Module
7
Electrical Machine Drives

Lesson 31

Energy Savings with Variable Speed Drives

Lesson Objectives

- To describe typical methods of flow control by industrial fans and pumps
- To be able to determine operating points from pump/fan and load characteristics
- To demonstrate energy saving with variable speed drive method of flow control compared to throttling

Introduction

The AC induction motor is the major converter of electrical energy into mechanical and other useable forms. For this purpose, about two thirds of the electrical energy produced is fed to motors. Much of the power that is consumed by AC motors goes into the operation of fans, blowers and pumps. It has been estimated that approximately 50% of the motors in use are for these types of loads. These particular loads — fans, blowers and pumps, are particularly attractive to look at for energy savings. Several alternate methods of control for fans and pumps have been advanced recently that show substantial energy savings over traditional methods.

Basically, fans and pumps are designed to be capable of meeting the maximum demand of the system in which they are installed. However, quite often the actual demand could vary and be much less than the designed capacity. These conditions are accommodated by adding outlet dampers to fans or throttling valves to pumps. These control methods are effective, inexpensive and simple, but severely affect the efficiency of the system.

Others forms of control are now available to adapt fans and pumps to varying demands, which do not decrease the efficiency of the system as much. Newer methods include direct variable speed control of the fan or pump motor. This method produces a more efficient means of flow control than the existing methods. In addition, adjustable frequency drives offer a distinct advantage over other forms of variable speed control.

Fans: Characteristics and Operation

Large fans and blowers are routinely used in central air conditioning systems, boilers, drives and the chemical operations. The most common fan is the centrifugal fan that imparts energy in to air by centrifugal force. This results in an increase in pressure and produces air flow at the outlet of the fan.

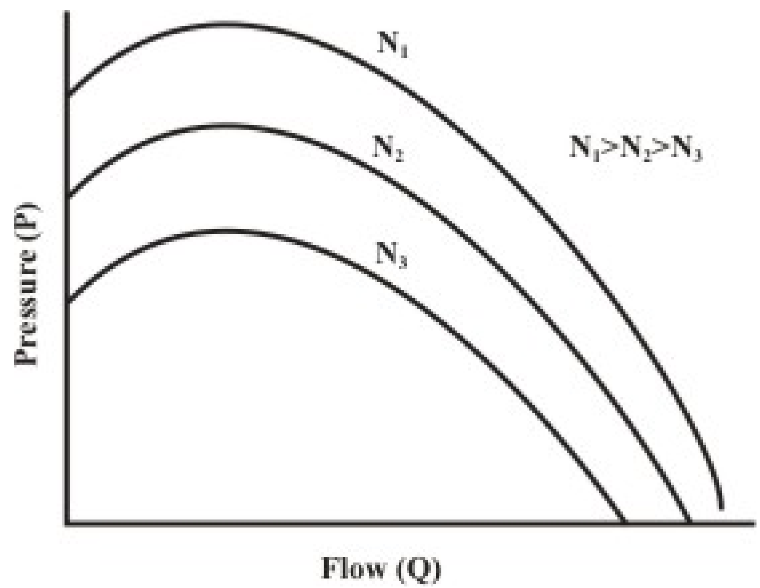


Fig. 31.1 Fan Curve

Fig. 31.1 is a plot of outlet pressure versus the flow of air of a typical centrifugal fan at a given speed. Standard fan curves usually show a number of curves for different fan speeds and include the loci of constant fan efficiencies and power requirements on the operating characteristics. These are all useful for selecting the optimum fan for any application. They also are needed to predict fan operation and other parameters when the fan operation is changed. Appendix 1 gives an example of a typical fan curve for an industrial fan.

Fig. 31.2 shows a typical system pressure-flow characteristics curve intersecting a typical fan curve.

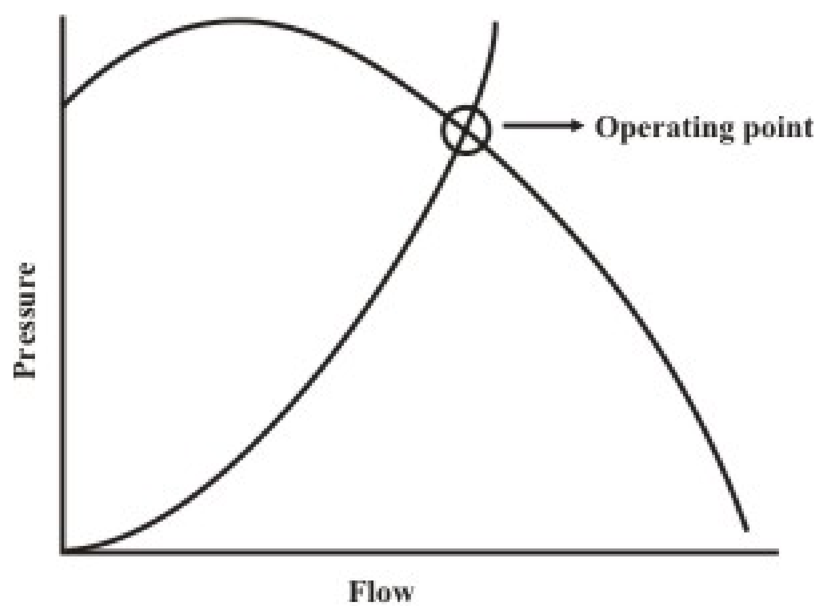


Fig. 31.2 System Curve

The system curve shows the requirements of the vent system that the fan is used on. It shows how much pressure is required from the fan to overcome system losses and produce airflow. The fan curve is a plot of fan capability independent of a system. The system curve is a plot of "load" requirement independent of the fan. The intersection of these two curves is the natural *operating point*. It is the actual pressure and flow that will occur at the fan outlet when this system is operated. Without external control, the fan will operate at this point.

Many systems however require operation at a wide variety of points. Fig. 31.3 shows a profile of the typical variations in flow experienced in a typical system.

