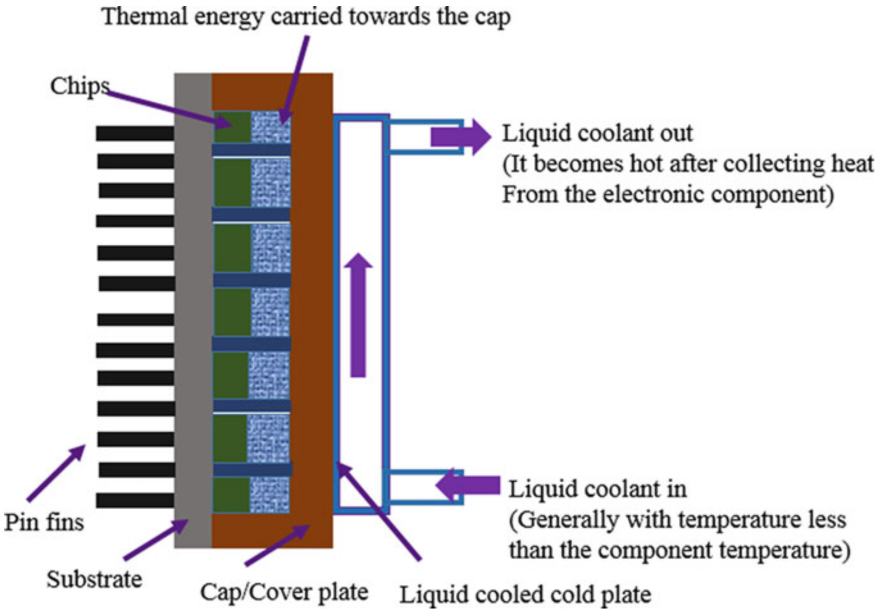


Fig. 4.28 Immersion cooling through the indirect contact of the liquid with the electronic components to be cooled

cooling system is shown in Fig. 4.29. The system used to cool the IT equipment is shown in Fig. 4.30. The most widely used phase of the working fluid is liquid, because of its high heat-carrying capacity. The amount of heat carried in this type of method is more than the air type of cooling. Because of no phase conversion (liquid to gas), chances of explosion are avoided.

4.2.9.4 Two-Phase Immersion Cooling

In this method, the working fluid used in the circuit changes its phase from liquid to gas after collecting the heat from the electronic components and hence it is called as two-phase immersion cooling system. The heat-carrying capacity of this type is more than the single-phase type, which helps to increase the power density up to 10 times as that of the power density of single-phase systems. It has simple construction and less cost. Figure 4.31 shows the two-phase immersion cooling system.

Advantages

(a) More heat-carrying capacity compared to the air cooling methods
(b) Water can be used as coolant which is easily available
(c) Cost is less with water-cooled systems
(d) Can be used in different-sized electronic systems
(e) Two-phase immersion cooling system allows to increase the power density

