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# Hydraulic System Design using the Static Performance Graph

## Abstract

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Integrating the graphical characteristics of static component models to formulate the steady state characteristics of a hydraulic system can provide design confirmation through an understandable methodology. Such an integrated performance approach is particularly useful for cross-checking analytical solution methods and providing ball-park answers and system design confirmation. This paper presents a graphical approach using static performance characteristics as its premise in providing a basis for assessing the validity of computer solutions and/or analytical results. It gives a means of double checking the results and the effectiveness of component integration as well as the design principle in a manner that can be understood by engineering staff members who do not possess computer skills.

## Introduction

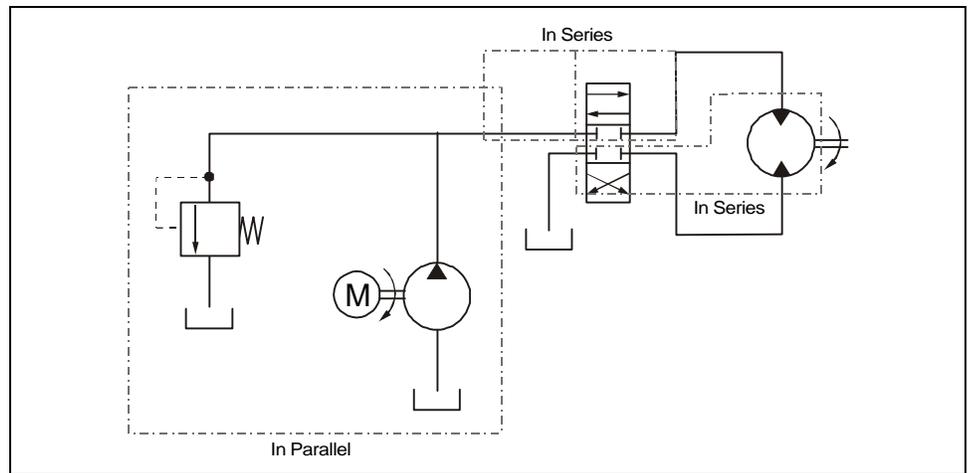
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The *Static Performance Graph (SPG)* is an extension of the concurrency chart. It is a graph presented on a Cartesian coordinate system. However, the construction of a static performance graph requires more involvement in handling functions and graphs. It not only has to understand the component characteristics but also to consider the interrelationships among various sets of component equations that form the particular system model. Prior to applying a static performance graph to analyze hydraulic systems, it is necessary to understand the nature of hydraulic circuitry.

There are two ways that components can be combined to form a system—series and parallel and of course combinations of the two. A series circuit is one in which each component in the circuit carries equal amount of fluid per unit time but the total system pressure drop is the sum of the pressure drops across each component in the circuit. Conversely, in a parallel circuit, each component has an equal amount of pressure drop but the total flow rate is the sum of the individual

flow rates through components. This circuit characteristic is governed by the 3-C principle (compatibility, continuity, and constraints) which is used in formulating system models. Consider a valve control motor system as shown in Fig. 1. It can be observed that the directional control valve is in series with the hydraulic motor. The same amount of fluid flows through the directional control valve into the motor and then returns through the valve to the tank. It can be noted that the pressure upstream of the directional control valve is the same as at the outlet of the pump and the inlet to the relief valve. Therefore, the pump and the relief valve are in parallel but their combination is in series with the directional control valve. This example implies that regardless of the complexity of a system circuit structure, it is possible to divide the circuit into subsystems containing components either in series or in parallel but not the combination of the two. Accordingly, if the data for constructing the static performance graph for component in series and in parallel are available, the construction of system performance graphs becomes feasible.

