THEORETICAL ANALYSIS AND GRAPHICAL REPRESENTATION OF THE SYSTEM CURVE FOR WATER PIPELINE CONNECTING ZAWIA DESALINATION PLANT WITH HARSHA TANKS

Abdulmenam A. Abdalla[1], Ali K. Muftah[2], Ahmed O. Amhamed[3]

[1, 2, 3] Mechanical department, Engineering faculty, Sabratha University

[1]Abdoali1977@yahoo.com, [2]ali.alkhtabe@yahoo.com, [3]ahmed_dbash@yahoo.com

Abstract

The flow of water within a pipeline system causes loss of energy due to friction effects. To overcome these losses, energy is added to the water through the pump. So, the right pump selection is important for providing the required flow rate. The first step to select a right pump for any pipeline system is calculating the performance curve of piping system, which is a graphical representation of the energy required to move a given flow rate through a piping system and is used to identify the characteristics of the system's pump. For this purpose, the system curve for the water pipeline connecting the main reservoirs of Zawia desalination plant to the sub-tanks in Harsha has been evaluated and represented graphically in H-Q curve of the selected pump. This water pipeline network consists of sets of pipes connected in parallel and series with a total length of 5 km. The system NPSHA at different water levels in the suction tank at the maximum system flow rate of 800 (m^3/hr) has been calculated to ensure avoiding cavitations problem in the selected pump.

Keywords: pipeline, system curve, pump curve, cavitation

Introduction

Water is transported and stored to be used within the requirements of everyday life through a network of pipes with a range of equipment needed to process and transport water. This network is called the pipeline system. Due to the dynamic friction losses in the pipes, and differences in level between the beginning and the end of the system, the energy is needed to overcome these losses by adding pump/pumps to afford energy to a water flow. Pipelines system has an important role in various fields of modern life, where the pipeline is used to transport potable water to residential consumers, for drinking, cooking, washing...etc. Pipeline Networks are widely used in agricultural, industrial and commercial applications; For example, transporting of natural gas and oil products. Water supply is also essential for business and industry uses for transportation of natural gas, and oil products. Therefore, the Pipeline usage is increasing significantly in developing nations. The pipeline may extend over long distances and may be above or below ground; it is connected between the supply and delivery points taking into account the operational requirements of the flow rate and pressure in addition to operational costs (N.S. Nandagopal 2007)**.**

Any pipeline system consists of pipes which represent the main part of the system in addition to fittings, accessories and equipments. The fluid is transferred through the pipeline system with different flow rates depending on friction and minor losses which affect the pressure head too. The relationship between the pressure head and the flow rate is known as the system curve. The system curve is graphically represented on Head-flow rate curve (H-Q curve) by calculating friction losses, minor losses and losses due to elevation, after collecting the information and data for the components of the system such as: pipe specifications and lengths, type and location of valves and joints, and any equipment fitted in the system. To provide the requirements for changes in flow rates in the system, pump/s must be added to the system taking into account the effect of variations in flow and pressure requirements **(**J. Paul Tullis 1994**)**. The relationship between flow rate and pressure in the pump is known as pump curve, when installing a pump in the system, and plotting the pump curve with the system curve on the same curve (H-Q curve) we get point where the pump performance curve and the system curve are intersecting. This point is known as the operating point, which determines the flow rate and pressure as well as pump efficiency and the brake horse power. The operating point changes by changing the flow rate and/or water level in the tanks (Terry Wright, and Philip M. Gerhart 2009).

Al-Harasha is considered to be one of the areas fed with desalinated water from Zawia desalination plant, where the desalinated water is transferred from the main reservoirs at the desalination plant to the storage tanks in reservoirs about 5 km away from the main reservoirs through a pipeline system containing equipment and fittings required to complete the process of transportation. The pipeline system consists of two main reservoirs. The water is pumped to the system through a network of pipes divided into eight lines that vary in diameter and length. Each line contains the necessary equipment and fittings. The water is pumped by a centrifugal pump to both sub-tanks in Harsha zone. The sub-tanks are connected to each other and have the same characteristics as the two main reservoirs. The plant contains two main reservoirs open to air to store the desalinated water after leaving the station, where the capacity of each tank is 20000 m^3 with a height of 15 m each.