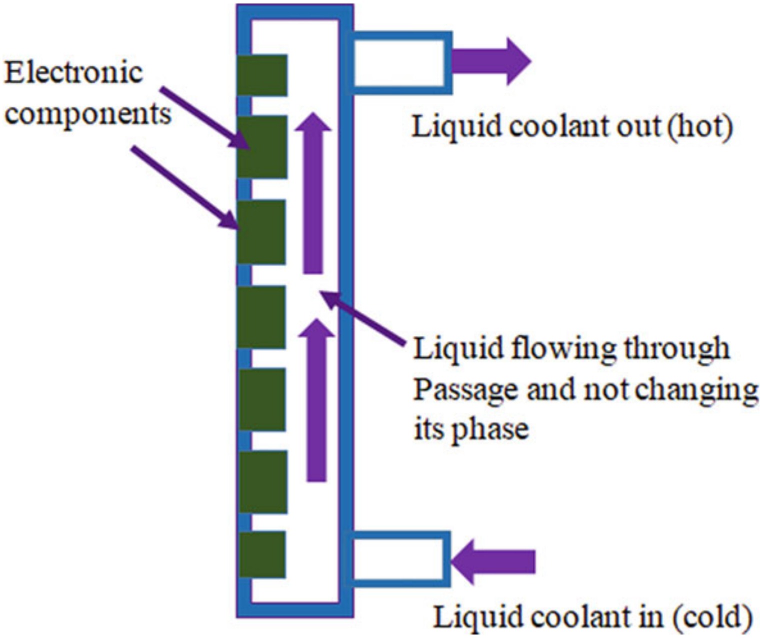


Fig. 4.29 Single-phase immersion cooling system

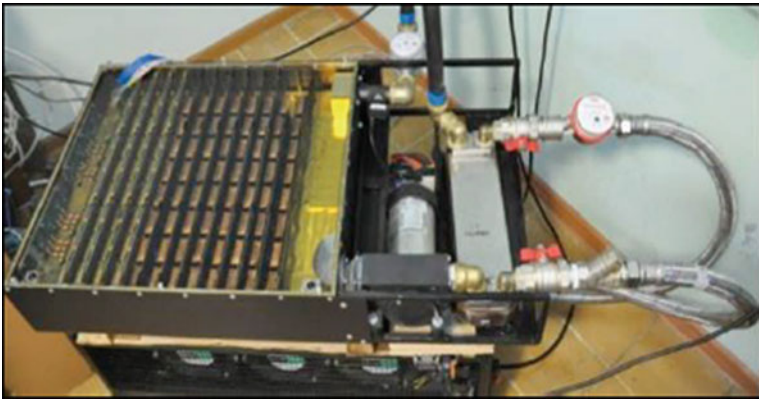


Fig. 4.30 Single-phase immersion cooling system used to cool IT equipment (Levin 2016)

Disadvantage

(a) The basic structure of the electronics needs to be modified as per the cooling system
(b) The cost of the system increases with coolants other than water
(c) The space required is more

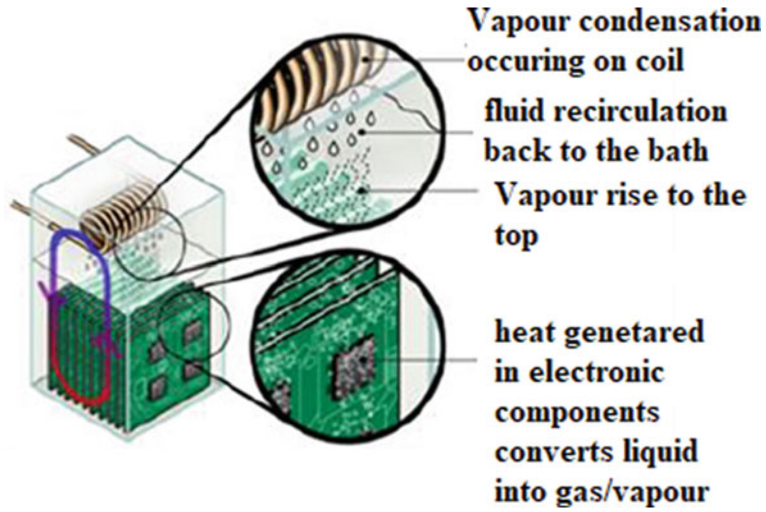


Fig. 4.31 Two-phase immersion cooling system (Kuncoro et al. 2019)

(d) The chances of leakage cannot be tolerated after some usage
(e) The weight of the system may increase.

Applications

(a) Cooling of the super computers
(b) Cooling of the commodity server (Kuncoro 2019)
(c) Cooling of the server clusters
(d) Cooling of the data centres (this is targeted application recently)
(e) Cooling of the solar cell through single-phase method (Sun et al. 2014)
(f) Cooling of the transformer through single-phase method (Testi 2018)
(g) Cooling of the IT equipment through single-phase method (Shah et al. 2016; Levin 2016)
(h) Cooling of the server through two-phase method (Lamaison et al. 2017)

4.2.10 *Use of the Phase Change Material*

The use of the phase change materials in the heat flow management of the microelectronics cooling is increased because of its easy availability and flexibility in design. This cooling method includes two important steps,

(a) Collection of the heat from the electronics components and
(b) Rejection of the collected heat.