Figure 1  
A Valve Control Motor System



Let's examine the characteristics of these two basic building blocks (series and parallel) using an orifice and a capillary as shown in Fig. 2. Assume the flow through the capillary is laminar. Thus,

$$Q_L = K_L \Delta P \tag{0.1}$$

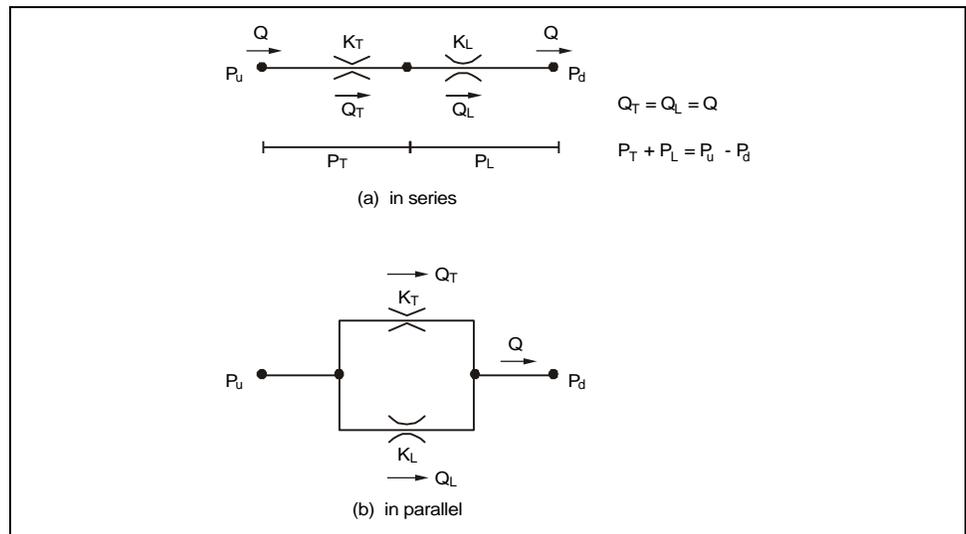
where  $Q_L$  = laminar flow through the capillary  
 $K_L$  = laminar flow –pressure coefficient  
 $\Delta P$  = pressure drop across the capillary

Furthermore, the flow through the orifice is turbulent and expressed as

$$Q_T = K_T \sqrt{\Delta P} \tag{0.2}$$

where  $Q_T$  = turbulent flow through the orifice  
 $K_T$  = orifice flow –pressure coefficient  
 $\Delta P$  = pressure drop across the orifice

Figure 2  
Components in Series and in  
Parallel Configurations



Now, let's assign numeric data for the parameters in the equations to construct the graphs. This should provide a more practical picture to grasp the concept quickly. Suppose that  $K_L = 0.1 \text{ gpm}\cdot\text{psi}^{-1}$ , and  $K_T = 1.0 \text{ gpm}\cdot\text{psi}^{-0.5}$ . In addition, let  $\Delta P$  range from 0 to 100 psi. Figure 3 shows the static curves when the orifice and the capillary are in series. Note that for a given flow rate  $Q$ , the pressure at the upstream of the orifice ( $P_s$ ) is the sum of the pressure drops across the orifice ( $P_T$ ) and that across the capillary ( $P_L$ ). In other words, the upstream pressure of the orifice is off set from its reference value by a quantity equal to the pressure drop across the capillary. This means that for a series configuration, the following procedure can be applied to construct a static performance graph.

1. Draw the static pressure-flow curves of each component in series.
2. Use the curve of the last component in the series as the reference datum
3. Add the pressure values at selected flow points of the next component to the matching pressure values of the reference component. Draw a new curve using these values. This will be the static curve that represents the upstream pressure of the component next to the reference component. This curve now becomes the new reference datum.
4. Repeat the above steps for each component till it reaches the first component in the series. By using this procedure, the cumulative flow-pressure curve for a given series configuration can be obtained.

Note: This procedure can also start from the highest pressure source. In this case, do the following:

1. Draw the static pressure-flow curves of each component in series.
2. Use the curve of the first component in the series as the reference datum
3. Subtract the pressure values at selected flow points of the next component to the matching pressure values of the reference component. Draw a new curve using these values. This will be the static curve that represents the downstream pressure of the component next to the reference component. This curve now becomes the new reference datum.

4. Repeat the above steps for each component till it reaches the last component in the series. By using this procedure, the resultant flow-pressure curve for a given series configuration can be obtained.

