



Process engineering

Pumps, turbines and compressors

Centrifugal pumps (3)

In this lesson the most commonly used methods for controlling centrifugal pumps will be considered. The simplest method is 'throttling' the discharge valve. However, this method will also bring about a significant deterioration in the efficiency of the pump or, more accurately, a deterioration in the efficiency of the system. Therefore, a better method would be to vary the speed of the pump. However, this method requires a large investment. This lesson will discuss the various advantages and disadvantages of these methods of control.

When one pump provides insufficient capacity, it is possible to connect a number of pumps in parallel. As an increased capacity will also result in an increased pipe resistance, the total capacity of two pumps lined up in parallel, for instance, will be less than twice the capacity of one pump. Especially with a high static head or a large pipe resistance, the effect of a second pump will be quite small. In those situations, a series arrangement of pumps will give a better result. In that case, it will be possible to overcome a static head that is higher than the manometric head of one pump.

Furthermore, the behaviour of a pump will be considered when it is subjected to an extension of the pipe system, as an existing system can be placed in series with another system. The possibility of connecting a system in parallel with the existing system will also be discussed. Finally, the lesson will consider the efficiency of a pump under anomalous conditions.

Contents of the lesson

- 1 Controlling the pump capacity
- 2 Control range of a centrifugal pump
- 3 Parallel line up of centrifugal pumps
- 4 Series line up of centrifugal pumps
- 5 The effect of lining up pipes in series
- 6 The effect of lining up pipes in parallel
- 7 The efficiency and the power requirements of centrifugal pumps



Lesson

1. Controlling the pump capacity

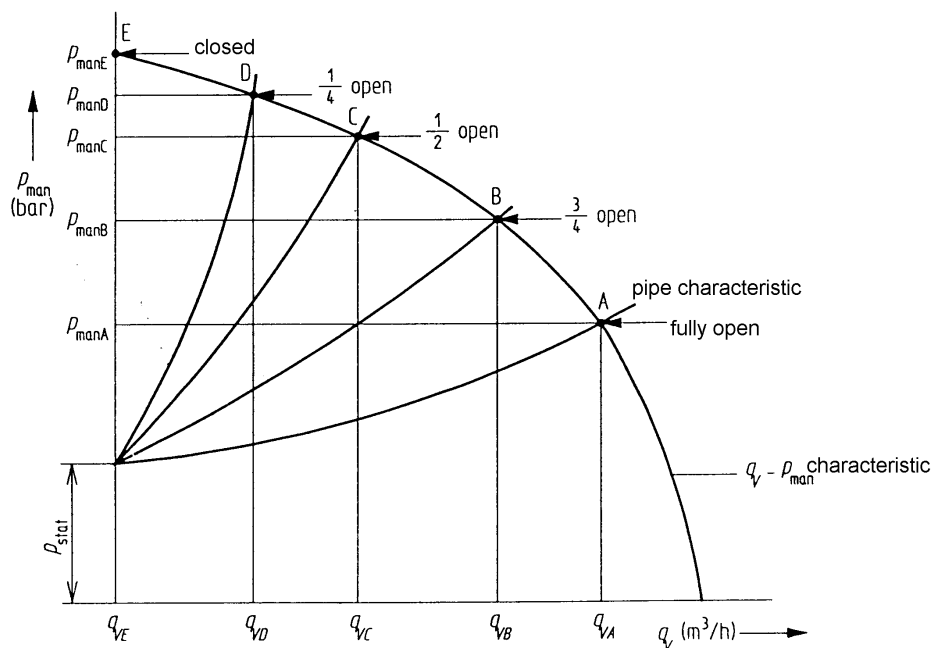
- two methods

- turbine

There are two ways of controlling the capacity of a pump. These are by throttling the discharge valve and by changing the number of revolutions of a pump. Controlling by means of the speed is eminently suitable for pumps that are driven by a turbine but less suitable for pumps that are driven by an electric motor.

1.1 Controlling the capacity by throttling the discharge valve

Figure 1 shows a pump characteristic together with the pipe characteristic for various settings of the discharge valve. The slope of the pipe characteristic increases as the resistance in the discharge pipe increases due to throttling of the discharge valve. Consequently the pipe characteristic will intersect the pump characteristic at an increasingly higher point (see points A, B, C, D and E). All lines originate from the same point because the static head p_{stat} remains constant. For points A, B, C, D and E, the capacity of the pump q_v is read from the horizontal axis and the related head p_{man} from the vertical axis.



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Figure 1
Decreasing the capacity by throttling the discharge valve

Question 1

What do you notice in figure 1 with respect to the power required by the pump at a decreased pump capacity?



- more
unfavourable

The head is at its maximum at point E but the capacity of the pump is zero. The operating point was initially in the most favourable area as far as efficiency is concerned. However, throttling the discharge valve moves the operating point and this has an unfavourable effect on efficiency. Part of the supplied power is not utilised and is converted into heat.

1.2 Controlling the capacity by changing the pump speed

Figure 2 shows the curves for the control of the capacity by changing the speed. Three pump characteristics have been plotted for speeds n_1 , n_2 and n_3 , where $n_2 < n_1 < n_3$, together with the pipe characteristic. The points of intersection B, A and C of the latter with the pump characteristics represent the related capacities $q_{v,2}$, $q_{v,1}$ and $q_{v,3}$, plotted on the horizontal axis, with the corresponding head $p_{man,2}$, $p_{man,1}$ and $p_{man,3}$ on the vertical axis. The lines 2, 1 and 3, drawn parallel to the vertical axis through the points of intersection B, A and C give us the points η_2 , η_1 and η_3 on the efficiency curves, representing the most favourable efficiency for each speed. With respect to the speed n_1 , it must be noted that the efficiency curve for the lower speed n_2 is displaced to the left and for the higher speed n_3 to the right. Hence, the efficiency of the pump at the various speeds of rotation remains the same. The figure also shows the required power $P_{n,2}$, $P_{n,1}$ and $P_{n,3}$.

Using the equation $P = p_{man} * q_v$, we can calculate the power of the pump.

