MPE 635: Electronics Cooling

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CONTENTS

Part A: Introduction to Electronics Cooling

1. Introduction
2. Packaging Trends and Thermal Management
3. Basics of Heat Transfer

Part B: Heat Transfer Principals in Electronics Cooling

4. Conduction Heat Transfer
5. Multi-Dimensional Conduction
6. Transient Conduction
7. Natural Convection in Electronic Devices
8. Forced Convection Heat Transfer
9. Forced Convection Correlations
10. Radiation Heat Transfer
11. Advanced Radiation
12. Case Study: Using EES in Electronics Cooling

Part C: Electronics Cooling Methods in Industry

13. Heat Sinks
14. Heat Pipes
15. Heat Pipes in Electronics Cooling (1)
15. Heat Pipes in Electronics Cooling (2)
17. Thermoelectric Cooling
18. Immersion Cooling
19. Cooling Techniques for High Density Electronics (1)
20. Cooling Techniques for High Density Electronics (2)

Part D: Packaging of Electronic Equipments

21. Components of Electronic Systems
22. Packaging of Electronic Equipments (1)
23. Packaging of Electronic Equipments (2)
24. Conduction Cooling for Chassis and Circuit Boards

Part E: Analysis of Thermal Failure of Electronic Components

25. Analysis of Thermal Stresses and Strain
26. Effect of PCB Bending Stiffness on Wire Stresses
27. Vibration Fatigue in Lead Wires and Solder Joints

Part F: Practical Applications

28. Fan-Cooled Enclosure of a PC System
29. Flow over a Heat Sink

Part G: Appendices

G.1 Course Specifications
G.2 Problem Bank
G.3 Solved Problems
G.4 Sample Exams
G.5 Contents of Courses and Books
G.6 Internet Links
G.7 References

COURSE OBJECTIVES

The objectives of "Electronics Cooling" course are as following:

1. To establish fundamental understanding of heat transfer in electronic equipment.
2. To select a suitable cooling processes for electronic components and systems.
3. To increase the capabilities of post-graduate students in design and analysis of cooling of electronic packages.
4. To analysis the thermal failure for electronic components and define the solution.

Part A: Introduction to Electronics Cooling

Indicative Contents

- **Introduction**
- **Packaging Trends and Thermal Management**
- **Basics of Heat Transfer**

1. Introduction

As a mechanical power engineer you have passed through your undergraduate studies by thermodynamics, fluid mechanics, and heat transfer. As you have graduated you should have had a good sense of the interaction between these three fields of science. Now in your postgraduate studies you should elaborate more on the relation between what you have learned and the modern engineering applications.

The ongoing graduate course, electronics cooling, will deal with electronic equipments design and packaging from the thermal view point. The proper thermal design of electronic equipment will increase its reliability and durability as the major failure cause of electronics equipment damages results from the excessive heating of the electronic components.

1.1 Importance of Electronics Cooling

Heat transfer as a science and art has been the key for industrial development, since the industrial revolution. At the beginnings of the industrial age scientists as Watt, Stevenson …etc, made use of heat transfer as a science for the design of heat equipments to run steam power cycles, nowadays the information technology revolution have also to rely on the heat transfer as the electronic industry develop in order to maintain proper working conditions for these fast developing equipments.

As electronic devices run they consume electric power, this power needs to be dissipated or otherwise heat will be accumulated and device's temperature may exceed to dangerous levels. Consider the simplest electronic component, the resistance, as the electric current pass through it heat is generated by Equation 1.1, now if this resistance is thermally insulated allover its surface what would happen?

$$P = I^2 \times R \tag{1.1}$$

Where;

P = Represents both the electric power and heat dissipated in W
I = Electric current in A
R = Electric resistance in Ω

Now if we get to a more complicated electronic component like the processor of a personal computer, what do you think will happen if the processor fan fails to operate? The common answer here is that the computer will not respond and any process will be failed. This answer needs more elaboration, so let us start our first case study concerning this problem.

1.2 Electronics Cooling Devices

1.2.1 CPU, an Electronic Component

The CPU is an integrated circuit made of silicon. It combines a lot of electronic components like transistors, resistances, capacitors, and inductances. By this large combination mathematical operations may be done, as the time goes on, this single IC incorporate more elements and thus more operations are done per second and the operation frequency is getting much higher.