Figure 3  
Static Performance Graph of  
Components in Series

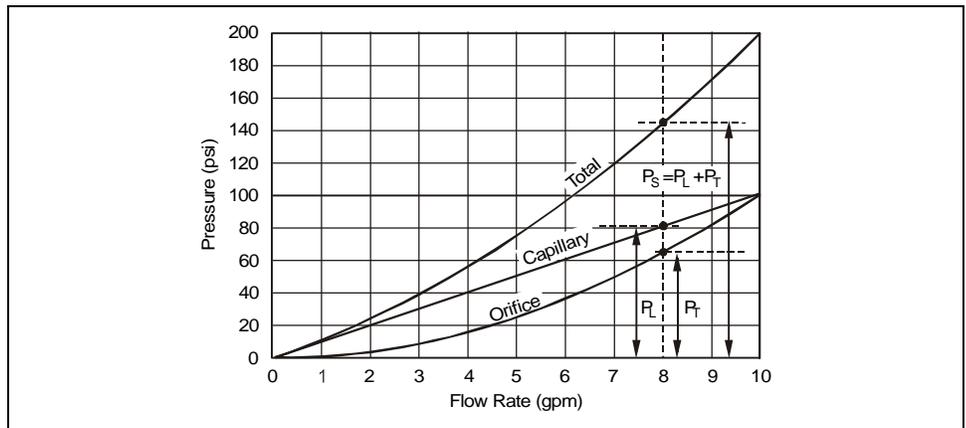


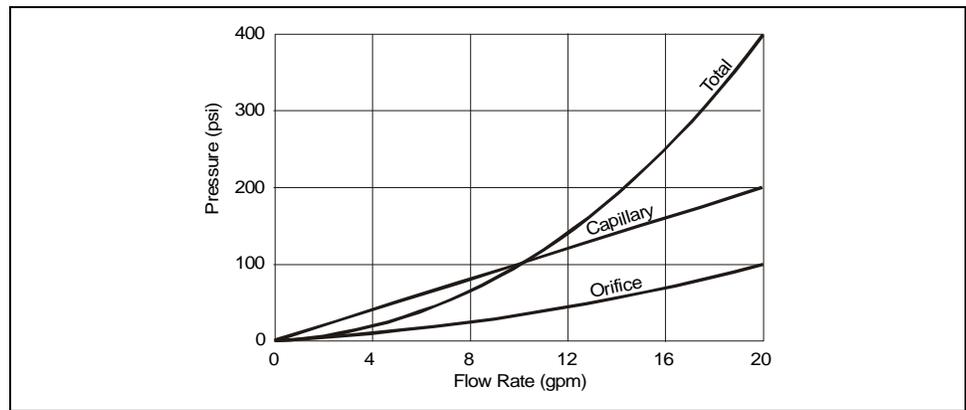
Figure 4 shows the static curves when the orifice and the capillary are in parallel. Notice that the resultant curve shifts to the right along the flow axis which is dramatically different from the case when components are in series where the resultant curve shifts upward along the pressure axis. For example, for a given pressure  $P$ , the system flow ( $Q_s$ ) is the sum of the flow through the capillary ( $Q_L$ ) and that through the orifice ( $Q_T$ ). Therefore, the procedure to construct a static performance graph for a parallel configuration is as follow:

1. Draw the static pressure-flow curves of each component in parallel.
2. Use the curve of an arbitrarily selected component in the parallel as the reference datum.
3. Add the flow values at selected pressure points of the next component to the matching flow values of the reference component. Draw a new curve using these values. This will be the static curve representing the total flow from the last two components.
4. Repeat the above step for each component. By using this procedure, the cumulative flow-pressure curve for a given parallel configuration can be obtained.

Note: This procedure can also start from the highest flow source. In this case, do the following:

1. Draw the static pressure-flow curves of each component in parallel.
2. Use the curve of the total flow of the components in the parallel as the reference datum.
3. Subtract the flow values at selected pressure points of the next component to the matching flow values of the reference component. Draw a new curve using these values. This will be the static curve representing the total flow from the last two components.
4. Repeat the above step for each component. By using this procedure, the resultant flow-pressure curve for a given parallel configuration can be obtained.