In which:

p_{man} = manometric head in (N/m²) (1 N/m² = 1 Pascal)

q_v = capacity (m³/s)

P = power (W) (1 W = 1 J/s = 1 N * m/s)

For the speeds of rotation n_1 , n_2 and n_3 , the respective required power will be:

$$P_{n,2} = p_{man,2} * q_{v,2}$$

$$P_{n,1} = p_{man,1} * q_{v,1}$$

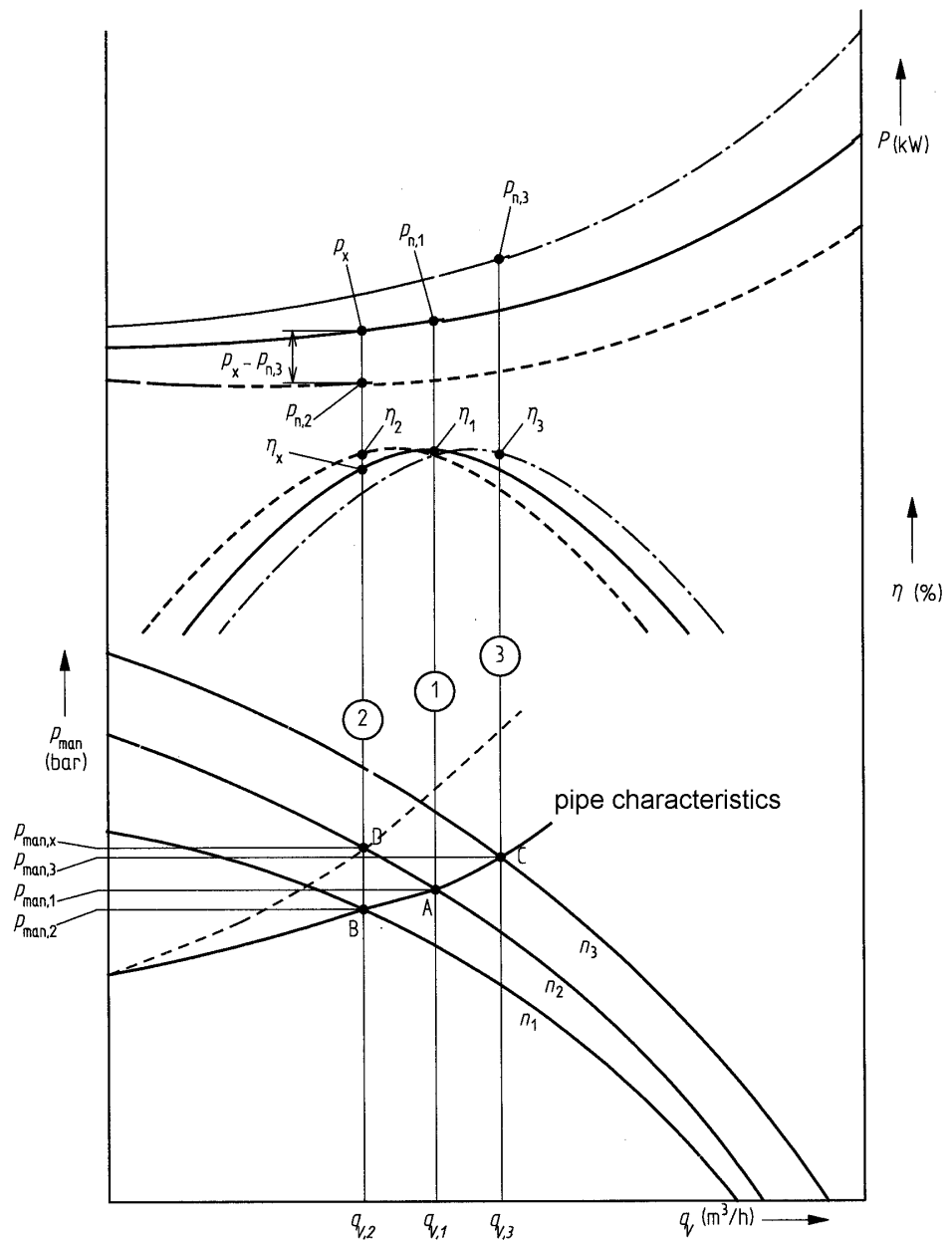
$$P_{n,3} = p_{man,3} * q_{v,3}$$

Since $p_{man,2} < p_{man,1} < p_{man,3}$ and $q_{v,2} < q_{v,1} < q_{v,3}$, it follows that $P_{n,2} < P_{n,1} < P_{n,3}$

Using figure 2, we will compare both methods. Assuming that the pump operates at a speed of n_1 , then the capacity will be $q_{v,1}$, the head $p_{man,1}$, the efficiency η_1 and the required power $P_{n,1}$. Decreasing the capacity to $q_{v,2}$ without changing the speed, can be achieved by throttling the discharge valve. The operating point will be displaced from A to D. The head then becomes $p_{man,x}$. If we follow line 2 upwards, we will see that the efficiency of the pump will be η_x and the required power P_x . From this it can be concluded that reduction in the capacity by throttling the discharge valve instead of changing the speed:

- lower capacity
- conclusion

- will unfavourably affect the efficiency of the pump;
- will hardly reduce the required power at all.



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Figure 2

Controlling the capacity by changing the speed of the pump. The figure also shows the trend for the efficiency and the power consumption

- converted into
heat

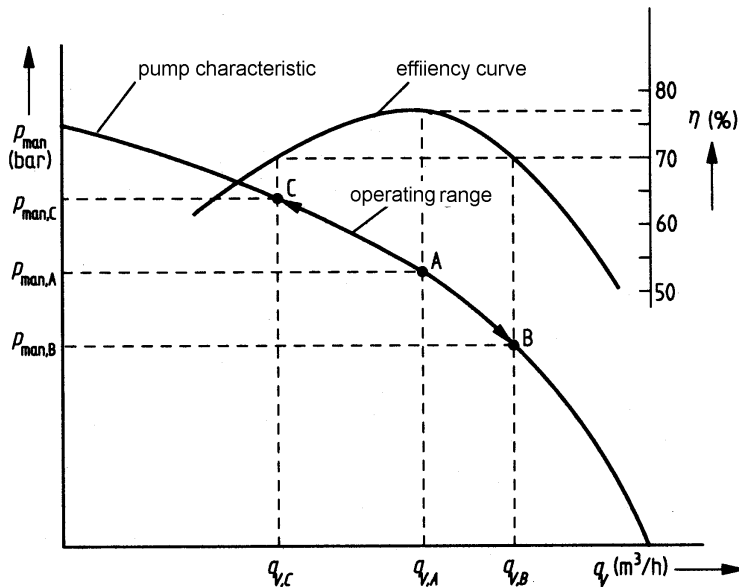
The proportional increase in power will only be partially utilised for the increased head created. Most of it will be converted into heat and this is considered to be lost energy. Hence, if possible, controlling the capacity by changing the speed is preferred over controlling the capacity by throttling the discharge valve.