(a) **Collection of the heat from the electronics components**

This process involves absorption of the sensible heat and latent heat. Initially, phase change material absorbs the sensible heat from the electronic components (source of the heat) and its temperature increases without changing its phase (its state is solid). The process involves storing of heat in the phase change material. When the temperature reaches to the melting point of the phase change material it starts absorbing latent heat from the electronic components and it starts melting. The large amount of latent heat is absorbed by the phase change material at constant temperature and the procedure is continued till the complete melting of the phase change material occurs. Hence before selecting the phase change material, one should have idea about amount of heat that is to be removed from the electronic components. The latent heat absorbed is generally higher than the regular materials (which cannot be reinstated by addition and removal of the heat).

(b) **Rejection of the collected heat**

During this process, the heat is rejected by the phase change material when the temperature of the surrounding drops. The heat rejection process converts the phase change of material from liquid into solid state and it is ready for the next cycle of the heat collection.

This type of cooling method is called as passive way of heat flow management in the electronic system. The phase change materials which include gas phases (e.g. liquid to gas or solid to gas) increase the volume of the cooling systems and hence these are not preferred in the micro-electronic cooling systems. The phase change materials can be used for continuous heat storage and intermittent heat storage. The details of the different phase change materials and their benefits and drawbacks for different applications are mentioned in Table 4.8.

Advantages

(a) These systems can be fabricated with low cost
(b) Systems are flexible in design because of different materials availability
(c) It gives more reliability in the cooling process
(d) This system can be used for both the intermittent and continuous cooling operations
(e) These systems can be fabricated in the smaller size (well below the size of electronic device)
(f) The capacity to absorb the heat (latent heat mainly) is more than other materials and hence effective way of cooling the systems
(g) These materials are readily available in the market
(h) These materials are chemically and thermally stable and hence can be connected directly in the electronic systems
(i) No electrical energy is required to operate the cooling system.

Table 4.8 Summary of phase change materials

Sr. No	PCM	Design	Benefits	Drawback	Reference
1	paraffin wax	The aluminium enclosure with 128 mm X 10 mm dimensions and internal cavity	The good transient response with intermittent operation reduced the weight and size of the system	The design of the phase change material with heat sinks was also tried and no significant change was observed	Kandasamy et al. (2008)
2	n-eicosane	The heat storage systems with cavity (filled with n-eicosane)	It was possible to stabilize the temperature and extend the duration of the operation of the system		Tan and Tso (2004)
3	n-eicosane	The heat sinks filled with the PCM (n-eicosane) The heat sinks with fins (21 mm height) and without fins	Decreases the rate of increase of the temperature	only applicable for the intermittent operations, e.g. Mobiles	Tan and Tso (2004)
4	Thermal energy storage	PCM with filled Thermal energy storage devices (size -101 mm X 62 mm X 12 mm)	Was able to control the temperature of the electronic components		Alawadhi and Amon (2003)
5	Paraffin	PCM for intermittent and continuous operation	Increase in the critical time by 320% The critical time is the time required to reach 77 °C		Gharbi et al. (2017)
6	Heat Pipe with tricosane	The heat pipes charged with both (a) tricosane and (b) water	PCM can lower the temperature of heater significantly (almost by 17 °C)		Weng et al. (2011)

(continued)

Table 4.8 (continued)

Sr. No	PCM	Design	Benefits	Drawback	Reference
7	(PMCD-32SP) paraffin) in polyethylene in a composite sheet form	The MPCM/polyethylene PCM used in tablets with sheet of 1.6 mm in thickness	It is possible to reduce the temperature and only polyethylene is sufficient to get delay in temperature rise by 50 °C in the study		Tomizawa et al. (2016)
8	PCM TES	PCM with TES with sheet thickness less than 2 mm	The delay in temperature observed for electronic system and its cover by 34% compared to the case of without PCM The PCMs with the melting temperature below 39 °C is suitable for the heat flow management in the electronic systems		Sponagle et al. (2017)
9	PCM TES	Use of the PCM for the tablets and tested for different heat inputs (3 W, 4 W, 6 W and 8 W)	PCMs can be used for continuous operations up to 60 min and temperatures were reduced substantially compared to case of without PCM		Ahmed et al. (2018)

Disadvantages

(a) The materials are corrosive in nature (Inorganic phase change materials)
(b) Problem of the instability of the material
(c) The complete conversion of the liquid to solid is not achieved in all the materials and all the time

(d) Some materials show a tendency of the super cool (Inorganic phase change materials)
(e) Phase change materials with conversion of solid to gas or liquid to gas cannot be used because of the restrictions on the volume in the micro-electronics cooling systems
(f) Less experience with long-term operation of the phase change material and cycles of operation.