Figure 4  
Static Performance Graph of  
Components in Parallel



## The Power Curves

The efficacy of using static performance graphs in hydraulic system design is enhanced by applying power curves to quickly identify the operating point under a particular condition. There are two types of power curves—the Available Power Curve (APC) and the Required Power Curve (RPC). An available power curve traces a set of points that characterizes the power available to the load driving component; whereas, the required power curve represents the power required to accomplish a particular engineering task. The intersection of the APC and RPC defines the static operating point (SOP). The SOP is the point (node) that immediately follows the downstream port of the last control element to the node. It is the same node that links directly to the upstream port of the load driving component. This critical node, also called the PCL node, which implies the node at which the state of power variables (pressure and flow, force and velocity, etc.) satisfies the power, control, and load requirements. The general procedures to construct both APC and RPC are as follows:

1. Identify the PCL connecting node, which is at the downstream port of the last control element or the upstream port of the load driving component.
2. Start from the main power supply, normally the system pump toward the PCL node. Draw the static performance curve of each component.
3. Construct the APC. Start with the component nearest the main system power source. If this component is in series with the power source, then follow the series procedure that starts from the highest pressure value. If this component is in parallel, then use the parallel procedure that starts from the highest flow value.
4. Construct the RPC. Start with the component nearest the main system Tank. If this component is in series with the tank, then follow the series procedure that starts from the lowest pressure value. If this component is in parallel, then start with the parallel procedure that starts from the lowest flow value.
5. Read the SOP from the point where APC intercepts RPC.

Obviously, in order to draw APC and RPC requires a knowledge of the way a hydraulic component behaves under static condition. Comprehensive descriptions of hydraulic component characteristics are presented in the companion book of *Hydraulic Component Design and Selection*. For the convenience of the reader, this section summarizes and presents the basic characteristic curves of the most commonly used hydraulic components.

## Component Performance Curves

The performance curves for the components needed to implement this graphical solution method are gained through the application of hardware physics or by experimental test results. In many cases, the performance curves for the various components can be obtained from the manufacturer of the equipment. Keep in mind that this performance based solution approach is strictly a steady state analysis of static component performance.

### Power Components

Power components are elements which provide the system's power. Typical power components are pumps, accumulators, boosters, etc. A hydraulic pump converts mechanical energy into hydraulic energy by imparting motion into a liquid. The pumping characteristics of a fixed displacement pump are graphically depicted in Fig. 5. Note that the theoretical flow curve is a straight line to the point where it intersects the pump casing structural strength; whereas, the actual flow is reduced by the amount of internal leakage occurring under operating conditions in the pump which is mathematically expressed as

$$Q = Q_{th} - K_p P \tag{0.3}$$

where  $Q$  = actual pump delivery  
 $Q_{th}$  = theoretical or ideal pump delivery  
 $K_p$  = slip coefficient  
 $P$  = pressure across pump

Figure 5  
 Typical Performance Curve of a  
 Fixed Displacement Pump

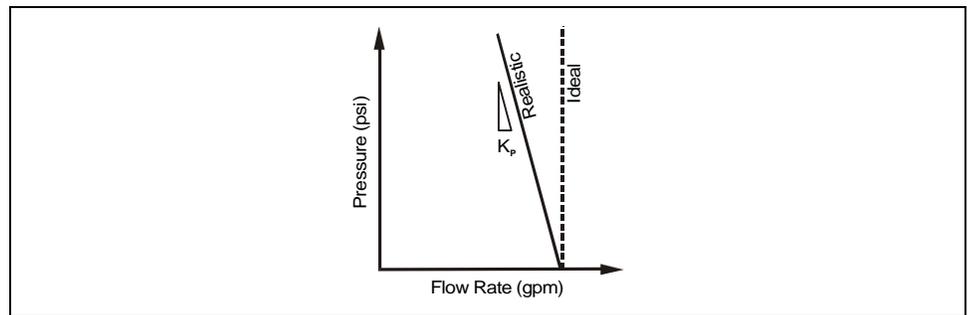


Table 1 lists typical performance curves of power components.