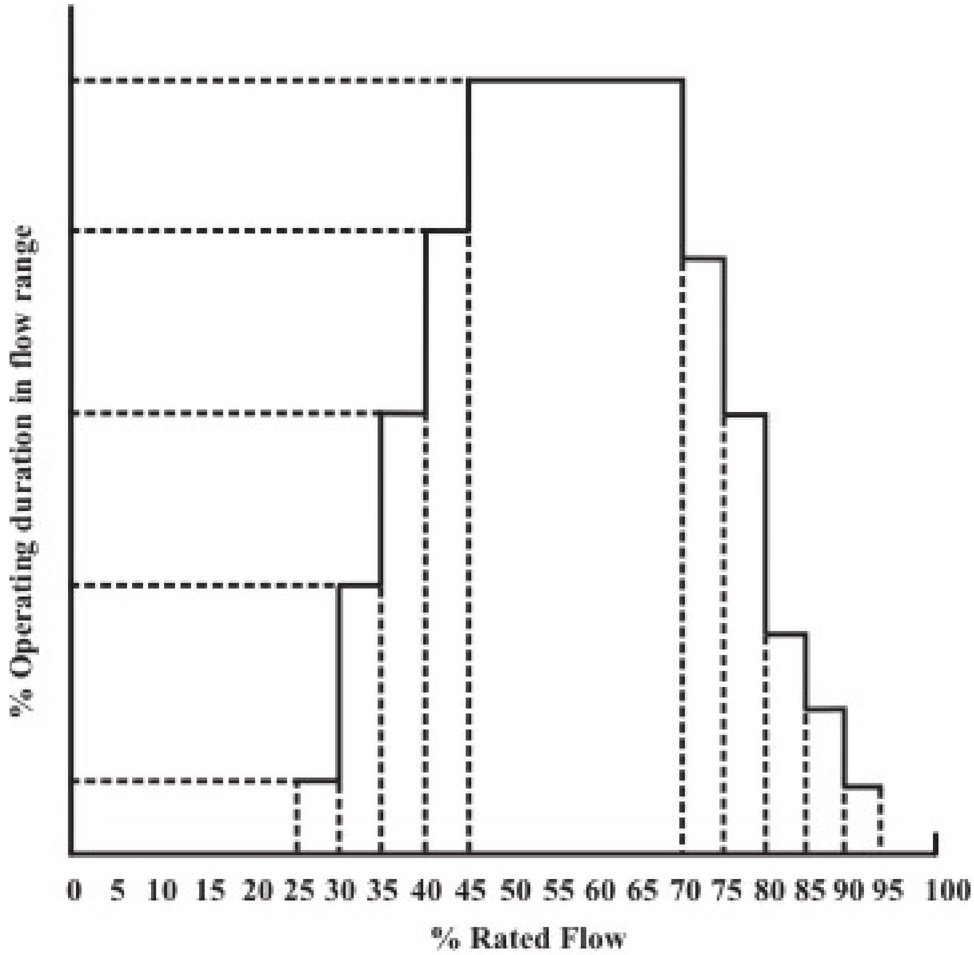


Fig. 31.3 Typical system flow-duration profile.

There are several methods used to modulate or vary the flow to achieve the optimum points. Apart from the method of cycling, the other methods affect either the system curve or the fan curve to produce a different natural operating point. In so doing, they also may change the fan's efficiency and the power requirements. Below these methods are explained in brief.

Points to Ponder: 1

A. *Why is it that typically load requirements are stated in terms of flow rates?*

B. *Why is it that the load requirements are generally show a parabolic pressure flow characteristics?*

On-Off Control

This is typically done in home heating systems and air conditioners. Here, depending on temperature of the space in question and the desired temperature setting, the fan is switched on and off, cyclically. Although the average temperature can be maintained by this method, this produces erratic airflow, causes temperature to oscillate and is generally unacceptable for commercial or industrial use.

Points to Ponder: 2

A. *Why is this system acceptable for home HVAC (the acronym for Heating Ventilation and Air Conditioning)?*

B. *Is it energy efficient?*

Outlet Dampers

The outlet dampers affect the system curve by increasing the resistance to air flow. The system curve is a simple function that can be stated **as**

$$\mathbf{P = K \times Q^2,}$$

where P is the pressure required to produce a given flow Q in the system. **K** is a characteristics of the system that represents the resistance to airflow. For different values of outlet vane opening, different values of **K** are obtained. Fig. 31.5 shows several different system curves indicating different outlet damper positions.

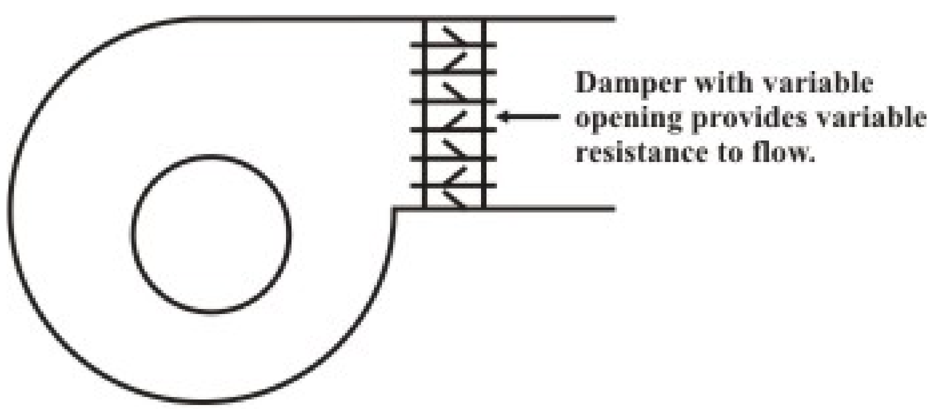


Fig. 31.4 Fan with outlet damper.

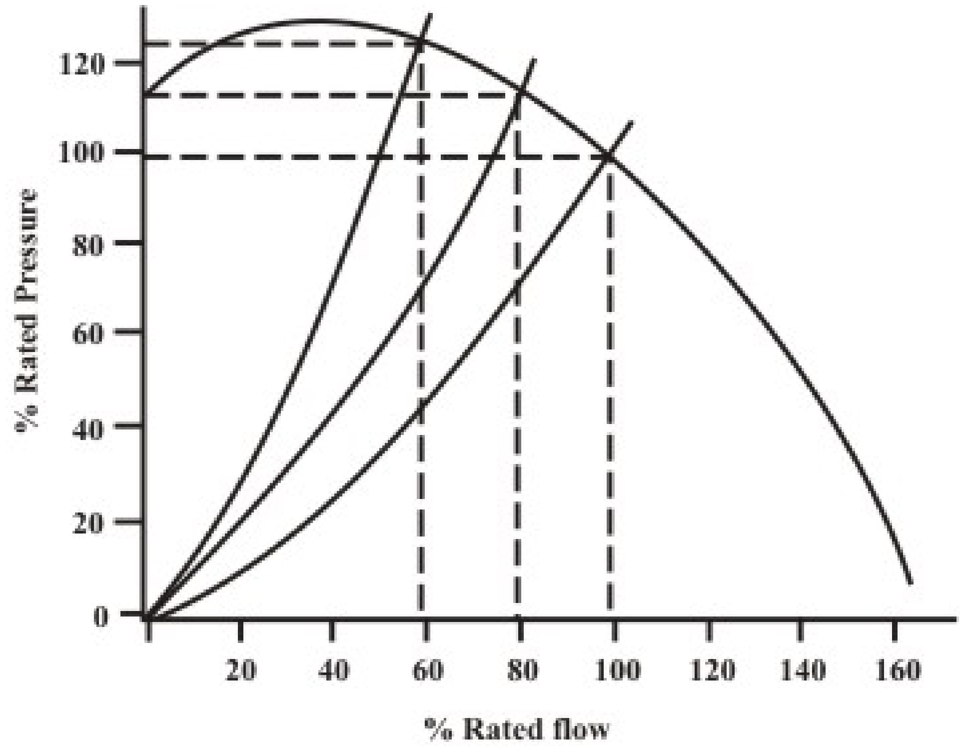


Fig. 31.5 Variations of System Pressure -Flow Characteristics with outlet dampers.