Theoretical background

Pump adds energy to move fluid through a pipeline system at a desired flow rate, so understanding of system and pump characteristic is necessary for the right pump selection and efficient pump operation.

Pump and pipeline system

The pipeline system is a system contains all parts of physical facilities through which fluid is transported, including pipes, valves, bends, elbows, tees, inlets, exits, and decrease or increase in pipe area, or any part of system where direction of flow changes. The fluid is transferred by pump/s operates within the system (Peter Smith 2007**)**. Pumps are classified into two types; dynamic and positive displacement. The most common type of dynamic pump is the centrifugal pump, which should generate enough pressure to overcome the hydraulic resistance of the system (Gulf Publishing Company 2016**).**

Pump characteristics curve

The pump's characteristic curves are a graphical representation of the pump's performance that define the range of possible operating conditions for the pump. The curves given by the manufacturer of the pump in different pump speeds and impeller sizes, and can be described by some characteristics are depicted in figure (1).

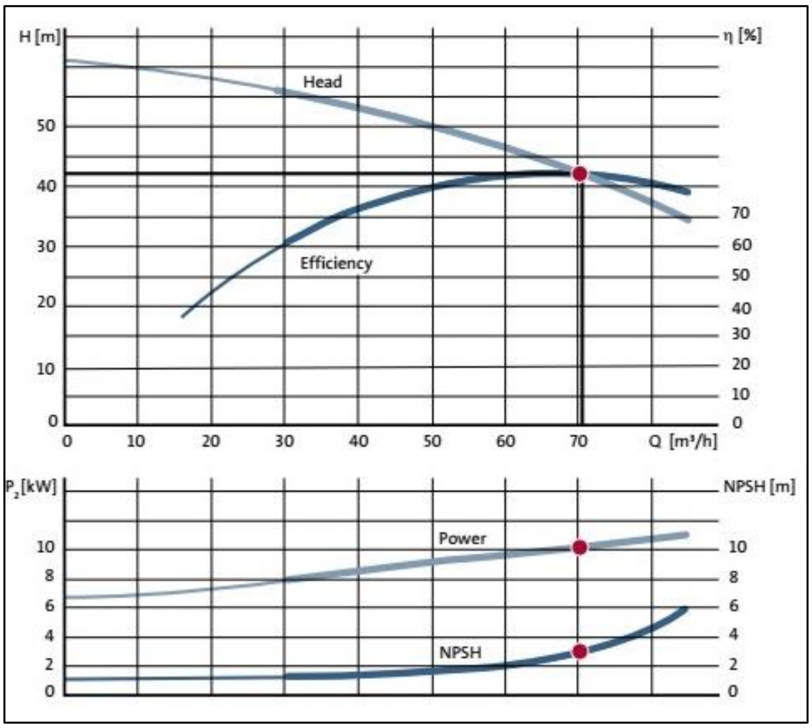

Figure (1): pump characteristiccurves

Flow rate - head curve

The flow rate-Head curve (Q-H curve) is the relation between the volume flow and the pressure at a constant speed of the pump. The pump develops energy called discharge pressure or total dynamic head (TDH). This pressure is expressed as the height of the column of liquid; it has a unit of meter, the centrifugal pumps develop different heads at different flow rates (SAM Yedidiah 1996).

Power Curve

The power curve gives information on the power required to operate a pump at a given flow rate which usually given in Watt. The brake horse power rises with the flow (Zane Satterfield, P. E 2013).

Efficiency Curve

Pump efficiency is the ratio of the liquid horsepower delivered by the pump and the brake horsepower delivered to the pump shaft, the efficiency lines are expressed as a percentage in the curve, each pump has efficiency varies throughout its operating range. The best efficiency point (BEP) is the point of highest efficiency of the pump; all points to the right or left of the BEP have a lower efficiency (Zane Satterfield, P. E 2013). Therefore, a pump that can supply the required head and flow rate is not necessarily a good choice for a piping system unless the efficiency of the pump at those conditions is at best efficiency area. So, the higher the efficiency, the less energy required to operate the pump.