2. Control range of a centrifugal pump

- pump specifications

The control range or operating range of a pump is considered to be the range in which the capacity of the pump, the head or both can be changed whilst maintaining an acceptable efficiency of the pump. Hence, when selecting a pump the requirements for the pump must be taken into consideration. Figure 3 shows a pump characteristic and an efficiency curve to clarify this reasoning.



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Figure 3

A typical pump characteristic together with an efficiency curve

Assuming that the pump operates at maximum efficiency at point A, then its capacity is $q_{v,A}$ and the head is $p_{man,A}$. A requirement could be that the efficiency of the pump is not allowed to be less than 70% for a capacity of $q_{v,B}$ and $q_{v,C}$ or a head of $p_{man,B}$ and $p_{man,C}$. To satisfy these requirements, we find the operating points B and C. The range BC on the pump characteristic is said to be the control range or operating range of the pump.

- control range or operating range

Question 2

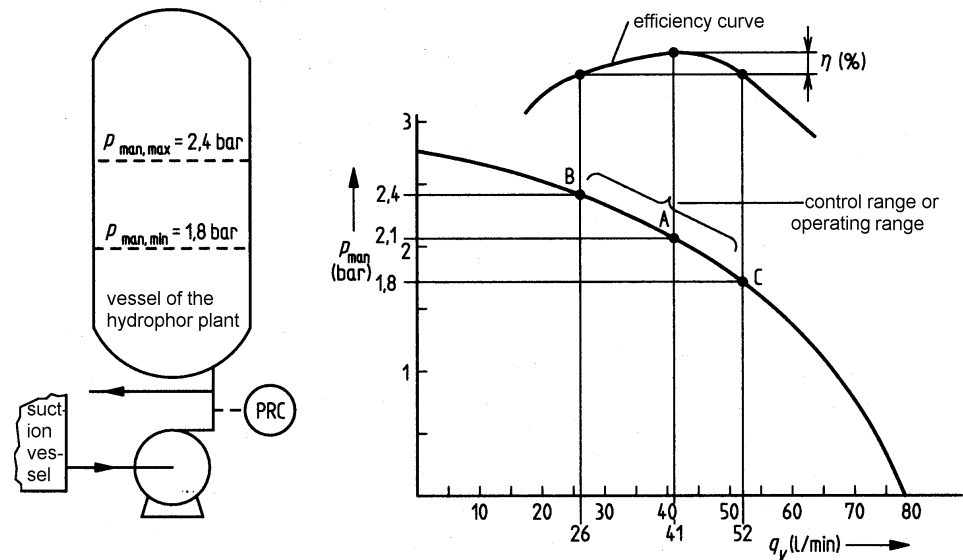
Which conditions must be met by the control range or operating range of a pump?

2.1 A detailed example

See figure 4.

- hydrophor plant

The pump in a hydrophor plant (that is an installation that keeps a system under a specific pressure) is directly connected to the suction vessel and the discharge vessel. The maximum and minimum manometric pressures in the system are 2.4 and 1.8 bar, respectively. The average manometric pressure is 2.1 bar. Under these conditions, the operating point of the pump will be situated at point A of the pump characteristic.



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Figure 4

Operating range of a centrifugal pump in a hydrophor installation

In this case, the efficiency is at its maximum. Due to the operation of a minimum-maximum automatic switch PRC, the pump will start at $p_{\min} = 1.8$ bar and stalls at $p_{\max} = 2.4$ bar. The nominal capacity at $p_{av} = 2.1$ bar is 41 l/minute. The manometric head fluctuates between 2.1 bar and 1.8 bar at a capacity of 26 l/minute and 52 l/minute, respectively. For these capacities and manometric heads, the operating point of the pump is situated at points B and C. The range BC of the pump characteristic is called the control or operating range of the pump.

Question 3

How large is the operating range of the pump depicted in figure 4?

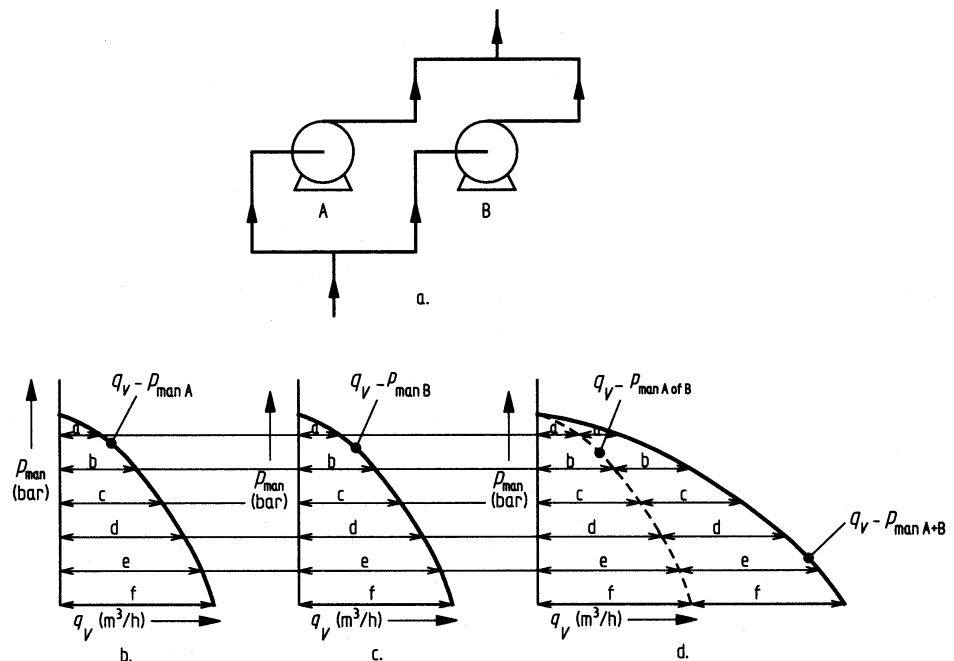
3. Parallel line up of centrifugal pumps

- greater volume flow

When a greater volume flow or head cannot be achieved with one pump, two or more pumps can be placed in parallel or in series. In a parallel line up, the pumps are connected to the same suction and/or discharge pipe in order to achieve a greater volume flow. In a series line up, the discharge side of one pump is connected to the suction side of the other pump. In the situation where the pumps are incorporated into a single casing, this is a two-stage, three-stage or multi-stage pump.