Applications

(a) The thermal energy storage and its release based on systems requirements in micro-electronics cooling
(b) The use of the phase change material is in the storing the solar energy and using it as per requirement during cooking of food
(c) Cooling of the batteries
(d) Cooling of the electrical and the heat engines
(e) Food storage by maintain the cold space temperature (heat removal from the space)
(f) Cooling of the human body under heavily worn clothes
(g) Heat balance in the micro-electronic systems (computer cooling, laptop cooling, other portable electronics cooling).

4.3 Summary

This chapter emphasizes mainly on the heat flow management required in the micro-electronic systems. The old and recently developed cooling techniques are discussed in detail. The working principle of all the recently developed cooling techniques along with advantages, disadvantages and the specific applications of particular techniques are presented under every single cooling technique. The different electronics cooling techniques such as heat sinks, cold plates, natural air cooling, forced air cooling, use of the heat pipes, Peltier effect for cooling, synthetic jets cooling, electrostatic fluid acceleration cooling, immersion cooling, phase change materials are compared and presented below in tabular form to understand their significance, dependence on parameters and use for specific application.

Heat sinks	Cold plates	Natural air cooling	Forced air cooling	Heat pipes	Peltier effect cooling	Synthetic jet cooling	Electrostatic fluid acceleration cooling	Immersion cooling	Phase change materials
Used to cool the electronics components Which are Smaller to medium size and cooling occurs by transferring the heat from electronics components to heat spreader through and then to fins through conduction, the heat from fins is convected and radiated in the cooling media. This is old method of cooling the electronic components. Performance depends on material of the heat sink, method used to supply air the heat sink	This method uses the metal plate (cold plate) between electronic component (source of the heat) and the working fluid which collects the heat from metal plate. The method is used to cool the micro-electronic circuits require higher thermal conductivity and higher heat flux carrying capacity. This is recent method and performance depends on fluid used for cooling, velocity of flow and material of the cold plate	This is the old and simple method used to cool the electronic systems. In this method, the naturally available air is used to cool the electronic systems. This method utilizes the concept of density difference to carry away heat from the systems. The performance depends on the amount of air available near the components, space available for the movement of the air, direction of the air movement	This method includes creation of the forced draught of the air through external agency (e.g. Fans or blowers). This is very common method used to cool the electronic systems. The air is used as media to remove the heat from the electronic components The performance depends on the mass flow rate of air (velocity of the air), vents location, size of blower/fan, etc.	Heat pipes have found to be the best method for portable electronic cooling devices. The heat pipe technology is used because of its simple structure, high efficiency, cost-effective and flexibility. The heat pipe uses the working fluids whose phase change can be used to collect the heat from one location and to transfer it to the another location. The performance depends on heat pipe material, fluid used in system, wick structure used, orientation of the pipe, etc.	The Peltier cooling devices works on the principle of the Peltier effect. As per this effect when two dissimilar metals are connected together to form the junctions and if DC current is applied at these junctions, this causes a temperature difference across these junctions. The performance depends on material of semiconductor used, temperatures of hot side and cold side, amount of heat transferred, losses in the system	The synthetic jet technology is well-proven technology in which flow of the air is generated with the help of the diaphragm (or actuator) movement in the cavity. The movement of the diaphragm is periodic and it is confined to one of the wall of the cavity. The performance depends on type of the actuator, cavity size, movement of the diaphragm, etc.	The method involves the use of device called as electrostatic fluid accelerator to get the movement of the targeted fluid (e.g. air) in the required direction. This technique uses the Coulomb force to accelerate the electrically charged molecules of the fluid (e.g. air). There are mainly three steps which are important in order to get the movement of the fluid in this technique and these are mentioned below, (a) Ionization of the working fluid particle, (b) Movement of the ionized and non-ionized working fluid particles in the downstream direction (through ion-ion or ion-neutral particle collisions), (c) Deionization of the working fluid particle. The performance depends on ionization and deionization of the working particles and movement of the particle, etc.	The immersion cooling technology involves the use of liquids to collect the heat from the source (location where heat is generated). This technique is useful to remove more heat flux compared to the conventional method of removing heat with the help of heat sinks. The performance depends on method of cooling (direct or indirect), working fluid used, heat transfer mode, etc.	The use of the phase change materials in the heat flow management of the micro-electronics cooling is increased because of its easy availability and flexibility in design. This cooling method includes two important steps, (a) Collection of the heat from the electronics components and (b) Rejection of the collected heat. The performance depends on material, type of cooling operation, surrounding temperature, etc.