Net Positive Suction Head Curve

The net positive suction head curve (NPSH) is the relation between the flow and the needs of the energy level at the suction side of the pump, in addition the vapour pressure of the water, it takes into consideration the suction pipe and connections, the elevation and absolute pressure of the liquid in the suction tank, the velocity of the liquid and the operating temperature **(**SAM Yedidiah 1996**)**.

The pump has value of Net Positive Suction Head Required (NPSHR) which needed at the pump suction to prevent the pump from cavitation, this value is a characteristic of the pump design and specified by a pump vendor. The system has the value of Net Positive Suction Head Available (NPSHA) as a characteristic of the system design at operating condition and calculated based on the friction losses in the system **(**Larry Bachus and Angel Custodio2003**).**

Cavitations in centrifugal pump

When the pressure at any point inside a pump reduced to a value equal to or below its vapor pressure, the liquid will vaporize, caused bubbles move along the impeller, these bubbles will act as a small stone caused wearing the pump material, and cavitations will occur. To avoid cavitations the NPSH available should be larger than the NPSH required (Clifford Matthews 2002).

System Head Curve

The system curve is a graphical relationship between flow and hydraulic losses in a piping system, these losses are a function of flow rate, which are increasing with the increase of flow. The system curve is totally independent of the pump characteristics curve. Each system has its own characteristic curve changes with the physical configuration of the system. The system losses are: static and friction head. Static head (H_s) is the difference in height of liquid level between suction and discharge reservoirs, which independent on flow rate, while friction head (dynamic head loss) (H_D) is the friction loss in pipes as liquid moved in pipes, valves and equipment in the system. Therefore, the total system head curve (H_{sys}) is a sum of static head and friction head (Larry Bachus and Angel Custodio2003).

Static Component

Static components represent static head loss, which does not depend on the flow rate, but depends on the nature of the system installation. It is symbolized by the symbol (H_s) and is divided into:

Suction Static Head (h_{ss})

Suction Static head is the vertical distance between water level in suction tank and pump axis as shown in figure (2).

Suction Pressure Head (h_{ps})

It is the measured pressure inside the suction tank represented by a column height of the liquid (Pressure Head), it is equal zero if the tank exposed to atmospheric pressure.

Discharge Static Head (h_{sd})

It is the vertical distance between water level in discharge tank and pump axis as shown in figure (2).

Discharge Pressure Head (h_{pd})

It is the measured pressure inside the discharge tank represented by a column height of the liquid (Pressure Head), it is equal zero if the tank exposed to atmospheric pressure.

Total Static Head (H_S)

The total static head is the sum of the static head of the suction and discharge lines, and can be calculated from the equation:

$$\boldsymbol{H_s} = (\mathbf{h_{sd}} + \mathbf{h_{pd}}) - (\mathbf{h_{ss}} + \mathbf{h_{ps}}) \qquad \textbf{(1)}$$