The power requirement can be derived from computing the rectangular areas shown in Fig. 31.5 at any operating point. Figure 31.7 shows the corresponding variations in power requirement for this type of operation. From the figure it can be seen that the power decreases gradually as the flow is decreased.

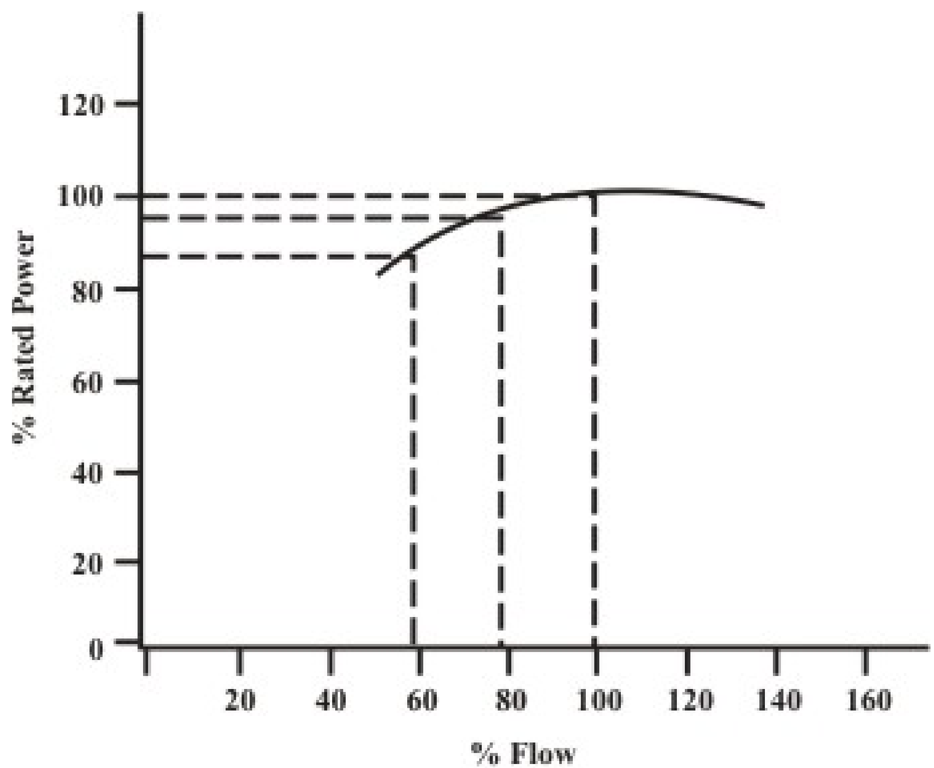


Fig. 31.6 Outlet Damper - Power Requirements

Points to Ponder: 3

A. *Can you identify, which of three system curves shown in Fig. 31.5 correspond to the maximum opening of the output damper?*

B. *Assume that the pressure-flow curve C shown in Fig. 31.5 represent the characteristics of the output element f the system. Then,*
   a. *Find the system efficiency at 60% of rated flow.*
   b. *Does the efficiency increase, or decrease with flow rate?*

Variable Speed Drive

This method changes fan curve by changing the speed of the fan. For a given load on the fan the pressures and flows at two different speeds, N_1 and N_2 are given as follows:

$$\frac{\mathbf{Q_2}}{\mathbf{Q_1}} = \frac{\mathbf{N_2}}{\mathbf{N_1}} \quad \frac{\mathbf{P_2}}{\mathbf{P_1}} = \left(\frac{\mathbf{N_2}}{\mathbf{N_1}}\right)^2 \quad \frac{\mathbf{W_2}}{\mathbf{W_1}} = \left(\frac{\mathbf{N_2}}{\mathbf{N_1}}\right)^3$$

where N= Fan Speed, Q= Volume Flow Rate, P= Pressure, W= Power. Note that eliminating speed from the above equations gives back the law, $P = K \times Q^2$ for the system. Thus, by this method, the operating point for a given system load shifts along the system characteristic curve as the speed of the fan is varied. Fig. 31.7 is a representation of the variable speed method.

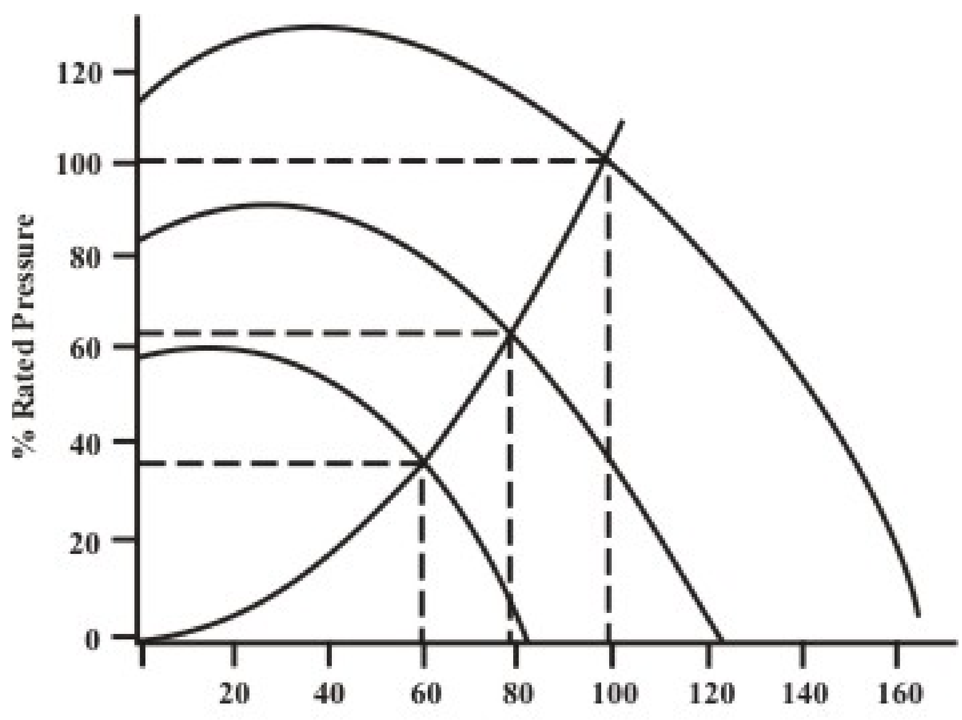


Fig. 31.7 Variable Speed Method

Fig. 31.7 shows the significant reduction in horsepower achieved by this method. Thus, in this method a desired amount of flow is achieved with the minimum of input power. The other two methods modify some system parameter, which generally results in the reduction of efficiency of the fan. This is why the power demand is greater than the variable speed method.