3.1 Parallel line up of two identical pumps

Figure 5a shows the set-up for two identical pumps A and B, lined up in parallel.



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Figure 5

Constructing the 'pump characteristic' for two identical centrifugal pumps lined up in parallel

The pumps have been connected to the same suction and discharge pipes. Identical pumps are pumps that have the same capacity for the same head. Hence, the q_v - p_{man} characteristics of pumps A and B are identical (see figures 5b and 5c). In figure 5d, the q_v - p_{man} characteristics of both pumps A and B have been plotted together. This curve has been obtained by adding the capacity q_v of pumps A and B at the same value for heads p_{man} . The characteristic for more than two identical pumps lined up in parallel is obtained in a similar manner.

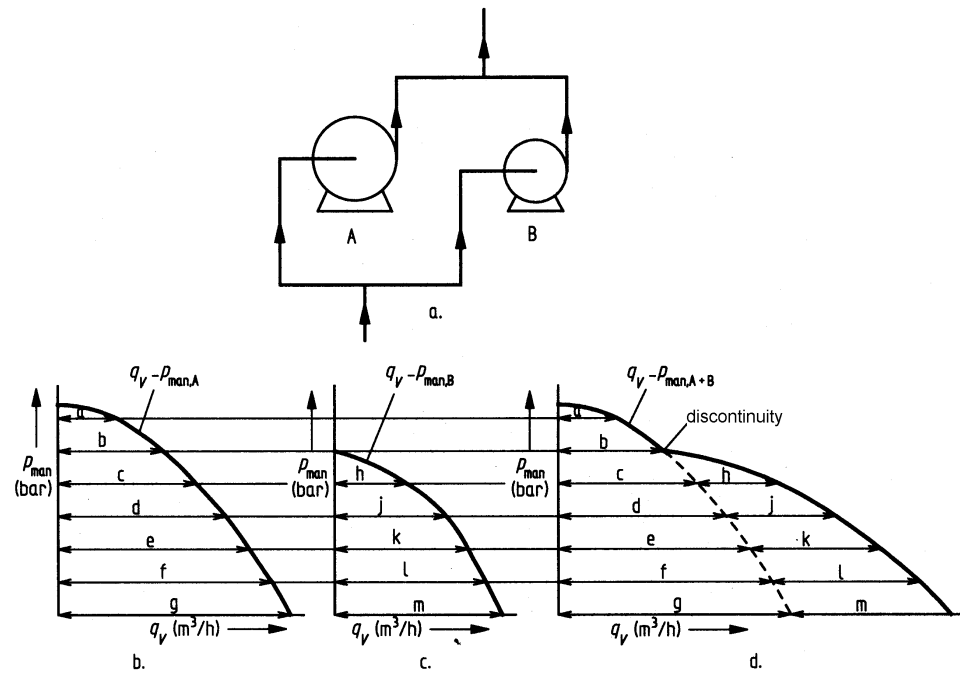
- summation

Question 4

Why is the maximum head in the combined graph the same as that for one pump?

3.2 Parallel line up of two different pumps

Different pumps are pumps whose head and/or capacity are different. Figure 6a shows the set-up for two different pumps A and B lined up in parallel. Pump A has a larger capacity and head than pump B.



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Figure 6

Constructing the 'pump characteristic' for two different centrifugal pumps lined up in parallel

In this situation, the pumps are also connected to the same suction and discharge pipes. Figures 6b and 6c show the q_v - p_{man} characteristics of pumps A and B, respectively. Figure 6d shows the combined characteristic of both pumps. This is calculated in the same way as in the case of two identical pumps lined up in parallel.

- different pumps

With different pumps, the q_v - p_{man} characteristic of the smallest pump (B) is always plotted against that of the larger pump (A) on the same scale. In figure 6d we see that the combined characteristic has a discontinuity at the position of the maximum head of the smaller pump. At this point, pump B no longer delivers any liquid.

- unacceptable

The power that is supplied to this pump is completely converted into heat, causing an unacceptable rise in temperature in the pump. Hence, the pump must be stopped before it reaches this discontinuity.