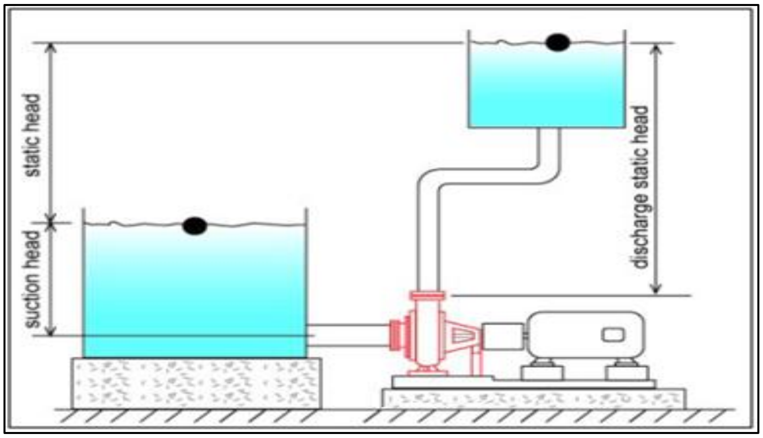

Figure (2): Suction and discharge static head

Dynamic Head

Dynamic components are the friction losses due to the flow of fluid in the system, and consist of the sum of major and minor losses, and symbolized by the symbol (H_D). Since friction losses depend on the length and area of the pipes and the velocity of the fluid inside the pipes, the dynamic head also depends on the flow rate. It is proportional to the flow rate square, and represented on the (H-Q curve) as in figure (3). It is clear that the greater the flow rate, the greater the loss due to friction. In most systems, the total system head is composed of the static head and the friction head, as shown in figure (3). The total system head (H_{sys}) is called the "System Curve", or the system loss curve, which is the relationship between discharge and the total loss head in the piping system.

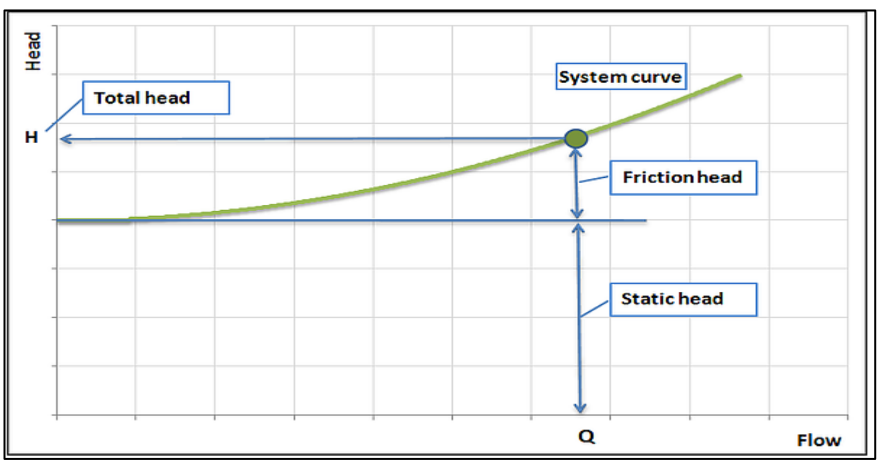

Figure (3): Total system head

Operating Point

The point of intersection between H-Q curve of a pump in a piping system and the system head curve is called the operating point. This is clearly shown in figure (4). This point is the head produced by the pump needed to overcome the head loss in the pipeline system at required flow rate. If the two curves do not intersect, the pump is not suitable for that application. So, calculating system head curve is important to avoid some pumping pitfalls (Clayton T. Crowe, Donald F. Elger, Barbara C. Wiliams, and John A. Roberson 2009**).**

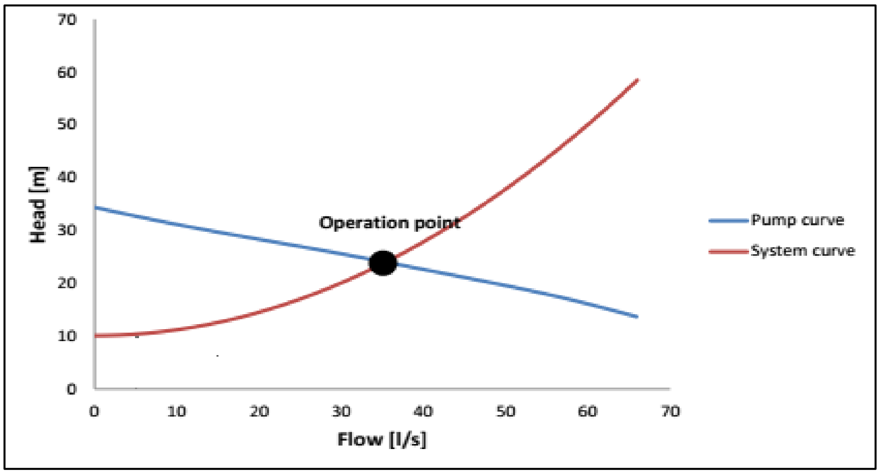

Figure (4): System and pump curve with operating point

Methodology

The system under study is a pipeline consists of a set of pipes connected in series and in parallel in which water is transferred from the main reservoirs of Zawia seawater desalination plant to the sub-tanks in Harsha. Desalination water is transported at a temperature of about 21°C across the system described in figure (5). The pipeline network is divided into eight lines of pipes, varying in diameter, flow, length, and the equipment required for the water transfer process. The water is pumped at a flow rate between 450-800 m^3/h through the system according to the operating conditions and requirements, to cover the needs of the area.