Points to Ponder: 4

A. *Can you identify, which of three system curves shown in Figure 31.8 correspond to the minimum speed of the pump?*

B. *Assume that the pressure-flow curve C shown in Figure 31.6 represent the characteristics of the output element f the system. Then,*
   a. *Find the system efficiency at 60% of rated flow.*
   b. *Does the efficiency increase, or decrease with pump speed?*

Energy Savings by Different Flow Control Methods

Outlet Damper

In this section the power consumption for two of the above methods, namely the variable speed method and the outlet damper method, and their associated costs of operation are estimated for a given load profile and a fan curve (shown in Appendix 1). Assume the fan selected has a rated speed of 300 RPM and 100% flow is to equal 100,000 CFM as shown on the chart. Assume the following load profile.

Flow (cfm)	**Duty Cycle (% of time)**
100%	10%
80%	40%
60%	40%
40%	10%

For each operating point, one can obtain the required power from the fan curve by locating the corresponding fan pressure. Note that, at all these operating points the speed is assumed constant. This power is multiplied by the fraction of the total time, for which the fan operates at this point. These "weighted horsepowers" are then summed to produce an average horsepower that represents the average energy consumption of the fan.

Flow(cfm)	**Duty Cycle**	**Power (hp)**	**Weighted Power(hp)**
100	10	35	3.5
80	40	35	14.0
60	40	31	12.4
40	10	27	2.7
			Total 32.6

Variable Speed Drive

To assess the energy savings, similar calculations are to be carried out to obtain an average horsepower for variable speed operation. The fan curve does not directly show the operating characteristics at varying speeds. However, these can be obtained using the laws of variation of pressure and flow with speed.

From the fan curve, 100% flow, (say Q_1**)** at 100% speed, (say $\mathbf{N_1}$**)** requires 35 HP. Now since, $\mathbf{Q_2/Q_1} = \mathbf{N_2/N_1}$**,** the new value of speed N_2 required to establish Q_2 can be obtained easily. This value of N_2, substituted into the power formula, $(\mathbf{P_2}/\ \mathbf{P_1}) = \mathbf{(N_2/N_1)^3}$ would then yield the new value of P_2 needed to establish Q_2 at speed N_2. When $\mathbf{Q_1}$ = 100% and W_1 = 35 HP, the values of W_2 for various values of $\mathbf{Q_2}$ **are shown below.**

$\mathbf{Q_2}$	80	60	40
$\mathbf{W_2}$	18	7.56	2.24

These calculated values do match the points available on the fan curve. Now it is possible to calculate the average horsepower.

Flow(cfm)	**Duty Cycle**	**Power (hp)**	**Weighted Power(hp)**
100	10	35	3.5
80	40	18	7.2
60	40	7.56	3.024
40	10	2.24	0.224
		TOTAL	13.948

Comparing the above figure with that calculated for the outlet damper method indicates the difference in energy consumption. The variable speed method requires less than half the energy of the outlet damper method (based on the typical duty cycle).
As an example of the cost difference between these methods, let's assume the system operates twenty-four hours per day (730 hours per month), and the cost of electricity is Rs. 2.00 per kilowatt-hour.

The cost of electricity is determined in terms of the energy in kilowatt hour per month.

	OUTLET DAMPER	**VARIABLE SPEED**
WEIGHTED HORSEPOWER	32.6	13.948
KW/HP	.746	.746
HR/MONTH	730	730
KWH/MONTH	17,753	7,596
COST (Rs./KWh)	2.00	2.00
TOTAL COST(Rs.)	35,506	15,192

There is over a 20,000 Rs. per month savings available by using the variable speed method instead of the outlet damper method.

This example only takes into account the operation of the fan. In practice the motor efficiency and the drive efficiency should also be taken into account. It is impractical to list or chart the motor and drive efficiencies in this lesson for all possible load conditions that could occur. However, since the same motor would be used in both examples shown here, the difference in motor efficiencies would be minimized and not significantly affect the results shown.

Points to Ponder: 5

A. *Is energy saving the only factor to determine which technology to adopt in a given industrial situation? If not, mention at least three other issues that also need to be considered, let us say, to decide whether to go for a throttling or a variable speed drive flow control system ?*

B. *How does the flow-demand profile affect the extent of energy savings? For example, would the energy saving be larger if the ratio of the minimum demand to maximum demand be high? How do the durations of these demand affects the saving?*

Pumps: Characteristics and Operation

Pumps are generally grouped into two broad categories, positive displacement pumps and centrifugal pumps. Positive displacement pumps use mechanical means to vary the size (or move), the fluid chamber to cause the fluid to flow. Centrifugal pumps impart a momentum in the fluid by rotating impellers immersed in the fluid. The momentum produces an increase in pressure or flow at the pump outlet. The vast majority of pumps used today are of the centrifugal type. Only centrifugal pumps are discussed here.

Fig. 31.8 again shows two independent curves. One is the pump curve which is solely a function of the physical characteristics of the pump. The other curve is the system curve. This curve is completely dependent on the size of pipe, the length of pipe, the number and location of elbows, etc.

Where these two curves intersect is called the natural operating point. That is where the pump pressure matches the system losses and everything is balanced. Note that this balance only occurs at one point (or at least should for stable system operation). If that point does occur at or at least come close to the desired point of operation, then the system is acceptable. If it does not come close enough then either the pump or the system physical arrangement has to be altered to correct to the desired point.

The following laws govern, similar to the case of fans, the operation of centrifugal pump characteristics at various pump speeds.

$$\frac{\mathbf{Q_2}}{\mathbf{Q_1}} = \frac{\mathbf{N_2}}{\mathbf{N_1}} \quad \frac{\mathbf{P_2}}{\mathbf{P_1}} = \left(\frac{\mathbf{N_2}}{\mathbf{N_1}}\right)^2 \quad \frac{\mathbf{W_2}}{\mathbf{W_2}} = \left(\frac{\mathbf{N_2}}{\mathbf{N_1}}\right)^3$$