### Control Components

There are three basic types of control components in hydraulic system—directional control, pressure control, and flow control. Directional control valves are normally characterized by the orifice flow equation with a metering factor as shown in Fig. 6 and expressed below:

$$Q = K_v S \sqrt{P} \tag{0.4}$$

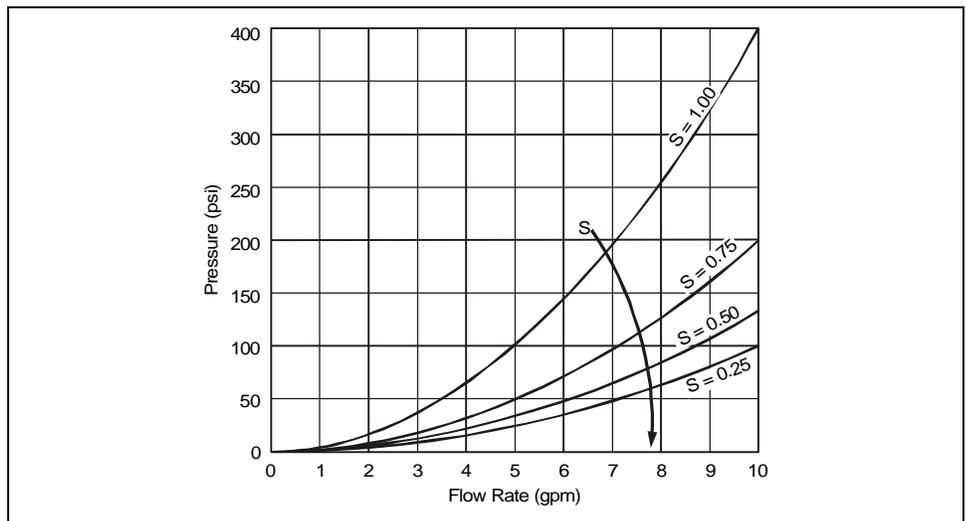
where  $Q$  = flow through the valve  
 $K_v$  = valve pressure flow coefficient  
 $S$  = metering factor ranges from 0 to 1  
 $P$  = pressure across the valve

Table 1  
List of Typical Performance Curves  
of Power Components

Type	Static Performance Graph	Model
1		$Q = Q_o - K_p P$
2		$Q = \alpha Q_o K_p P$
3		$Q = Q_o - K_p P$ if $P \leq P_c$ $= Q_c \left( \frac{P - P_c}{P_F - P_c} \right) Q_c$
4		$PQ = \text{const.}$
5		$Q = K_v \sqrt{P}$

Note:  $K_p$  = pump slip coefficient;  $K_v$  = valve pressure-flow coefficient (turbulent);  $\alpha$  = displacement fraction.

Figure 6  
Typical Performance Curve of a  
Directional Control Valve

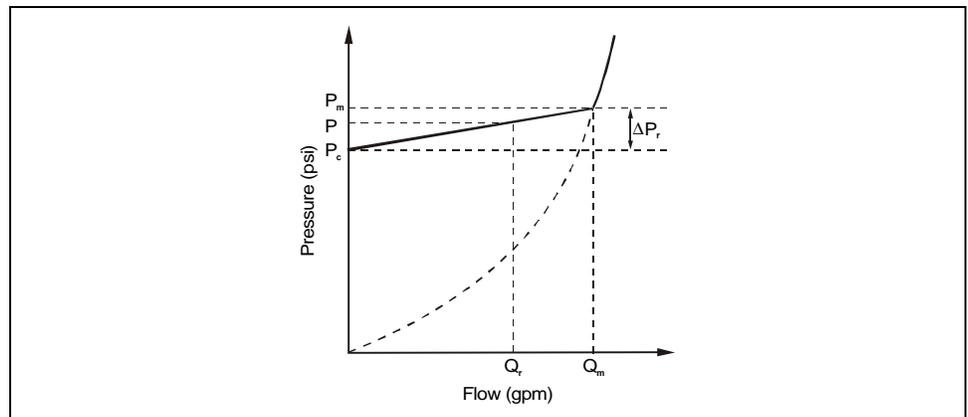


Pressure control valves restrict the flow of fluid to limit operating pressure. The simplest model of a generic pressure component, in general, has two distinct portions—one linear portion represents the control characteristics, whereas the non-linear portion represents uncontrollable or out of design specifications. For example, the characteristic curve of a relief valve is shown in Fig. 7 and the corresponding model is as follow:

$$\begin{aligned}
 Q &= 0 \text{ if } P \leq P_c \\
 &= Q_m \left( \frac{P - P_c}{P_m - P_c} \right) \text{ if } P_c < P \leq P_m \\
 &= K_{vr} \sqrt{P} \text{ if } P > P_m
 \end{aligned}
 \tag{0.5}$$

where  $Q$  = flow through the valve  
 $P$  = system pressure (assume a zero tank pressure)  
 $P_c$  = cracking pressure  
 $P_m$  = maximum pressure in the linear range  
 $Q_m$  = flow at  $P_m$   
 $K_{vr}$  = pressure flow coefficient ( $= Q_m / \sqrt{P_m}$ )

Figure 7  
 Typical Performance Curve of a  
 Pressure Relief Valve



Flow control valves are components to limit flow for a given pressure. Figure 8 illustrates typical performance curves of an uncompensated flow control valve. The governing equation is

$$Q = K_v P^n
 \tag{0.6}$$

where  $Q$  = flow through the valve  
 $K_v$  = valve pressure flow coefficient  
 $P$  = pressure across the valve  
 $n$  = an exponent ranges from 0.5 (turbulent) to 1.0 (laminar)

Figure 8  
Typical Performance Curves of an  
Uncompensated Flow Control Valve

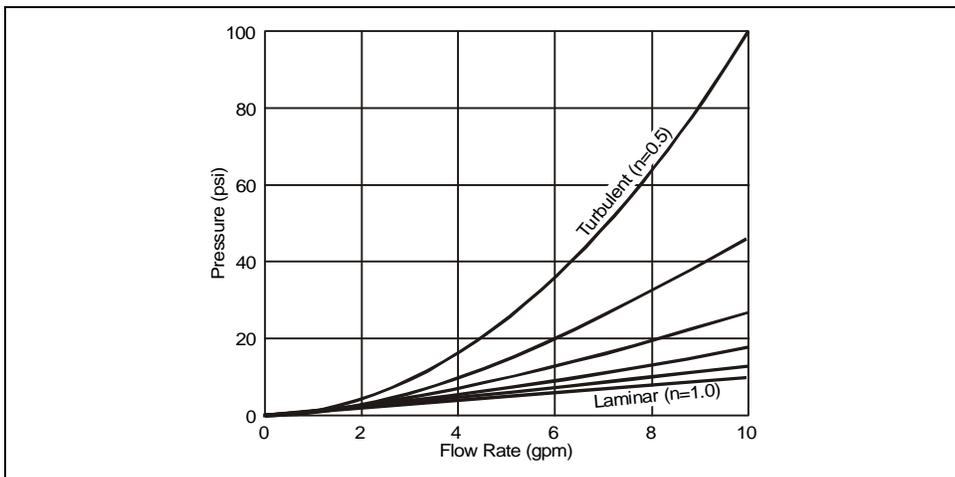


Table 2 lists typical performance curves of control components.