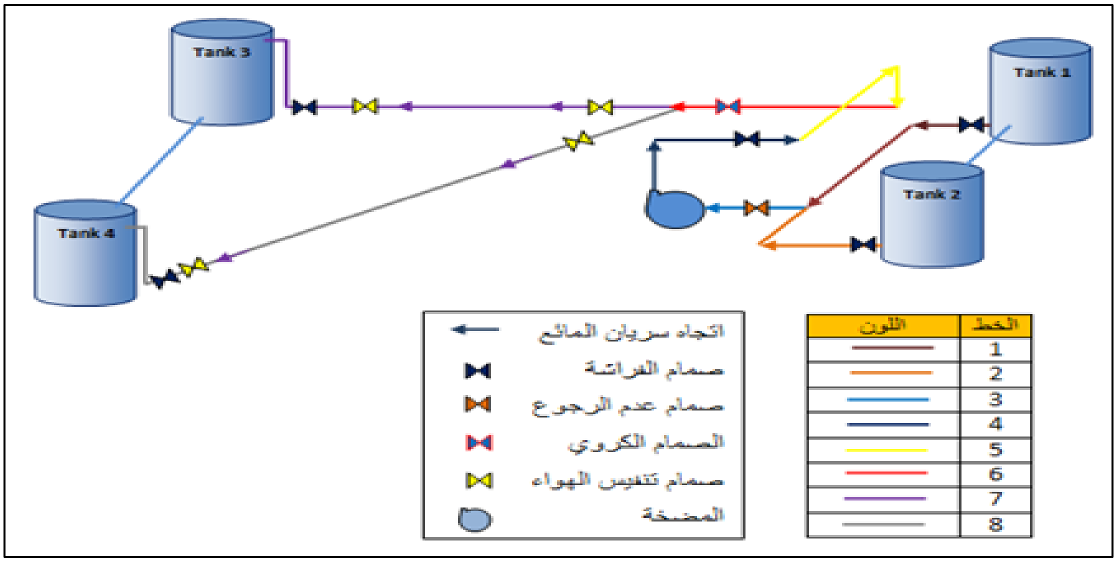

Figure (5): layout of the pipeline system

The dimensions of each pipe and its specifications (length (L), diameter (D), material, and pipe roughness *(e))* as well as the contents of equipment and fitting accessories for each pipe (with the *minor loss coefficient* K) are shownin table 1.

Table (1): Dimensions and spécifications of pipes and system equipments.

Line NO	L (m)	D (m)	Pipe material	e (m)	No. of Elbow90°& (K)	No. of Elbow45°& (K)	No. of Butterfly valves& (K)	N0. of Ball Valves & (K)	No. of Check valves &(K)	No. of Air Relief valves
1	34	1	Fibreglass	$5x10^{-6}$	1 (0.75)	2 (0.35)	1 (118)	-	-	-
2	20	1	Fibreglass	$5x10^{-6}$	1 (0.75)	2 (0.35)	1 (118)	-	-	-
3	3.5	0.6	Fibreglass	$5x10^{-6}$	-	-	1 (118)	-	-	-
4	4	0.4	Fibreglass	$5x10^{-6}$	-	-	-	-	1(10)	-
5	34	0.7	Fibreglass	$5x10^{-6}$	1 (0.75)	-	-	-	-	-
6*	20	0.6	Fibreglass	$5x10^{-6}$	1 (0.75)	-	-	1 (70)	-	-
7	5000	0.6	Concrete	3050 $x10^{-6}$	4(0.75)	9 (0.35)	1 (118)	-	-	2
8	5000	0.6	Concrete	3050 $x10^{-6}$	4 (0.75)	9 (0.35)	1 (118)	-	-	2

*Line 6 contains gradual Expansion and Contraction and Orifice Plate Flow Meter

Determination and graphical representation of the system curve.