where, N= Pump Speed
Q= Flow
P= Pressure
W= Horsepower

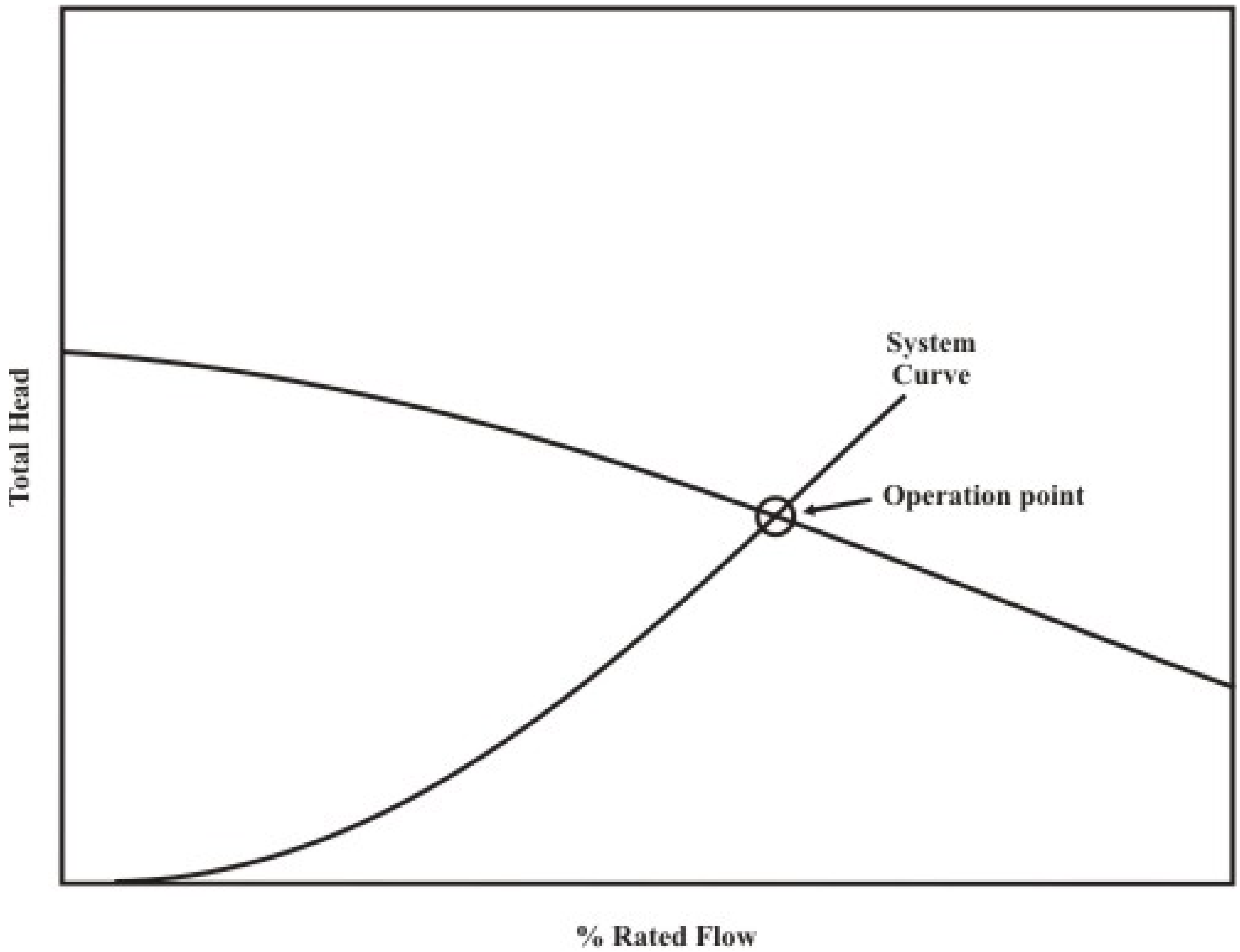


Fig. 31.8 Pump and System Curves.

Flow Control

Similar to the case of fans, there are two main methods of flow control in pumps, namely, use of a control or throttling valve and variable speed control of the pump. In view of the similarity, these are described in brief below.

Throttling

Consider a throttling system shown in Fig. 31.9. Two conditions of the system curve are shown, one with the valve open and the other with the valve throttled or partially closed. The result is that when the flow in the system is decreased, the pump head increases.

Variable Speed Drive

In comparison, the variable speed method takes advantage of the change in pump characteristics that occur when the pump impeller speed is changed. The new pump characteristics can be predicted from the laws stated earlier. In this method is that the pump head decreases as the flow is decreased. Fig. 31.10 on the following page gives an example of the system controlled from a variable speed pump.

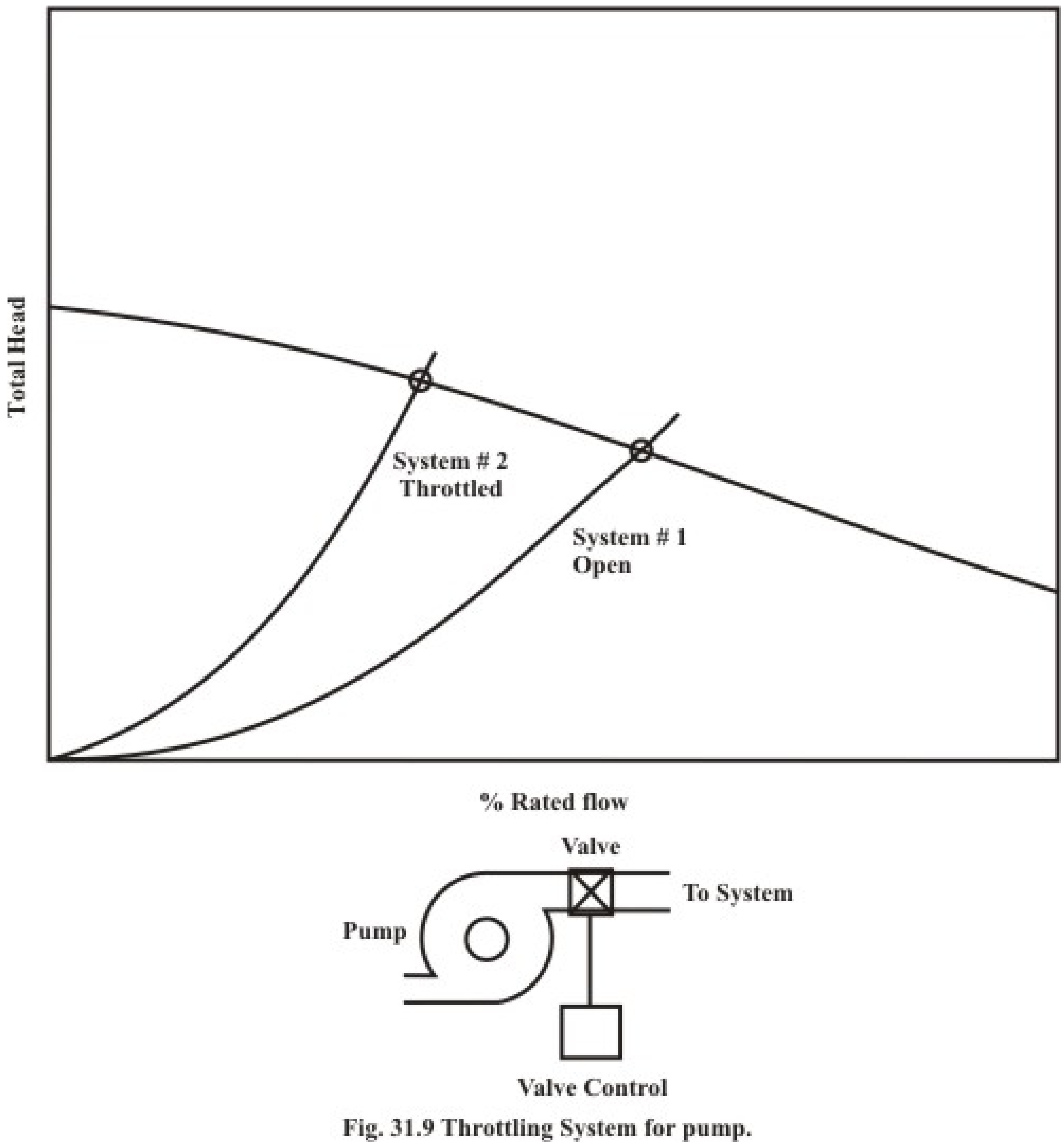


Fig. 31.9 Throttling System for pump.