Table 2  
List of Typical Performance Curves  
of Control Components

Type	Static Performance Graph	Model
1		$Q = K_v \sqrt{P}$
2		$Q = 0$ if $P \leq P_c$ $= Q_m \left( \frac{P - P_c}{P_m - P_c} \right)$ if $P_c < P \leq P_m$ $= 0$ if $P > P_m$
3		$Q = K_v \sqrt{P}$ if $P \leq P_c$ $= Q_c \left( \frac{P_m - P}{P_m - P_c} \right)$ if $P_c < P \leq P_m$ $= 0$ if $P > P_m$
4		$Q = K_L P$ for laminar flow $Q = K_v \sqrt{P}$ for turbulent flow
5		$Q = K_v \sqrt{P}$ if $P \leq P_c$ $= Q_m + \delta(P - P_c)$ if $P > P_c$

Note:  $K_v$  = valve pressure-flow coefficient (turbulent);  $K_L$  = valve pressure-flow coefficient (laminar);  $\delta$  = fraction of flow increment.

### Load Components

Load components include both the load driving and load driven components. Load driving components are those to drive the external loads including cylinders for linear motion and motors for rotary motion. On the other hand, the load driven components are those which impose resistance to the driving units. The load curve for a load driving component is simply a function of pressure but independent to flow; whereas, the load driven curve depends on characteristics of the component. For example, an orifice has a parabolic curve in terms of pressure and flow.

Consider a single-rod-double-acting cylinder driving a constant load from piston side to rod side as shown in Fig. 9. The driving pressure is

$$P = \frac{1}{A_p} (P_r (A_p - A_r) + F) \tag{0.7}$$

where  $P$  = driving pressure at piston side  
 $A_p$  ( $A_r$ ) = piston (rod) area  
 $F$  = external load

Note that flow is not involved in the pressure-load equation.

It is often of interest to find the velocity of the cylinder at a particular operating point. This is easily approached by drawing a line with a slope  $K_c$  (the slip coefficient) from the given operating point that will intersect the flow axis. Note that this statement is true only if the graph is constructed on a normalized coordinate. Otherwise, the actual value of  $K_c$  must be normalized to the corresponding coordinate scale prior to drawing the line. The intersection point is the theoretical flow rate pumping into the piston chamber. The velocity,  $u$ , can be obtained by dividing the theoretical flow by the piston area as follows:

$$u = \frac{1}{A_p} (Q - K_c P) \tag{0.8}$$

Figure 9  
Typical Performance  
Curve of a Cylinder

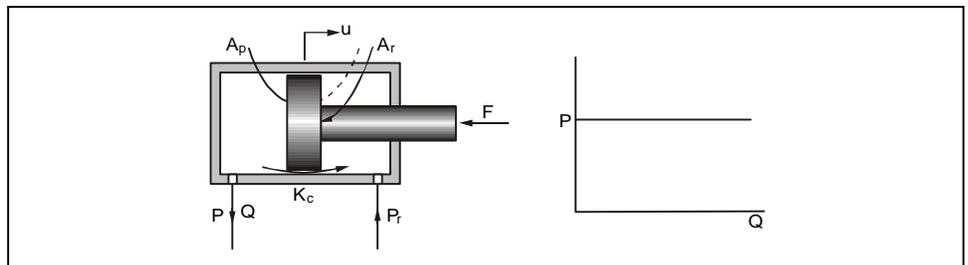


Table 3 lists typical performance curves of load components.

Table 3  
List of Typical Performance  
Curves of Load Components

Type	Static Performance Graph	Model
1		$P = \frac{1}{A_h} (F - P_r A_r)$
2		$P = \frac{1}{A} (F - P_2 A)$
3		$P = \frac{T}{D_m}$ $Q_m = \omega D_m = Q_o + K_m P$

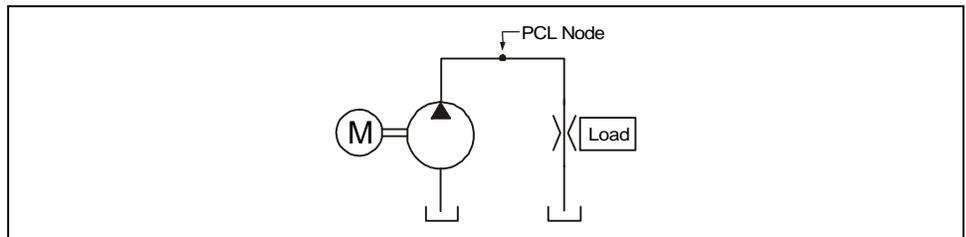
Note:  $A_h$  = head side area;  $A_r$  = rod side area;  $A_2$  = 2<sup>nd</sup> port side;  $K_m$  = motor slip coefficient;  $D_m$  = motor displacement;  $\omega$  = rotational speed;  $T$  = external torque;  $F$  = external force.