The system curve will be drawn on (H-Q curve) at different flow rates, by drawing the dynamic loss curve (friction losses) graphically and determining the static loss head, by the following steps:

1- Calculate the friction losses for each line in terms of the coefficient of resistance, as a function of the flow rate using the following equation:

$$H_D = (C_f + C_k)Q^2 \qquad (2)$$

Where; $C_f$is major resistance coefficient, $C_K$is minor resistance coefficient, and Q is volume flow rate.

$$C_f = f \frac{L}{D^5} \frac{8}{\pi^2 g} \qquad (3)$$

Where; f is the friction factor which is a function of the Reynolds number (R_e) and the relative roughness (e/D), L is the pipe length (m), D is the pipe diameter (m), and g is the gravity (m/s^2).

$$C_k = K \frac{1}{D^4} \frac{8}{\pi^2 g} \qquad (4)$$

Where; K is the *minor loss coefficient*, which depends on the geometry and type of the component.

2- Draw the dynamic loss curve on (H-Q Curve) for each line by using equation (2) after calculating the total resistance coefficient.

3- For each two lines connected in parallel, the equivalent curve is obtained by summation the flow rates at the same head. The equivalent curve becomes connected in series with the rest of the system line.

4- After calculating the curve of each line and drawing the equivalent curve for each two parallel lines, the head is added at the same flow rate for all lines as all lines become connected in series. Then, the dynamic loss curve (friction losses) of the systemis determined.

5- The total static head of the system is calculated from equation (1).

6- After calculation of the static head, the system curve is drawn from the point at the head of H_S. The value of the friction head is added to the value of the static head at each flow rate, according to equation (5).

$$H_{sys} = H_S + (C_f + C_K)\, Q^2 \qquad (5)$$

Calculation of the possibility of cavitations

The cavitations phenomenon is dangerous to the pipe system, and especially on the pump. It reduces the pump's efficiency and often damages it. To avoid it, the following condition must be satisfied:

$$\text{NPSHa} > N\text{PSHr}$$

The NPSHa is calculated using equation (6) as follows;

$$\mathbf{NPSHa} = \frac{\mathbf{p_a}}{\boldsymbol{\gamma}} - \frac{\mathbf{p_v}}{\boldsymbol{\gamma}} - \mathbf{h_{fs}} + \mathbf{h_{ss}} \qquad (\mathbf{6})$$

Where; P_a is the absolute pressure of the suction tank (Pa), P_v is the vapour pressure of the liquid at operation temperature (Pa), γ is the specific weight (N/m^3), and the h_{fs} is the friction head of the suction line (m) **(**C.P. Kothandaraman, and R. Rudramoorthy 2007**)**.

While the NPSHr is the characteristic of the pump design and specified by pump vendor.

Results and Discussion

Water is transferred to the pump from the main reservoirs by lines 1 and 2 at different flow rates according to system requirements, the calculations have been done at required flow rate of 525 m3/h. where the 875 m^3/h is delivered to lines 1 and 2, a part of flow rate (350 m^3/h) delivered to line out of a study system, the rest of flow rate (525 m^3/h) has passed to the line 3. Results are shown in Table 2.

Table (2): Dynamic head equation at flow rate of 525 m^3/h

Pipeline	L (m)	D (m)	Q (m^3/h)	V (m/s)	Re (x 10^5)	f	C_f (s^2/m^5)	C_k (s^2/m^5)	H_D (m), Q (m^3/s)
1	34	1	425	0.150	1.503	0.0165	0.0463	24.788	24.834 Q^2
2	20	1	450	0.159	1.592	0.0163	0.0269	24.788	24.815 Q^2
3	3.5	0.6	525	0.516	3.095	0.0144	0.0535	127.511	127.564 Q^2
4	5	0.4	525	1.161	4.642	0.0135	0.5428	580.970	581.513 Q^2
5	34	0.7	525	0.379	2.653	0.0148	0.2471	10.324	10.571Q^2
6	20	0.6	525	0.516	3.095	0.0144	0.3057	510.042	510.348 Q^2
7	5000	0.6	262.5	0.258	1.547	0.0313	166.379	65.030	231.409 Q^2
8	5000	0.6	262.5	0.258	1.547	0.0313	166.379	65.030	231.409 Q^2
1 & 2	---	---	---	---	---	---	---	---	6.206 Q^2
1 to 3	---	---	---	---	---	---	---	---	133.770 Q^2