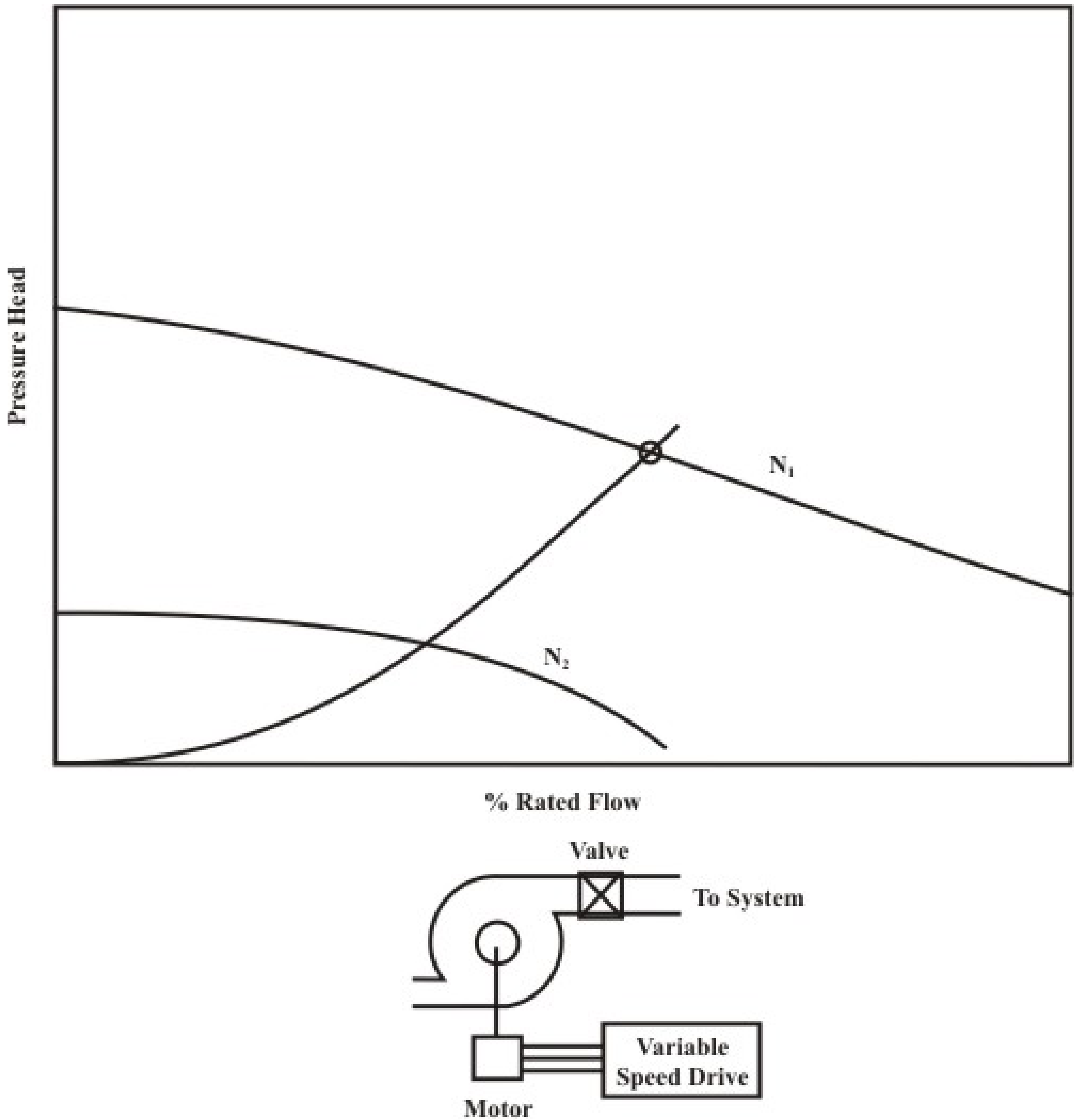


Fig. 31.10 Throttling System - Variable Speed Pump Control.

Static Head

Static head is the pressure required to overcome an elevation change in the system. To get water from the base to a spout at the top of a vessel would cause a static head on this pump. A system with a static head does change the system curve and the horsepower requirements will change from that shown previously. Fig. 31.11 shows the system curves for systems with different static heads. Fig. 31.12 shows the horsepower requirements for each system.

The system corresponding to the curve A is without static head. The system corresponding to the curve B requires a static head. The system corresponding to the curve C requires a double the static head and still has the same operations with the pump. Fig. 31.12 shows the power curves for the variable speed operations for the three systems A, B, and C. Curve D corresponds to throttle control. The dynamic operation of the throttling system does not change with static head. The static head does part of the work for the throttling valve. However, note that the horsepower requirement for this method remains above that of the variable speed method.