As each operation is done thousands of transistors switch on and back off again resulting in a huge heat dissipation requirement. If this heat is not dissipated properly, the processor temperature will rise to dangerous limits (above 120 ºC), which may result in the destruction of the IC's structure and components.

1.2.2 CPU, Heat Dissipation

Now considering the heat transfer area of an electronic processor, this area would not be sufficient to dissipate the large heat generated inside it, this is due to:

- Compact design of ICs.
- Low heat transfer by natural convection.
- Small allowable temperature difference (20-70 ºC)

These drawbacks need to be solved, and by common engineering sense, the use of extended surfaces seems to be a solution for the first limitation, also the PCB itself may be used as another heat sink. As for the second limitation, we may increase the heat transfer rate by forced convection instead of natural convection; this may be accomplished by the aid of a fan that increases the air velocities over the fins.

Now as the processor capability differs, the thermal design of the heat sink will change. This is your assignment to search for the various processors and the appropriate thermal design for each. Remember this is due for next week!?

1.2.3 Fans

Exercise 1.1: Submit a report for cooling by fans

1.2.4 Heat Sink

Exercise 1.1: Submit a report for cooling by heat sink

1.3 Introduction to Thermo-Fluid Issues in Electronic Manufacturing

Thermal issues in the electronic product life cycle appear to be crucial. Electronics manufacturing incorporate many stages that depend on the thermal behavior of the processing techniques such as:

- Crystal growth.
- Rapid thermal processing.
- Thin film processing.
- Soldering.
- Rework.
- Testing.

But none of the above mentioned processes are within our scope of study. Actually we are more interested in the thermal issues in electronics packaging. In this case we have to differentiate between the various electronic, optoelectronic, and power packaging requirements.

Therefore thermal management should be studied to incorporate passive or active techniques or a combination of both. The thermal characteristics may be analyzed and studied by computer modeling and experimentation.

1.3.1 Reliability and Temperature

The exponential advancement in electronic industries has led to greater emphasis being placed on reliability of electronic products; as electronic applications are used in military systems, medical instruments, aircraft control and other many sensitive applications. Reliability may be increased by improving components quality and in particular on cooling.

Recent studies of electronic equipment have shown that the field reliability of equipment is temperature related. This relation is affected by the mod of heat transfer being natural or forced convection.

The reliability of an electronic system comprising a group of components is most simply stated as the probability, expressed in percent, of operating continuously over a specified period of time with no failures. For most solid-state electronic devices, the reliability handbooks which establish a common basis for comparing competitive designs utilize an Arrhenius-type failure-rate model of the form:

$$\lambda_i = B_i e^{\left(-A_i / \lambda_j(T)\right)} + E_i \tag{1.2}$$

Where; the coefficients A_i, B_i, and E_i are independent of temperature.

Considering that each part has a particular failure rate expressed in number of failures per million hours, the mean time between failures MTBF for a group of components constituting a system is expressed as:

$$MTBF = 1 \Big/ \sum_{i=1}^{n} \lambda_i(T) \tag{1.3}$$

The reliability R, which is the probability of no failures over the operating time t, is, in terms of MTBF,

$$R = e^{-t/MTBF} \tag{1.4}$$

Therefore for a module consisting of 1000 devices, each having an assumed failure rate λ_i of 1.0 ppm, the MTBF is 1000 h [from Equation 1.3], and the probability of operating with zero failures over only 100 h is 90.5 percent [from Equation 1.4]. Furthermore, assuming there are 10 identical assemblies or modules constituting a package, the overall package MTBF is only 100 h and the reliability for a 100-h operating time is reduced to 36.8 percent. The inclusion of nine additional modules effectively lowers the reliability by 59 percent.

In some cases we would like to know the MTBF required to achieve a given reliability. For example, in the case cited, if the desired reliability of the 10-module system is 0.95, that is, 95 percent probability of failure-free operation for 100 h, the resulting system MTBF, from Equation 1.4, is 1949 h, or 19,490 h per module.