(continued)

(continued)

Heat sinks	Cold plates	Natural air cooling	Forced air cooling	Heat pipes	Peltier effect cooling	Synthetic jet cooling	Electrostatic fluid acceleration cooling	Immersion cooling	Phase change materials
Applications: cooling of CPU, laptop, engine, etc.	Applications: cooling of CPU, IGBT, transistor, battery, fuel cells, medical equipments, etc.	Applications: cooling of electronic board and condenser, etc.	Applications: cooling of the CPU, laptop battery, LEDs, inverters, etc.	Applications: cooling of capacitor, transistor, desktop, laptop, etc. and can work as a refrigeration and air condition systems	Applications: cooling of Camera's (CCD), micro-processors, laser diodes, blood analyzing devices, etc.	Applications: cooling of Laptop, handheld PCs, controllers, etc.	Applications: Micro-processor cooling, development of flow patterns etc.	Applications: Cooling of super computers, commodity server, server clusters, data centres, solar cell, transformer, IT equipment, etc.	Applications: Storing the solar energy and cooling of the batteries, electrical and the heat engines, computer, laptop, etc.

Comparison of the cooling techniques:

4.4 Future Scope/Recommendations

There is lot of scope to work in the following fields,

(a) Development of the Peltier materials
(b) Development of the cold plate designs which can be very easily connected to the micro-electronic systems
(c) Development of the heat pipes or vapours chambers in micro-electronic components (e.g. mobiles, laptops, etc.)
(d) Developments in the synthetic jet techniques
(e) Scope to check the compatibility of different working coolants used in the different cooling techniques
(f) Scope to minimize the losses in the connectivity of micro-electronic structures
(g) Scope to minimize the pressure losses and improve flow characteristics in the micro channels.

References

Ahmed T, Bhouri M, Groulx D, White MA (2018) Passive thermal management of tablet PCs using phase change materials: continuous operation. Int J Thermal Sci 134:101–115

Alawadhi EM, Amon CH (2003) PCM thermal control unit for portable electronic devices: experimental and numerical studies. IEEE Trans Compon Packag Technol 26:116–125

Ali MS, Kamarudin SK, Masdar MS, Mohamed A (2014) An overview of power electronics applications in fuel cell systems: DC and AC converters. Sci World J 2014(103709)

Arshad A, Jabbal M, Yan Y (2020) Synthetic jet actuators for heat transfer enhancement—a critical review. Int J Heat Mass Transfer 146:118815

Chanyoung K, Hongchao W, Je-Hyeong B, Hoon K, Woochul K (2015) Thermoelectric materials and devices. Hierarchical Nanostruct Energy Devices 35

Cheung C, Noska B, Van der Heide K (2009) Comparison of passive and active cooling effectiveness. LED Prof Rev Mag

Danielson RD, Tousignant L, Bar-Cohen A (1987) Saturated pool boiling characteristics of commercially available perfluorinated liquids. In: Proceedings of ASME/JSME thermal engineering joint conference

Didden N (1979) On the Formation of Vortex Rings: Rolling-up and Production of Circulation. J Appl Math Phys (ZAMP) 30:101–116

Elnaggar MH, Abdullah MZ, Abdul Mujeebu M (2011a) Experimental analysis and FEM simulation of finned U-shaped multi heat pipe for desktop PC cooling. Energy Convers Manag 52(8–9):2937–2944

Elnaggar MHA, Abdullah MZ, Mujeebu M (2011b) Experimental investigation and optimization of heat input and coolant velocity of finned twin U-shaped heat pipe for CPU cooling. Exp Tech.