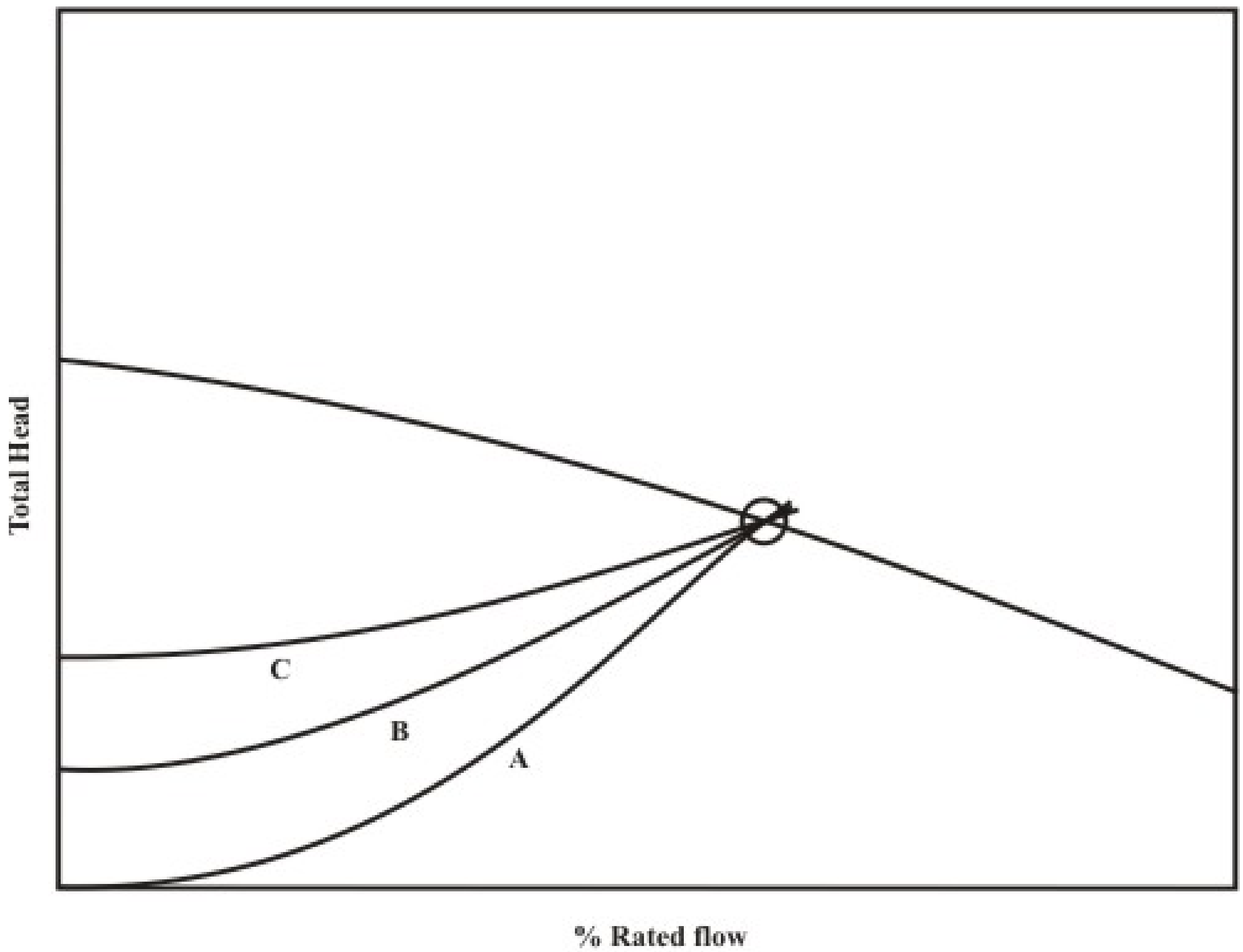


Fig. 31.11 Pump operation for a system with varying static head.

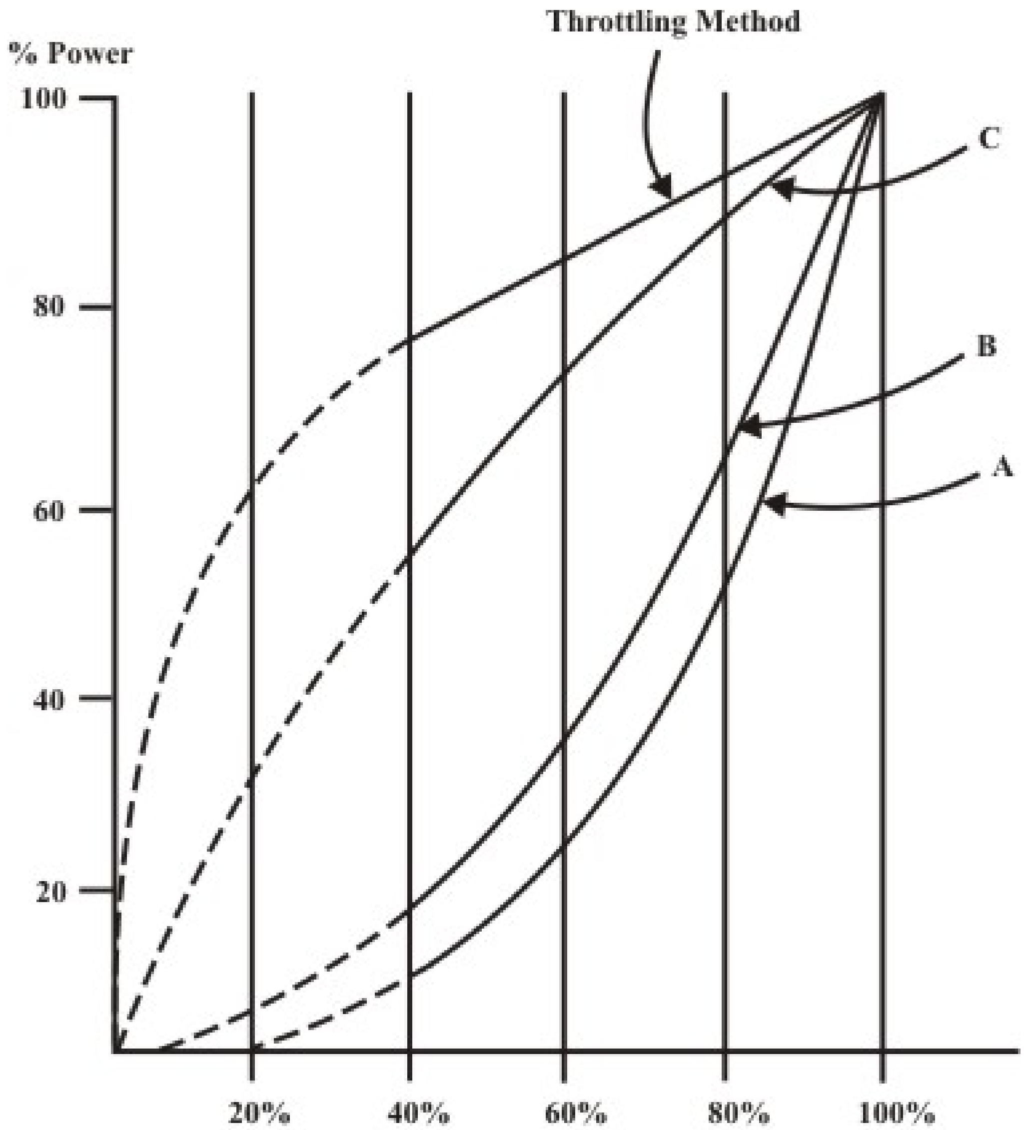


Fig. 31.12 Power-Flow Characteristics for Pumps.

Lesson Summary

In this lesson we have presented the main methods for flow control with special focus on energy savings. Specifically, the following have been discussed.

A. Major methods of flow control, such as, by output dampers and variable speed drives.

B. Assessment of energy requirements by the two methods in a practical example and comparative energy savings by the variable speed method.

C. Major methods of flow control by pumps, such as, by flow control valves and variable speed drives.

D. Assessment of energy requirements by the two methods in a practical example and comparative energy savings by the variable speed method.

E. Analysis of the effect of static heads in flow control of pumps.

Answers, Remarks and Hints to Points to Ponder

Points to Ponder: 1

A. Why is it that typically load requirements are stated in terms of flow rates?

Ans: Major applications for fans, blowers and pumps are for cooling, combustion, heat exchange, as feed mechanisms for chemical process etc. Notice that in all these applications the volumetric flow rate of the fluid is what needs to be controlled.