As to what is considered a proper level of operation, Figure 1.1 illustrates typical junction temperatures for equipment presently operating in a large number of field applications. The acceptable operating range for semiconductor junctions is shown to be generally 40 to 60 °C, although even fewer failures occur, down to as low as 0 °C. Below 0 °C, reliability is uncertain and some semiconductors cease operating, only to return to operation at higher temperatures with no apparent permanent damage. It must be recognized that the allowable junction temperature for any system required to meet a specified reliability may vary considerably due to many factors, including parts count, type of components and dissipation levels. Nevertheless, the upper limit for commercial applications is usually set at 85 °C, and for military equipment the acceptable upper limit is 100 to 110 °C for all semiconductors in power supplies and processors. It should also be recognized that other electronic components, diodes, capacitors, resistors, and so on, are also sensitive with respect to temperature, even though in general these components do not drive systems with regard to reliability. Nevertheless, in determining MTBF, all components become contributors and as such figure into the overall computation.

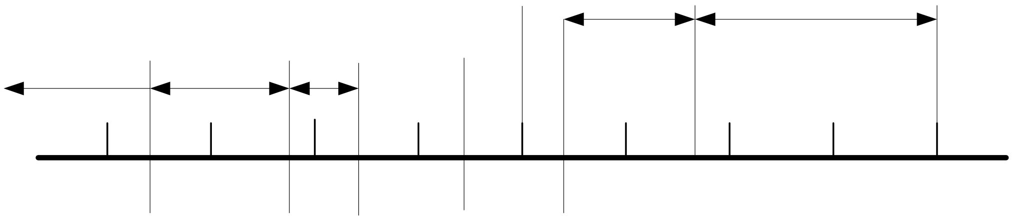


Figure 1.1 Temperature spectrum of operating junctions

1.3.2 Liquid Cooling Systems Considerations

System Types

There are two types of liquid systems used extensively in electronic cooling, direct and indirect. In the direct cooling system approach, the coolant flows over the component to remove heat from the surface and as such must be capable of sustaining a voltage gradient; alternatively in cold-plate cooling, which is indirect, there is no such requirement. The direct method is an efficient means of heat removal because the coolant is closest to the heat source. Even so, in critical applications where the heat flux rates are high, surface temperatures are best determined through actual measurements of temperature rather than exclusive dependence on analytical predictions. Some examples of direct liquid cooling of electronic equipment and the coolants used in these systems appear in Table 1.1. Common to these applications is the necessity for the maintenance of coolant purity, which is obtained through a means of filtration consistent with the dielectric requirements. Experience has shown that in direct cooling of components, the system must be absolutely airtight in order to prevent air or moisture from degrading the heat transfer performance of the coolant. In addition, moisture absorption can lead to a chemical breakdown in some coolants, which in turn lowers the flash point, hence creating a potential safety hazard. Extreme care is thus required in selecting a dielectric for direct cooling applications.

The category of indirect liquid cooling refers to the use of cold plates for the absorption of heat. Some recent examples of this type of cooling include cold plates for use in antenna array modules having solid-state circuitry and in high-heat flux power supply modules in aircraft applications. Commercial applications include mainframe computers where a refrigerant system provides a heat sink for the liquid used to cool high-heat chip packages.

Table 1.1 Common examples of direct liquid cooling

Coolant	**Application**
FC.77	Cray-2 supercomputer
FC-104, EWG, deionized water	Laser target illumination for electro-optical systems
C25R	Radar transmitter and TWTs on F-15 and F-16 fighter aircraft and others
FC-77, EWG	Antenna and klystron tubes for E3-AWACS radar system
C25R, PAO	

Coolant Selection

The choice of coolant in these applications, whether direct or indirect, often depends on the forced convection figures of merit (FOM) derived from the four basic coolant properties, c_p, μ, k and ρ. Table 1.2 lists these properties at 1 atm for five coolants at the three temperatures of -40, 25, 93.3 °C. It is important to note that absolute viscosity [in kg/(m.s)] varies widely with temperature and as such has significant implications in the coolant selection process. Figures 1.2 and 1.3 illustrate the coolant figures of merit as functions of temperature for straight finned or tubular channel flow operating in the laminar and turbulent regimes. These cases define typical flow conditions in liquid systems used in electronic applications. Equations 1.5 and 1.6 express the figure of merit FOM for these two cases of interest.
For laminar flow at the entrance to the cold plate,