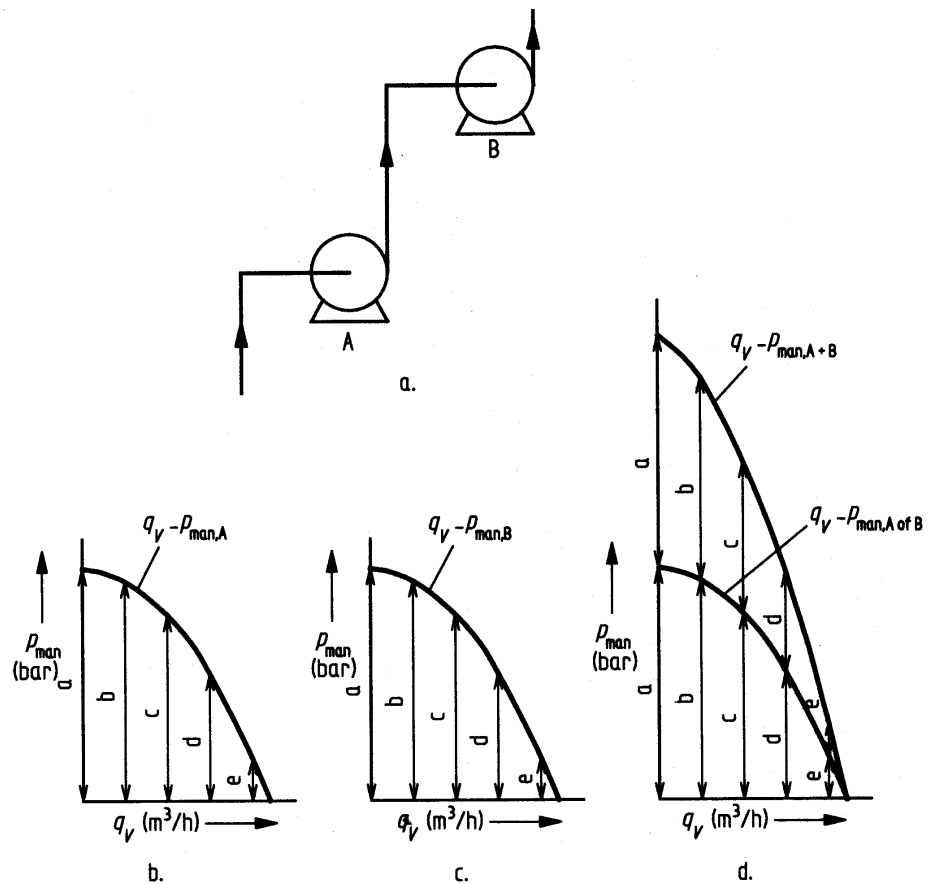


4. Series line up of centrifugal pumps

4.1 Series line up of two identical pumps

- sum

When two pumps are lined up in series in a pipe system, the head obtained is equal to the sum of the heads of each individual pump.



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Figure 7

Constructing the pump characteristic for two identical centrifugal pumps lined up in series

Figure 7a shows the set-up for two identical pumps A and B lined up in series. The capacity q_v and the head p_{man} of both pumps are the same. Figures 7b and 7c show the $q_v - p_{\text{man}}$ characteristics of pumps A and B, respectively, whereas figure 7d shows the characteristic for the combination of both pumps. This graph is constructed by plotting the heads p_{man} of both pumps on the vertical lines that have been drawn from points of equal capacity. It is as if the characteristic of one pump is placed on top of the characteristic of the other pump.

- placed on top of the other

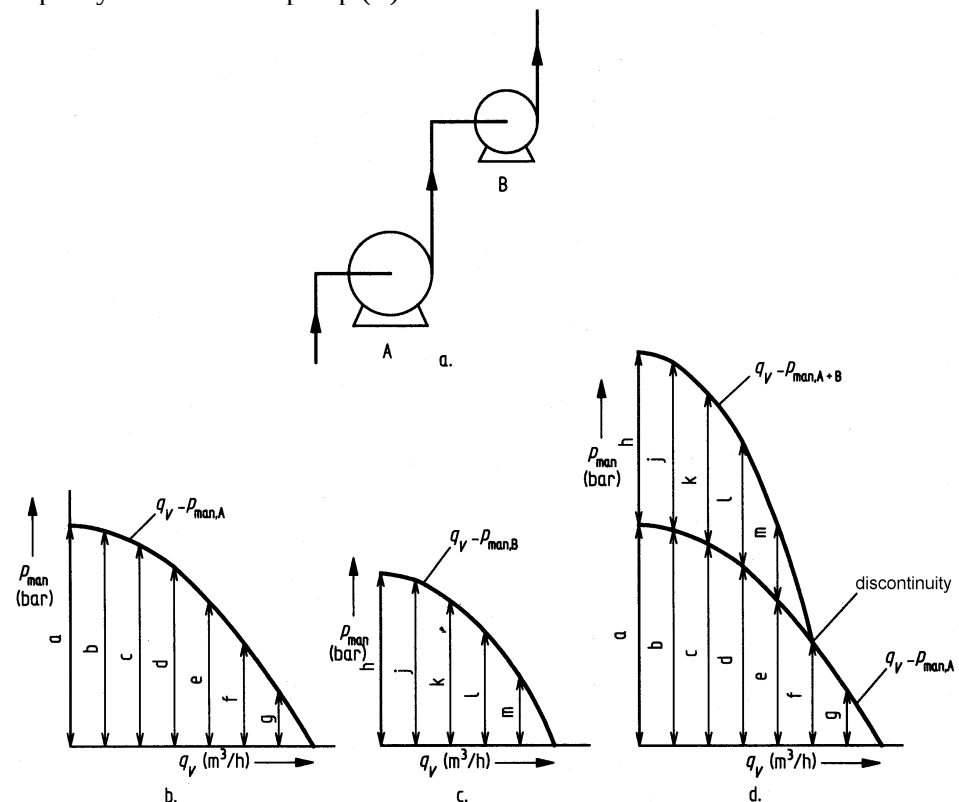


4.2 Series line up of two different pumps

- different

Figure 8a shows the set-up of two different pumps A and B lined up in series. Pump A has a larger capacity q_v and a higher head p_{man} than pump B. Figures 8b and 8c show the characteristics of pump A and pump B, respectively, whereas figure 8d shows the characteristic of both pumps operating together.

This characteristic is obtained by placing the characteristic of the smaller pump (B) on top of the characteristic of the larger pump (A). The head of the two pumps operating together is obtained by adding the heads of each individual pump. The combined characteristic shows a discontinuity at the maximum capacity of the smaller pump (B).



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Figure 8

Constructing the pump characteristic for two different centrifugal pumps lined up in series

- does not contribute anymore
- resistance

- cavitation

This indicates not only that after this point of discontinuity the smaller pump ceases to contribute to increasing the head but also that it will act as a resistance to the larger pump. This implies that the head for different pumps lined up in series must always be greater than the head of the head reached at the point of discontinuity. Furthermore, the capacity of the whole system must be smaller than the capacity of the smallest pump at the point of the discontinuity. In the set-up shown in figure 8a, the larger pump A is placed upstream from the smaller pump B. If pump A is placed downstream from pump B, cavitation could occur in pump A when the head falls below the point of discontinuity.



5. The effect of lining up pipes in series

Placing pipes in series is, in fact, extending the pipe system. The resistance of a pipe is directly proportional to its length and inversely proportional to its diameter. Because the same volume flow passes through the series-lined up pipes, the resistance of the individual pipe segments are added together.