1 to 4	---	---	---	---	---	---	---	---	$715.283\ Q^2$
1 to 5	---	---	---	---	---	---	---	---	$725.854\ Q^2$
1 to 6	---	---	---	---	---	---	---	---	$1236.202\ Q^2$
7 & 8	---	---	---	---	---	---	---	---	$57.990\ Q^2$
1 to 8	---	---	---	---	---	---	---	---	$1249.192\ Q^2$

Graphical representation of the system curve

By considering the dynamic head of the pipe lines on (H-Q curve), the system friction curve at flow rate of 525 m^3/h has been obtained. As shown in figure (6).

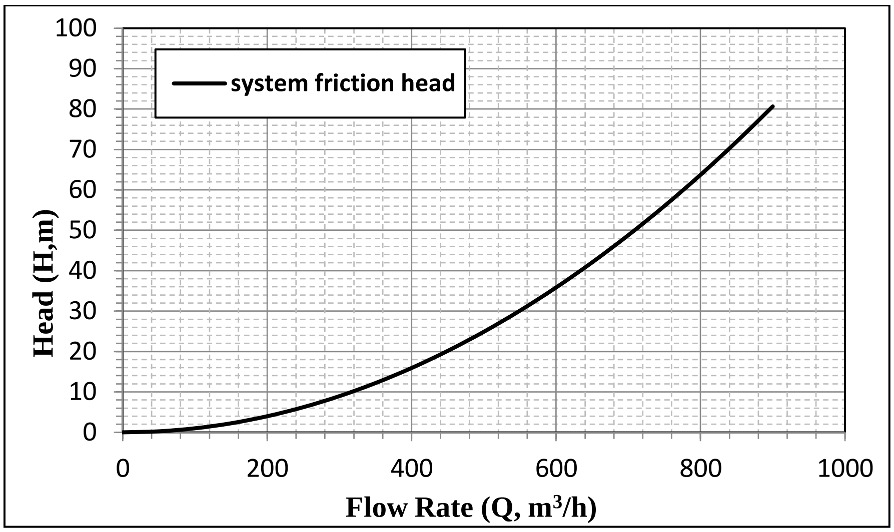

Figure (6): System friction head

The static head depends on the level of water in the suction tank, which varies according to the rate of production of the desalination plant; the average level of water in suction tank is 12 m.

The static head is calculated from equation (1). Where:

$$\mathbf{h_{sd} = 45\ \boldsymbol{m}}\ , \qquad \mathbf{h_{pd}} = \boldsymbol{h_{ps}} = \mathbf{0}\ , \qquad \mathbf{h_{ss} = 12\ \boldsymbol{m}}$$

$$\boldsymbol{H_s} = \mathbf{(45 + 0) - (12 + 0) = 33}\ \boldsymbol{m}$$

Then add the static head (33m) to the friction head (dynamic losses) curve of the whole system shown in figure (7) to getthe system curve shown in figure (8) below.