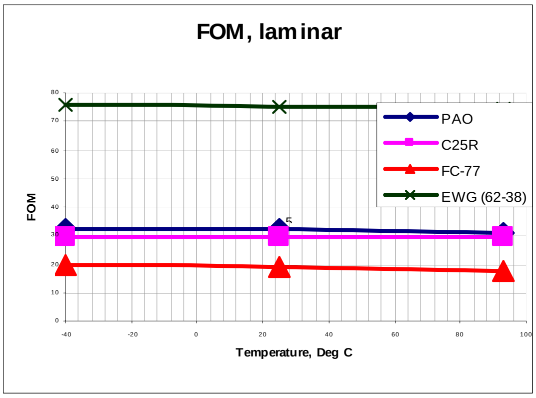
$$FOM \approx k^{0.66} \rho^{0.33} c_p^{0.33} \qquad (1.5)$$

For fully developed turbulent flow in the cold plate,

$$FOM \approx \frac{k^{0.6} \rho^{0.8} c_p^{0.4}}{\mu^{0.4}} \qquad (1.6)$$

Table 1.2 Coolants properties

	PAO Chevron Chemical Company			C25R Monsanto Company			FC-77 3M Company			EWG (62-38) E.I. du pont de Nemours & Company, Inc.			Water		
	-40	25	93.33	-40	25	93.33	-40	25	93.33	-40	25	93.33	-40	25	93.33
c	2051	2261	2428	1549	1842	2177	921.1	1047	1172	2763	3098	3433	N/A	4145	4187
miu	0.22	0.006	0.001	0.076	0.005	0.001	0.008	0.001	5E-04	0.2	0.005	1E-03	N/A	9E-04	3E-04
k	0.149	0.144	0.137	0.137	0.13	0.126	0.069	0.064	0.057	0.398	0.381	0.363	N/A	0.606	0.675
rho	839.4	789.7	743.3	949.9	900.2	839.4	1938	1778	1589	1121	1080	1030	N/A	999.6	962.7



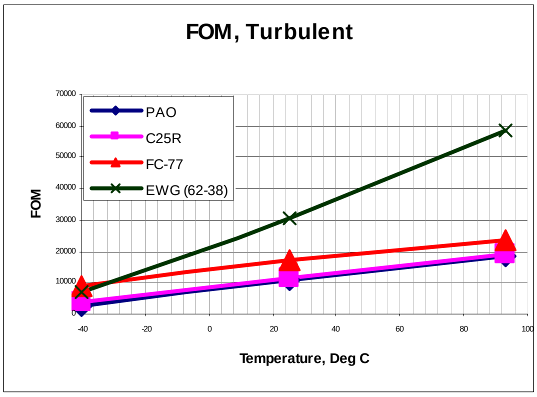


Figure 1.2 Figures of merit for liquid coolants in laminar flow	Figure 1.3 Figures of merit for liquid coolants in turbulent flow

Good design practice for cold plates operating in the laminar region, which is common in liquid systems, dictates that critical components be located near the entrance of cold plates in order to benefit from the low inlet coolant temperature but also to take advantage of the higher cold-plate film coefficients. As to coolant selection, the heat transfer figures of merit shown in Figures. 1.2 and 1.3 are to be used judiciously along with other criteria deemed important to specific applications. These parameters include the following:

- Toxicity
- Pour point
- Maximum wet wall temperature
- Flammability
- Cost per gallon Freeze point
- Material compatibility
- Corrosion
- Pressure drop characteristics
- Water absorption sensitivity

Pressure Drop and Pump Requirements

The cold plate heat transfer design is best expressed in terms of a friction factor f and a heat transfer j, both being functions of the Reynolds number. For the viscous pressure drop through the heat exchanger core, neglecting the entrance and exit losses,

$$\Delta P_{core} = 4f\frac{\ell}{d_h}\left(\frac{\rho V^2}{2}\right) = 4f\frac{\ell}{d_h}\left(\frac{G^2}{2\rho}\right) \tag{1.7}$$

In Equation 1.7 the term of $(\rho V^2/2)$ is replaced by $(G^2/2\rho)$, where G is the mass flow per unit area, kg/m^2.s, a more commonly used heat exchanger parameter.