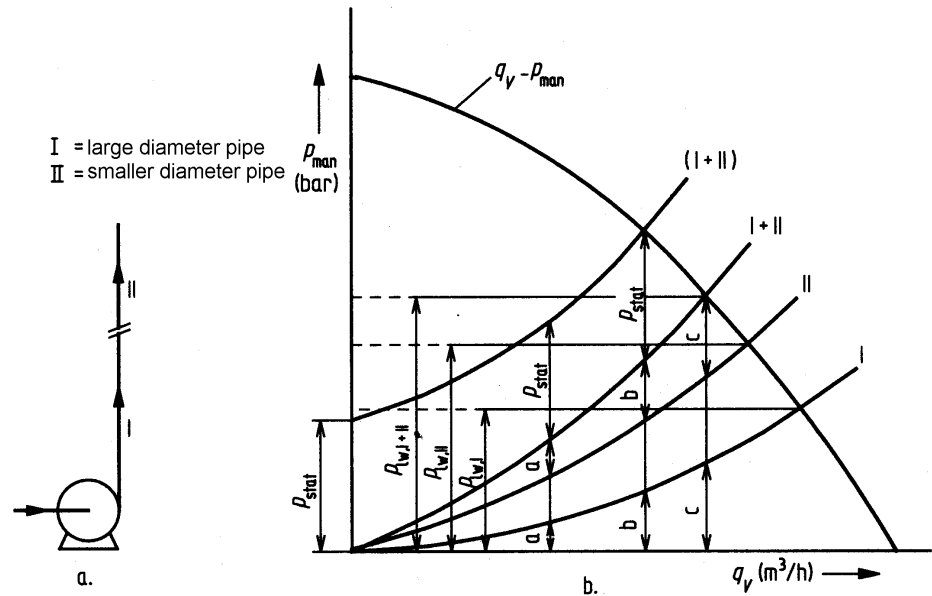


Figure 9
Generating a series line up of pipe systems

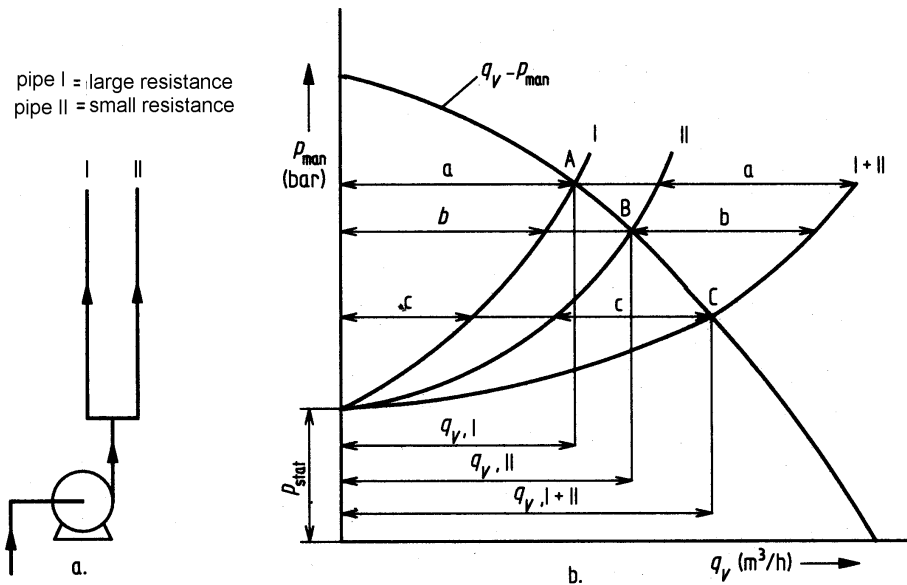
Figure 9a shows a pump to which a large diameter pipe I is connected. Lined up in series to this pipe is a smaller diameter pipe II. Figure 9b shows the pipe characteristics of the individual pipes I and II, as well as the pipe characteristic for the combined pipes I + II. The characteristics show the behaviour of the pipes at various volume flows q_v . The pipe characteristic I + II is constructed by adding the resistance of the individual pipes at various volume flows. If, however, a static head p_{stat} is also present, the characteristic I + II will be displaced upwards by an amount equivalent to this value, resulting in characteristic (I + II). To complete the picture, figure 9b also shows the $q_v - p_{man}$ characteristic of the pump.



6. The effect of lining up pipes in parallel

With a pipe system lined up in parallel, the capacity q_v of the pump is divided across the pipes. Depending on the pipe characteristic, more will flow through one pipe than through the other.

Figure 10a shows the case of a pump to which two pipes are lined up in parallel. Pipe I has a greater resistance than pipe II. This is illustrated in the graph of figure 10b by the steeper slope of pipe characteristic I compared to that of pipe characteristic II.



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Figure 10

The generation of the parallel line up of pipe systems

- behaviour of both pipes

The behaviour of both pipes operating together is shown by pipe characteristic I + II. This characteristic is constructed by adding the separate volume flows through pipes I and II. Plotting the pump characteristic in the same graph results in the points of intersection A, B and C with the pipe characteristics of pipe I, II and I + II, respectively. These points of intersection are all situated within the operating range of the pump. From these points of intersection, the volume flow $q_{v,I}$, $q_{v,II}$ and $q_{v,I+II}$, together with the related heads p_{man} , can be determined. The volume flow $q_{v,I}$ through pipe I occurs when pipe II is closed off and volume flow $q_{v,II}$ occurs when pipe I is closed off. Volume flow $q_{v,I+II}$ occurs when both pipes are open.



7. The efficiency and the power requirements of centrifugal pumps

Apart from the relationship between capacity and manometric head, it is also important to know the power that the pump requires for a given capacity, as well as the corresponding efficiency. These values can also be expressed in a graph. In order to obtain a clear picture, these lines are often incorporated into one graph. Figure 11 is an example. This figure shows the curves of the power consumption, efficiency and the head as a function of the capacity.

In this figure the capacity q_v in m^3/h is plotted on the horizontal axis and the manometric head in bar, the required power in kW and the efficiency as a percentage are plotted on the vertical axis. From figure 11 we can see, in first instance, that the maximum manometric head of 2 bar is reached when the discharge valve is closed, i.e. $q_v = 0$. Because the capacity is zero, it must be expected that the required power is also zero.

No work is performed and, hence, no power is required. Yet, from the power curve we can see that 4 kW of power is still required. In that situation, the efficiency is

$$\frac{0}{4} * 100\% = 0\% \text{ (i.e. 'One gains nothing out of something')}$$

The power consumed is completely converted into heat by the friction of the impeller in the liquid, the eddy currents of the liquid and the friction of the shaft in the bearings and seals. This also shows that it is not recommended to run the pump for any length of time with a closed discharge valve because the pump will soon become unacceptably hot from the supplied power.

- not recommended

Question 5

Is it possible to explain why a centrifugal pump can be started with a closed discharge valve?