B. Why is it that the load requirements generally exhibit a parabolic pressure flow characteristics?

Ans: Because that is the characteristics of pressure drops whenever turbulent flow occurs, by Bernoulli's principle. $\Delta P \propto V^2 \propto Q^2$

Points to Ponder: 2

A. Why is this system acceptable for home HVAC?

Ans: Because the large thermal capacitance of home spaces is high compared to the heat loads. Therefore, even with on-off control, temperature oscillations are small. Finally, the cost saving is acceptable to customers in comparison with comfort requirements which are non critical.

B. Is it energy efficient?

Ans: It is more energy efficient compared to the outlet damper method. However it has some disadvantages compared to the variable speed drive method. Firstly the continuous start-stop process causes additional energy loss. It also causes maintenance problems. For these reasons, on-off control is not employed in large pumps and fans.

Points to Ponder: 3

A. Can you identify, which of three system curves shown in Fig. 31.6 correspond to the maximum opening of the output damper?

Ans: Curve A, because it has the lowest pressure drop for a given flow.

B. Assume that the pressure-flow curve C shown in Fig. 31.6 represent the characteristics of the output element f the system. Then,

a. Find the system efficiency at 60% of rated flow.

Ans: Assume that in the fully open position, the pressure drop across the valve is zero, so that, the characteristics of the output element is given by Curve A. From curve C, the pressure drop across the output element is about 45%. Therefore the drop across the output element is about 85%. Thus the efficiency of the system at 60% flow is about 65%.

b. *Does the efficiency increase, or decrease with flow rate?*

Ans: The efficiency of the system obviously increases with flowrate. Check for the efficiencies for 80% and 100% flows.

Points to Ponder: 4

A. *Can you identify, which of three system curves shown in Fig. 31.8 correspond to the maximum speed of the pump?*

Ans: Curve A, because it has the highest flow for a given pressure and the highest pressure for a given flow. That is consistent with the laws.

B. *Assume that the pressure-flow curve C shown in Fig. 31.8 represent the characteristics of the output element f the system. Then,*

a. *Find the system efficiency at 60% of rated flow.*

Ans: The efficiency is always 100 %, if we ignore the pipe losses and the efficiency of the motor and the drive. This is because there is never any pressure drop across a damper, and so the whole of the pump power is deployed in the load.

b. *Does the efficiency increase, or decrease with flow rate?*

Ans: The efficiency of the system remains more or less constant, notwithstanding the efficiency of the motor and the drive which are likely to fall to some extent with speed.

Points to Ponder: 5

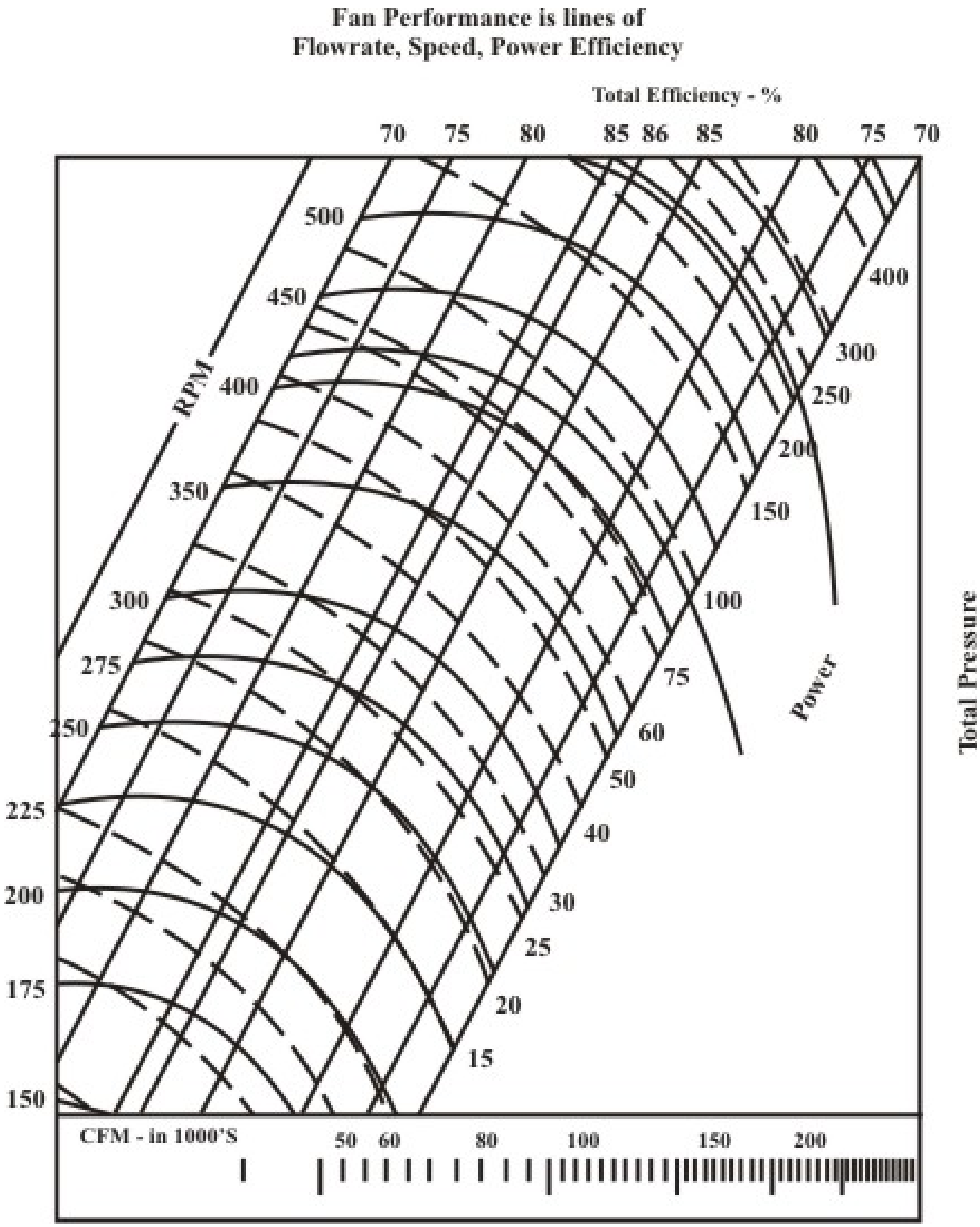
A. *Is energy saving the only factor to determine which technology to adopt in a given industrial situation? If not, mention at least two other issues that also need to be considered, let us say, to decide whether to go for a throttling or a variable speed drive flow control system ?*

Ans: Two other issues are:

i. Equipment cost
ii. Maintenance cost

B. *How does the flow-demand profile affect the extent of energy savings? For example, would the energy saving be larger if the ratio of the minimum demand to maximum demand be high? How do the durations of these demand affects the saving?*

Ans: The energy saving of the variable speed drive system is realized if the ratio of the maximum to minimum loads is high and also if the system operates at less than maximum load for a significant fraction of time.



Source:http://www.nptel.ac.in/courses/Webcourse-contents/IIT%20Kharagpur/Industrial%20Automation%20control/pdf/L-31(SM)%20(IA&C)%20((EE)NPTEL).pdf