The total system pressure drop of a common system as in Figure 1.6 includes the cold-plate and heat exchanger viscous core drops and the inviscid entrance and exit losses within the exchangers as well as line pressure drops throughout. Loss coefficients through valves, expansion, and contractions may be obtained by the equation:

$$\Delta P = \frac{kG^2}{2\rho} \tag{1.8}$$

The pump characteristic curve showing flow versus pressure drop is then used together with superposition of the system resistance to obtain the operating point as shown in Figure 1.4.

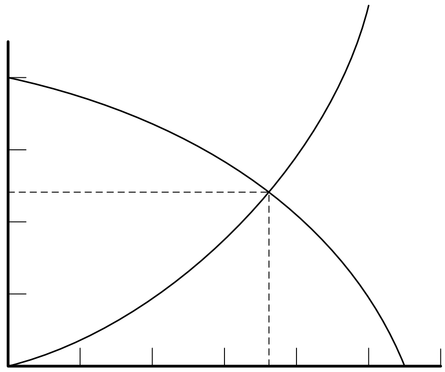


Figure 1.4 pump characteristic curves

Air Cooling System Consideration

In electronic systems, air seems to be a competitive coolant due to its availability, properties, and simple system requirements. The essential components of air cooling systems are the prime movers, fans and blowers, and the heat exchangers. For small heat dissipation, the prime mover of the air cooling system may be the draft or circulation created by density variations.

Induced or Draft Cooling

The use of induced draft air cooling in electronic application with low dissipation results in increased reliability, less number of system components, and decrease in maintenance operation. This method of cooling is applicable if the heat dissipation is less than 3500 W/m^3.

The driving force in induced-air cooling is the pressure difference caused by a change in air density between the lower and upper regions of a cabinet. This so called chimney effect produces an air motion within the enclosure which cools the component as the air moves from the bottom upward. Resisting this motive force is the internal friction and the losses associated with area changes within the enclosure. The operating point for a cabinet is where a balance exists between the system pressure or resistance and the induced draft. The latter is expressed as the flotation pressure ΔP_f (in Pa) in the equation

$$\Delta P_f = H\rho g \ln\left(\frac{T_2}{T_1}\right) \tag{1.9}$$

Here T_2 and T_1 are outlet and inlet absolute temperatures (°K), respectively. In the application of Equation 1.9, the height H (m) is related to the manner in which the cabinet heat is dissipated, that is. H is the full height whenever the entire heat is located at the console bottom, whereas for uniform heat spreading top to bottom, H is equal to one-half the cabinet height. For any other distribution of heat the centroid of heat as measured to the exit or top of the cabinet is the desired height. Figure 1.5 shows a typical cabinet, 457 by 483 by 1524 mm. with four layers or PCB buckets stacked vertically. The operating point for this cabinet is obtained from a plot of the cabinet resistance made up of the sum of friction loss and the entrance and exit losses balanced against the induced draft pressure defined by Equation 1.9.

Figure 1.6 represents the solution for the above mentioned cabinet including 42 active PCBs out of a total of 60 slots, having an average dissipation of 12 W each. If the flow rate is not suitable to dissipate the required heat a fan or a blower may be used to reach the best heat transfer design.

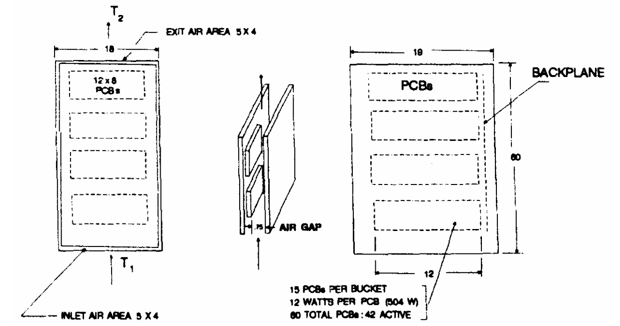


Figure 1.5 Types of induced-draft-cooled cabinet.