Elnaggar MH, Abdullah MZ, Munusamy SR (2013) Experimental and numerical studies of finned L-shape heat pipe for notebook-PC cooling. IEEE Trans Compon Packag Manuf Technol 3(6): 978–988

Elnaggar MH, Edwan E (2016) Heat pipes for computer cooling applications. Electron Cooling

Gharbi S, Harmand S, Jabrallah SB (2017) Experimental study of the cooling performance of phase change material with discrete heat sources—continuous and intermittent regimes. Appl Therm Eng 111:103–111

Gil P (2019) Bluff body drag control using synthetic jet. J Appl Fluid Mech 12:293–302

Gil P, Wilk J (2020) Heat transfer coefficients during the impingement cooling with the use of synthetic jet. Int J Therm Sci 147:106132

http://www.nordichardware.com/news-archive/112-archive/18645.html

Hung YM, Seng QB (2011) Effects of the geometric design on the thermal performance of star groove micro heat pipes. Int J Heat Mass Transf 54(5–6):1198–1209

Incropera, DeWitt, Bergham, Lavine (2007) Introduction to heat transfer, 5th edn., p 6. ISBN 978-0-471-45727-5

Kandasamy R, Wang XQ,Mujumdar AS (2008) Transient cooling of electronics using phase change material (PCM)-based heat sinks. Appl Therm Eng 28(8–9):1047–1057

Kim KS, Won MH, Kim JW, Back BJ (2003) Heat pipe cooling technology for desktop PC CPU. Appl Therm Eng 23(9):11371144

Kuncoro IW, Pambudi NA, Biddinika MK, Widiastuti I, Hijriawan M, Wibowo KM (2019) Immersion cooling as a next technology for data center cooling: a review. J Phys Conf Ser 1402:044057

Lamaison N, Ong CL, Marcinichen JB, Thome JR (2017) Two-phase mini-thermosyphon electronics cooling: dynamic modeling, experimental validation and application to 2U servers. Appl Therm Eng 110:481–494

Legierski J, Wiecek B (2001) Steady state analysis of cooling electronic circuits using heat pipes. IEEE Trans Compon Packag Technol 24(4):549–553

Levi C, Phillip T (2012) Numerical prediction of the junction-to-fluid thermal resistance of a 2-phase immersion-cooled IBM dual core POWER6 processor. In: 28th IEEE SEMI-THERM symposium

Levin III, Dordopulo AII, Doronchenko YII, Raskladkin MKK, Fedorov AMM, Kalyaev ZVV (2016) Immersion liquid cooling FPGA-based reconfigurable computer system. IFAC-Papers On Line vol 49 (Elsevier B.V.), pp 366–71

Levine MA (1989) Solid state cooling with thermoelectric. Electron Packag Prod

Li Y, Zhou W, He J, Yan Y, Li B, Zeng Z (2019) Thermal performance of ultra-thin flattened heat pipes with composite wick structure. Appl Therm Eng 102:487–499

Liang TS, Hung YM (2010) Experimental investigations on the thermal performance and optimization of the heat sink with U-shape heat pipes. Energy Convers Manage 51(11):2109–2116

Mahalingam R, Huffington S, Jones L, Williams R (2007) Synthetic jets for the forced air cooling of electronics. Electron Cooling

Mark M (1958) Cold plate design for airborne electronic equipment. IRE Trans Aeronaut Navigational Electron

Mathew VK, Hotta TK (2018) Numerical investigation on optimal arrangement of IC chips mounted on a SMPS board cooled under mixed convection. Therm Sci Eng Progress

Melcor Corporation (1995) Thermoelectric Handbook

Michael JF (2006) Design and testing of micro-fabricated electrostatic fluid accelerator. ELECTRONICS-NNIN REU 2006, Research Accomplishments

Mjallal I, Farhat H, Hammoud M, Ali S, Shaer AA, Assi A (2017) Cooling performance of heat sinks used in electronic devices. ISBN 978-1-5090-5173-1 © 2017 IEEE

Mohammad E, Ezzaldeen E (2016) Heat pipes for the computer cooling applications

Rampunggoon P (2001) Interaction of a synthetic jet with a flat-plate boundary layer, PhD thesis, Department of Mechanical Engineering, University of Florida, Gainesville

Rowe DM (1995) CRC handbook of thermoelectrics. CRC Press, Inc.