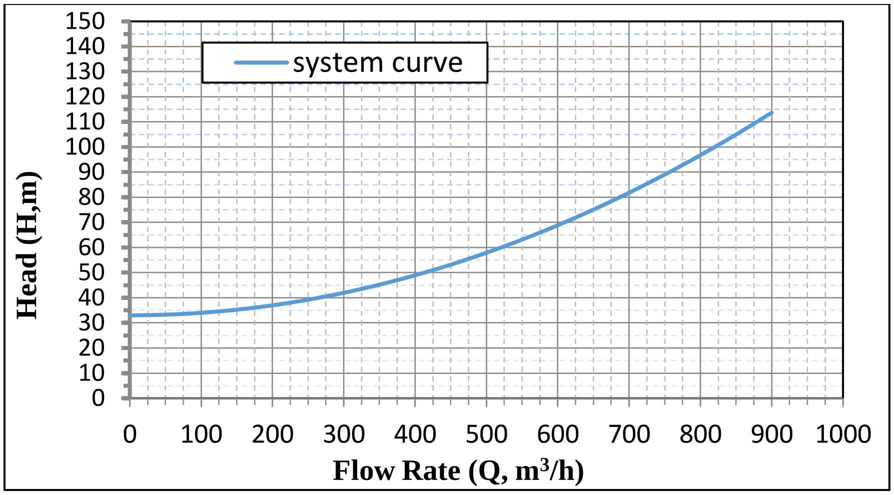

Figure (7): Total system head at 525m^3/h

Controlling of flow using a control valve

To control the flow rate of water according to system requirements, a control valve is used. When the valve is closed, the system curve becomes steeper due to the increase in friction losses. In contrary, it becomes smoother when the valve is opened by minimizing friction losses. This change is followed by a corresponding change in the operating point as well. It will move to the right or to the left on the pump curve. This process is called suffocation as shown in figure (8).

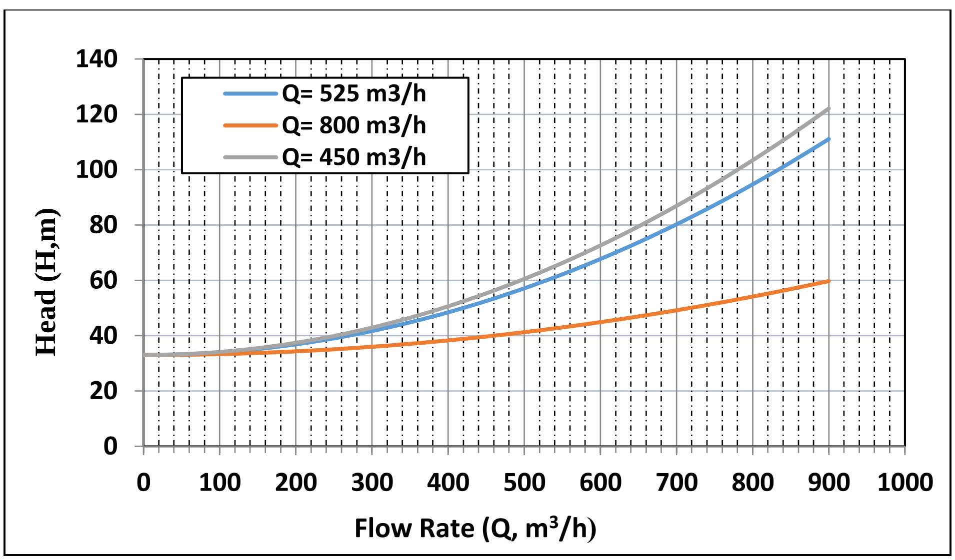

Figure (8): System curve with suffocation process

Calculation of NPSHA at different suction heads

The Net Positive Suction Head Available (NPSHA) is a characteristic of the system design at operating condition and depending on the suction tank surface pressure, vapour pressure of the liquid, the friction losses of the suction line, and the vertical distance between water level in suction tank and pump axis (suction static head). In this system the flow rate changes according to the operation requirements and the change in the static head, from 8 m to 12 m. As the NPSHR for the pump increases, the flow through the pump increases too. So, the NPSHA at different levels of water surface in the suction tank has been calculated using equation (6) at maximum flow rate of 800 m^3/h and the results were tabulated in the Table 3.

Table (3): NPSHA at different suction static heads

Water level in the suction tank (m)	Net Positive Suction Head Available (NPSHA) (m)
12	21.98
10	19.97
8	17.96
6	15.95

Conclusion

In any pipeline system, the system head curve demonstrates a good indication of how the system will operate under a variety of operating conditions. So, the pump is selected based on how well its curve and the system head curve match. For the pipeline system used to transfer water from the main reservoirs of Zawia seawater desalination plant to the sub-tanks in Harsha, which is graphically represented on H-Q curve, results show that the pump should be selected with operating points at flow rates between 450-800 m^3/h in its best efficiency zone with a total head between 40-105 m under different operation condition.

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