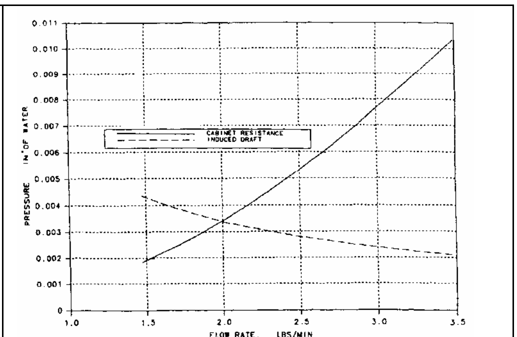


Figure 1.6 Cabinet draft and flow resistance curves.

Fans and Blowers

In the selection of fans and blowers, the flow and pressure head are the major parameters of interest, but also important are the noise level, life, ac (60 Hz or 400 Hz) or dc operation, size, and, in some cases, operation at other than sea level.

Fan laws are sometimes used to compare the operation of a specific fan under varying assumptions of speed, flow, density, and size:

Speed change

$$\dot{Q}_2 = \frac{\dot{Q}_1 N_2}{N_1} \quad (1.10)$$

$$P_2 = P_1 \left(\frac{N_2}{N_1} \right)^2 \quad (1.11)$$

Density change

$$\dot{Q}_2 = \dot{Q}_1 \quad (1.12)$$

$$P_2 = P_1 \left(\frac{\rho_2}{\rho_1} \right) \quad (1.13)$$

Size change

$$\dot{Q}_2 = \dot{Q}_1 \left(\frac{d_2}{d_1} \right)^3 \quad (1.14)$$

$$P_2 = P_1 \left(\frac{d_2}{d_1} \right)^2 \qquad (1.15)$$

The relation ships, in Equations 1.10 through 1.15, express the fan laws under the stated conditions. The assumption of constant efficiency is inherent in these equations, whereas practical fan designs will alter this assumption. The air power P_a, (in W) at a given flow (m^3/s) and pressure (Pa) is in accordance with the equation

$$P_a = \Delta P \dot{Q} \qquad (1.16)$$

Fans are sometimes used to simply purge air from a cabinet in order to prevent heat buildup, or they can provide air circulation within enclosures, as in ground equipment racks, or in many cases they provide a high-velocity air flow over components to increase the convection coefficient h These many uses cover a broad spectrum of pressure and flow conditions, leading to the development of different wheel designs tailored to match a wide range of applications. The general classification of blowers is best defined in terms of specific speed.

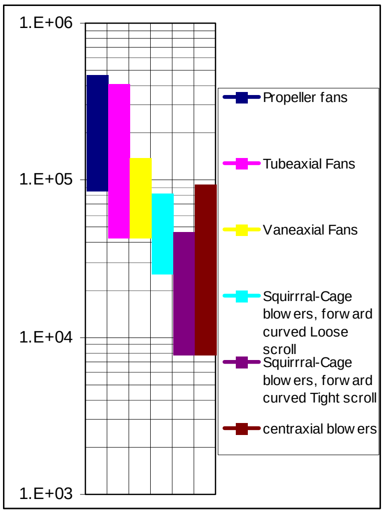
Specific speed, N_s, is expressed by the equation

$$N_s = \text{rpm} \frac{\dot{Q}^{0.5}}{\Delta P^{0.75}} \qquad (1.17)$$

Where; in terms of the flow Q (in ft^3/min) and the pressure ΔP (in inches of water).

Figure 1.7 shows the range of specific speeds for several wheel designs commonly used in electronic cooling. These devices are illustrated in Figure. 1.8. The propeller fan is a high-pressure device used mostly as a circulating fan. The tubeaxial fan provides higher pressure versus flow than a propeller fan and represents a logical extension of fan design. Vaneaxial fans are compact high-frequency (400-Hz) units whose airflow is parallel to the motor shaft. The impeller and correctional vanes of these units are airfoil designs installed to develop maximum efficiency. The other centrifugal impellers in Figure.1.8 vary in blade configuration, which is either radial, forward, or backward curved. In small sizes, the forward- curved blades often provide the best overall performance.

The performance of fans and blowers is represented by a constant-speed plot of pressure head, Δp verses flow $\dot{Q}$. A typical example of a constant speed fan is shown in Figure. 1.9 along with a system impedance curve. The intersection of the system impedance curve and the fan curve defines an operating point.