Shah JM, Eiland R, Siddarth A, Agonafer D (2016) Effects of mineral oil immersion cooling on IT equipment reliability and reliability enhancements to data center operations. In: Proceedings of the 15th InterSociety conference on thermal and thermomechanical phenomena in electronic systems, ITherm, pp 316–325

Smythe R (1995) Thermoelectric coolers take the heat out of today's hotchips. Electronic Products

Sponagle B, Maranda S, Groulx D (2017) investigation of the thermal behaviour of thin phase change material packages as a solution to temperature control in electronics. In: Proceedings of the ASME 2017 summer heat transfer conference, Bellevue, WA, USA, 9–14 July 2017

Sukhvinder K, David M, John C (2007) Closed loop liquid cooling for high performance computer systems. ASME InterPACK '07, July 8–12, Vancouver, British Columbia, CANADA

Sukhvinder SK (2012) Advanced cooling for power electronics. Presented by invitation at international conference on integrated power electronics systems CIPS 2012, March 6–8, Nuremberg, Germany

Sun Y, Wang Y, Zhu L, Yin B, Xiang H, Huang Q (2014) Direct liquid-immersion cooling of concentrator silicon solar cells in a linear concentrating photovoltaic receiver. Energy 65:264–271

Tan F, Tso CP (2004) Cooling of mobile electronic devices using phase change materials. Appl Therm Eng 24:159–169

Testi D (2018) Heat transfer enhancement by an impinging ionic jet in a viscous transformer coolant. Int Commun Heat Mass Transf 91:256–261

Thermal management system for portable electronic devices, US Patent.

Tomizawa Y, Sasaki K, Kuroda A, Takeda R, Kaito Y (2016) Experimental and numerical study on phase change material (PCM) for thermal management of mobile devices. Appl Therm Eng 98:320–329

Tousif A, Maha B, Dominic G, Mary AW (2019) Passive thermal management of tablet PCs using phase change materials: intermittent operation. Appl Sci 9:902. https://doi.org/10.3390/app9050902

Van Le L, Nhu CN, Tai TN, Dinh TX, Tran C, Bao LD, Bui TT, Dau VT, Duc TC (2019) Liquid pimping and mixing by PZT synthetic jet. In: 20th international conference on solid-state sensors, actuators microsystems, transducers EUROSENSORS XXXIII. IEEE, Berlin, pp 198–201

Wang JC (2008) Novel thermal resistance network analysis of heat sink with embedded heat pipes. Jordan J Mech Indust Eng 2(1):23–30

Wang JC (2011) L-type heat pipes application in electronic cooling systems. Int J Thermal Sci 50(1):97–105

Wang Y, Vafai K (2000) An experimental investigation of the thermal performance of an asymmetrical flat plate heat pipe. Int J Heat Mass Transf 43(15):2657–2668

Wang JC, Huang HS, Chen SL (2007) Experimental investigations of thermal resistance of a heat sink with horizontal embedded heat pipes. Int Commun Heat Mass Transfer 34(8):958–970

Weng YC, Cho HP, Chang CC, Chen SL (2011) Heat pipe with PCM for electronic cooling. Appl Energy 88:1825–1833

Xinxi L, Dequan Z, Guoqing Z, Cong W, Ruheng L, Zhaoda Z (2019) Experimental investigation of the thermal performance of silicon cold plate for battery thermal management system. Appl Therm Eng 155:331–340

Yeatman EM (2007) Applications of MEMS in power sources and circuits. J Micro-Mech Micro-Eng 17:184–188

Yu ZZ, Harvey T (2000) The precision engineered heat pipe for cooling Pentium II in Compact PCI design. Thermal and Thermo-Mechanical Phenomena in Electronic Systems, ITHERM 2000 The Seventh Intersociety Conference, vol 102, pp 102–105