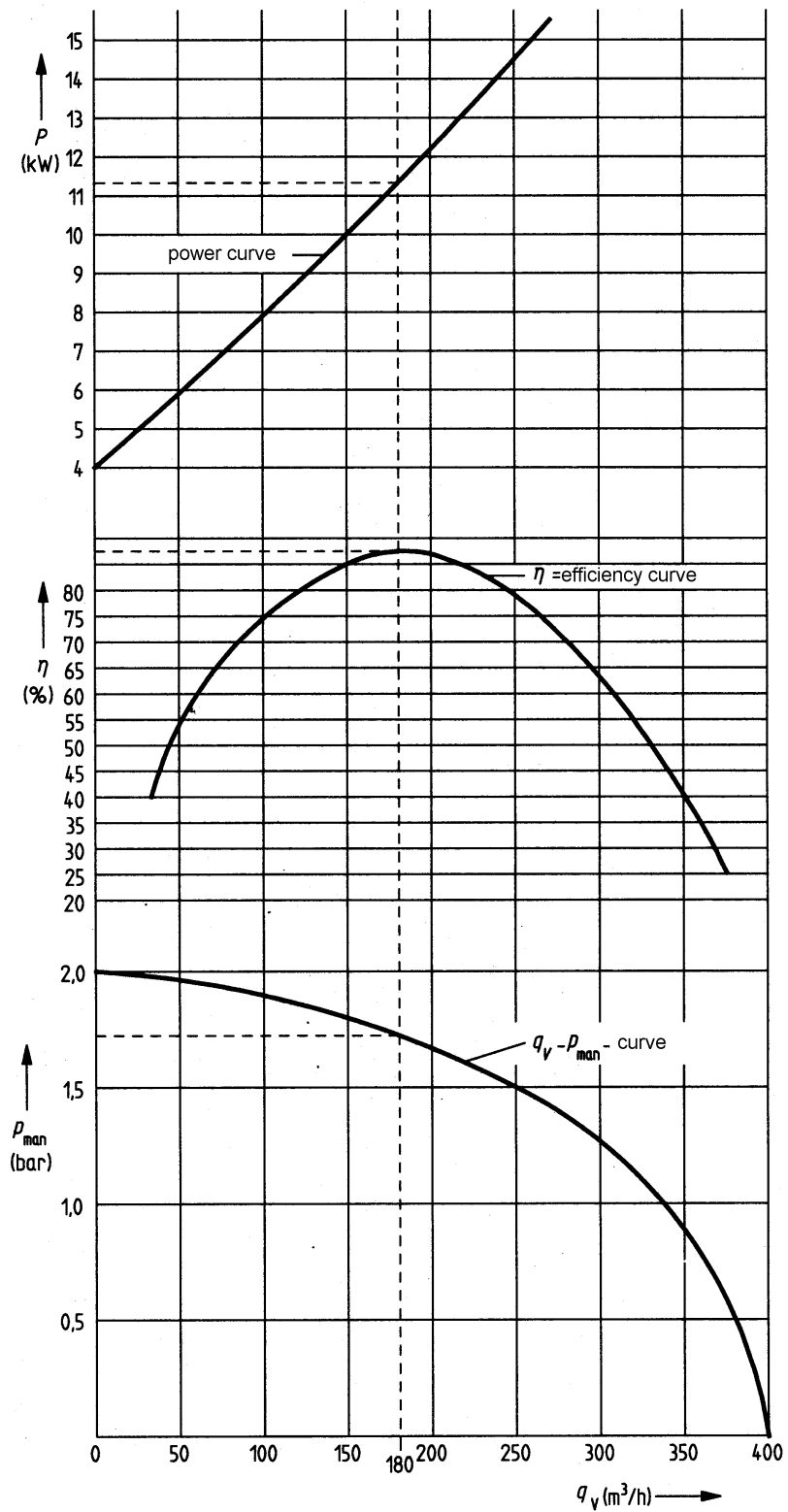
The pump will deliver the liquid as soon as the discharge valve is opened. The manometric head will decrease but the efficiency and the required power will increase until the maximum efficiency is reached at a capacity of approximately $180 \text{ m}^3/\text{h}$. The power loss will then be minimum. At a capacity of $180 \text{ m}^3/\text{h}$ ($= 0.05 \text{ m}^3/\text{s}$), the increase in pressure will be 1.7 bar (p_{man}).

The power transferred to the liquid is then:

$$\begin{aligned} P &= p_{\text{man}} * q_v = [\text{N}/\text{m}^2 * \text{m}^3/\text{s}] \\ &= 1.7 * 10^5 * 0.05 \\ &= 8500 \text{ N}\cdot\text{m}/\text{s} = 8500 \text{ W} = 8.5 \text{ kW} \end{aligned}$$

However, the power supplied to the pump is $\frac{P}{\eta} = \frac{8.5}{0.875} = 9.7 \text{ kW}$

For a new pump, the values q_v , p_{man} , η and P are determined on a test bench.



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Figure 11
The curve of the head, the efficiency and the required power as a function of the capacity of a centrifugal pump



- **stable q_v - p_{man} curve**
- **unstable q_v - p_{man} curve**
- **two volume flows**

In practice, however, leakage loss will increase after a period of time due to, for example, wear of the wear rings. Consequently, the volumetric efficiency of the pump will decrease. Furthermore, there may be a deviation in the q_v - p_{man} curve with respect to the stable q_v - p_{man} curve. A stable q_v - p_{man} curve is a curve where the head p_{man} decreases as q_v increases from 0 to its maximum value. The contrary is true for an unstable curve. This is a curve where p_{man} does not attain its maximum value when q_v is 0. As q_v increases, p_{man} will first increase to a certain maximum value and then start to decrease. Over a certain range of the curve, there will be two possible volume flows q_v for one value of p_{man} .



Summary

This lesson discussed the various ways of controlling the capacity of a centrifugal pump. Therefore a detailed study was made of the concept of 'Control range of the pump'. This may be understood to mean that particular capacity and that particular head under which the pump can still attain a certain efficiency. In situations where a pipe system needs to deliver a greater capacity, pumps can be lined up in parallel. When a system must provide a greater head, then the pumps must be lined up in series. Finally, the lesson provided an explanation regarding the operation of a centrifugal pump when the pipe system is extended. This extension may be in parallel or in series.