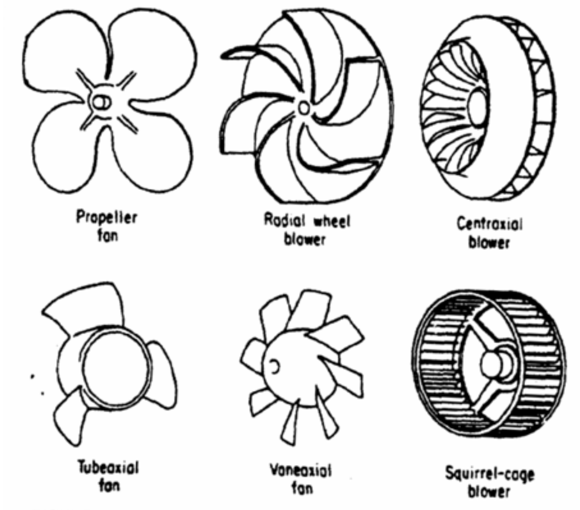


Figure 1.7 Range of specific speeds for various Fans and blowers	Figure 1.8 Fan and blower impeller designs

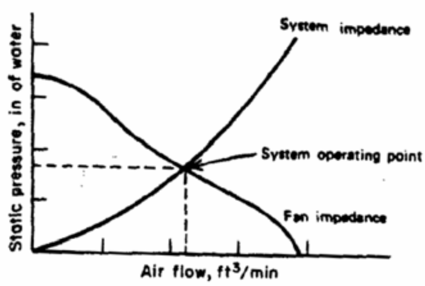


Figure1.9 Typical fan and system operating point

Exercise 1.3: Submit a report to illustrate the steps requires to obtain the operating point for a fan.

Example 1.1: The cabinet depicted in Figure. 1.5 is to be converted into a fan-cooled cabinet in order to lower the component temperatures. A further 10 PCBs are also added, each dissipating 15 W, for a total cabinet dissipation of 654 W. Select a fan based on a desired temperature rise of only 10 °C inlet to outlet having an operating speed of 1750 or 3450 rpm (60 Hz). The cabinet inlet air temperature is 21.1 °C. (Assume the airflow pressure drop in the cabinet to be 0.059 in of water.)

Solution:

1. Apply energy balance on the air flow:

$$\dot{m}_{air} c_{p_{air}} (\Delta T_{air}) = 654$$

Rearranging,

$$\dot{m}_{air} = \frac{654}{c_{p_{air}} (\Delta T_{air})} = 0.0652 \quad kg/s$$

2. The average density is

$$\bar{\rho} = \frac{P}{RT} = \frac{1.01325 \times 10^5}{287 \times (273.15 + 26.1)} = 1.18 \quad kg/m^3$$

3. The air flow is

$$Q^{\bullet}_{air} = \frac{m^{\bullet}_{air}}{\bar{\rho}} = 0.0553 \quad m^3/s = 116.8 \quad ft^3/\min$$

4. The specific speed is

$$N_s = rpm \frac{\sqrt{Q^{\bullet}_{air}}}{\Delta P^{0.75}} = 1750 \frac{\sqrt{116.8}}{(0.059)^{0.75}} = 157918$$

5. From the Figure. 1.8, the chart indicates a propeller fan as a likely candidate and further examination of catalog data reveals that a type BS-650l satisfies the requirements. A plot of this fan's curve along with the cabinet resistance line defines an operating point at the intersection of 120 ft^3/min and 0.062 in of water pressure drop (Figure. 1.10). The fan operates at 1750 rpm, 60 Hz. and draws only 10 W at full load.

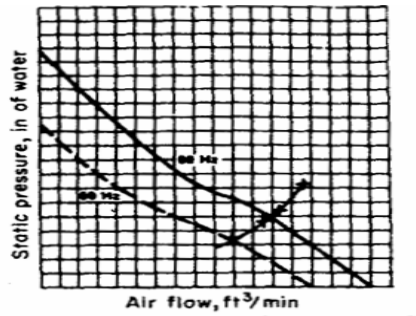


Figure 1.10 Vaneaxial fan curve