Test

Exercises

Do not send in your answers for correction

1. One of the possible methods mentioned to control the capacity of a pump is the throttling of the discharge valve. What is the drawback of controlling the capacity by means of throttling the suction valve?
2. Give a simple explanation of why a centrifugal pump can be started with a closed discharge valve without any adverse effects and why, in fact, this is actually recommended. Also include in your answer the reason why it is not recommended to allow such a situation to continue for an extended period of time (operating the pump with a closed discharge valve).
3. When a certain system requires a larger volume flow, would you choose a series or parallel line up of the pumps. Illustrate your answer with a simple drawing of an q_v - p_{man} curve.

Answers to the questions in the lesson

1. Since the required power of a centrifugal pump is determined by multiplying the capacity (m^3/h or m^3/s) with the delivered manometric head

$$(\text{bar or N/m}^2), \text{ power will be expressed in } \frac{\text{m}^3}{\text{s}} * \frac{\text{N}}{\text{m}^2} = \frac{\text{Nm}}{\text{s}} = \text{W}$$

In figure 1 we see that throttling the discharge valve causes a decrease in capacity but an increase in manometric head. The product of the two will only change slightly within the operating range. The required power of the pump will therefore hardly change at all, whereas the performance will decrease. Hence, the efficiency decreases.

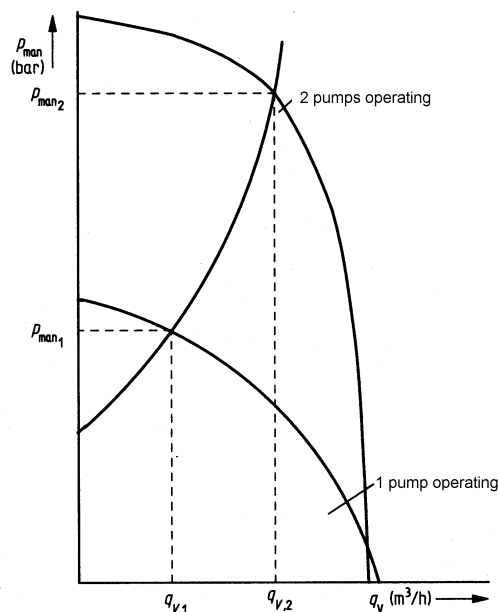
2. With regard to the efficiency of the pump it should be possible to control the capacity or head in an acceptable manner.
3. From a capacity of 52 l/minute and a manometric head of 1.8 bar to a capacity of 26 l/minute at a head of 2.4 bar.
4. The pumps are lined up in parallel. Furthermore, both pumps are identical. Therefore, the maximum head of pump I has no effect at all on the head of the second pump. Each pump displaces its own volume of liquid. However, when both pumps deliver together to one and the same pipe system, pipe resistance will increase and, consequently, the manometric head of each pump will also increase, but not the maximum head of the pump.



5. When a pump does not have to deliver a capacity, the required power during the start-up of the pump will only be determined by the friction that the liquid causes on the accelerating impeller and the mechanical losses in the bearings. However, power is not required for the displacement of liquid, thanks to the closed discharge valve.

Answers to the exercises

1. If the capacity of a centrifugal pump were to be controlled by means of throttling the suction valve, the effect, for example, would be the same as that of a contaminated system filter (in the suction side of the pipe system). The local pressure in the suction side of the pump may approach the vapour pressure associated with the temperature of the liquid to be pumped. The risk that cavitation and, hence, damage will occur, increases tremendously. The $NPSH_A$ will approach zero.
2. The power of a pump is determined by the product of its capacity and its head. When a pump is prevented from delivering its capacity this will theoretically mean that no power is required. In practice, this will certainly require power. This power is required to overcome, amongst other things, frictional losses. When a pump is allowed to operate in such a situation for an excessive period of time, the liquid in the pump will reach very high temperatures. In that situation, the pump could possibly break down.
3. If a greater capacity is required from a specific system, then it will depend on the static head as to whether the second pump needs to be lined up in series or parallel to the first pump. Figure 12 shows the situation where a second pump lined up in series results in a substantial increase in the capacity.



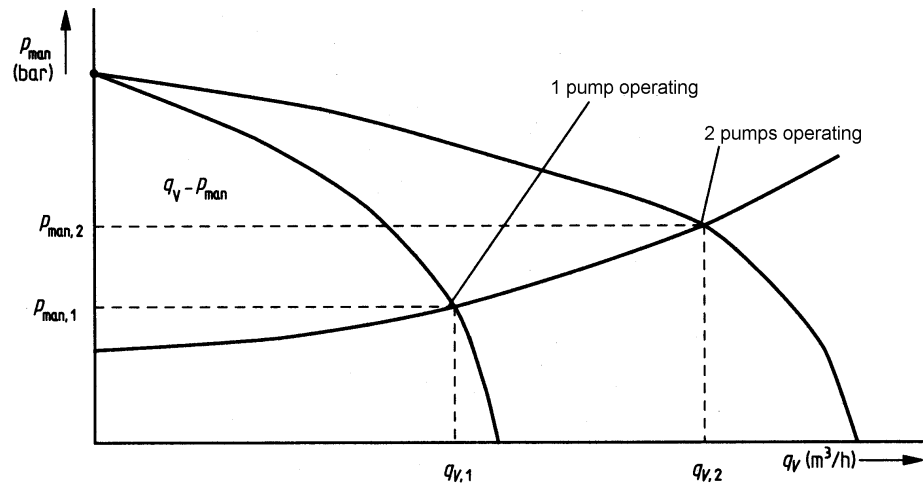
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Figure 12
Two pumps lined up in series with high pipe resistance



Figure 12 shows that a greater capacity can be obtained by connecting the pumps in series. This is only useful if the resistance curve of that particular system is steep. Lining up pumps in parallel is only useful when the resistance curve of the particular system is fairly flat.

This is illustrated in figure 13



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Figure 13

Two pumps lined up in parallel with low pipe resistance

Problems and assignments

Answer and send in for correction

1. In which situation must multi-stage centrifugal pumps be used?
2. Explain, using Euler's equation, why a centrifugal pump is not self-priming.
3. Which factors determine the volumetric capacity of a centrifugal pump?
4. Some centrifugal pumps have a diffuser ring fitted in the casing. Make a simple drawing of this ring and explain the operation of this diffuser ring.
5. Draw a combined characteristic of two pumps lined up in parallel having different capacities and heads. Indicate by means of a resistance curve when the smallest pump ceases to have an effect on the capacity.