## Examples

### Example 1

Consider a pump driving an orifice load system as shown in Fig. 10. The theoretical delivery of the pump is 20 gpm with a slip coefficient of 0.001 gpm·psi<sup>-1</sup>. The orifice has a pressure-flow coefficient of 0.5 gpm·psi<sup>-0.5</sup>. Determine graphically the static operating parameters at the PCL node indicated in the figure.

Figure 10  
A Pump-Driving-Orifice-Load  
System



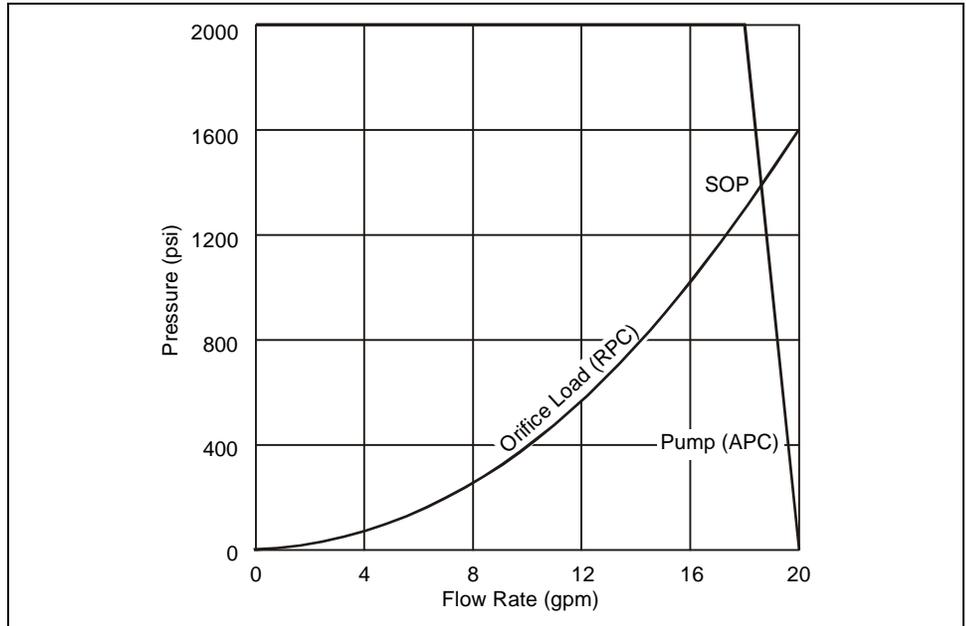
### Solution

Observing the given circuit will reveal that the system consists of only a power component (i.e., the pump) and a load component (i.e., the orifice). There is no control component in the circuit. The PCL node is at the node connecting the pump outlet and the orifice inlet. Therefore, the APC is the characteristic curve of the pump governed by Eq. (0.3).

1. Prepare a suitable drawing area, such as a graph paper or a computer screen.

2. Assign flow rate Q to the X-axis ranging from 0 to 25 gpm. In addition, assign pressure to the Y-axis ranging from 0 to 2000 psi.
3. Using the data given ( $Q_{th} = 20$  gpm, and  $K_p = 0.001$  gpm·psi<sup>-1</sup>), locate two (Q, P) points at (20, 0) and (19, 1000) and draw a straight line through these two points. This action forms the associated APC as shown in Fig. 11.

Figure 11  
The Static Performance Graph of A Pump-Driving-Orifice-Load System



4. Similarly, the RPC can be drawn using the orifice flow equation ( $Q = K_v \sqrt{P}$ ) with  $K_v = 0.5$  gpm·psi<sup>-0.5</sup>.
5. For our example, let's take the following set of power points:

X (Q)	0	1.5	5	15	20
Y (P)	0	9	100	900	1600

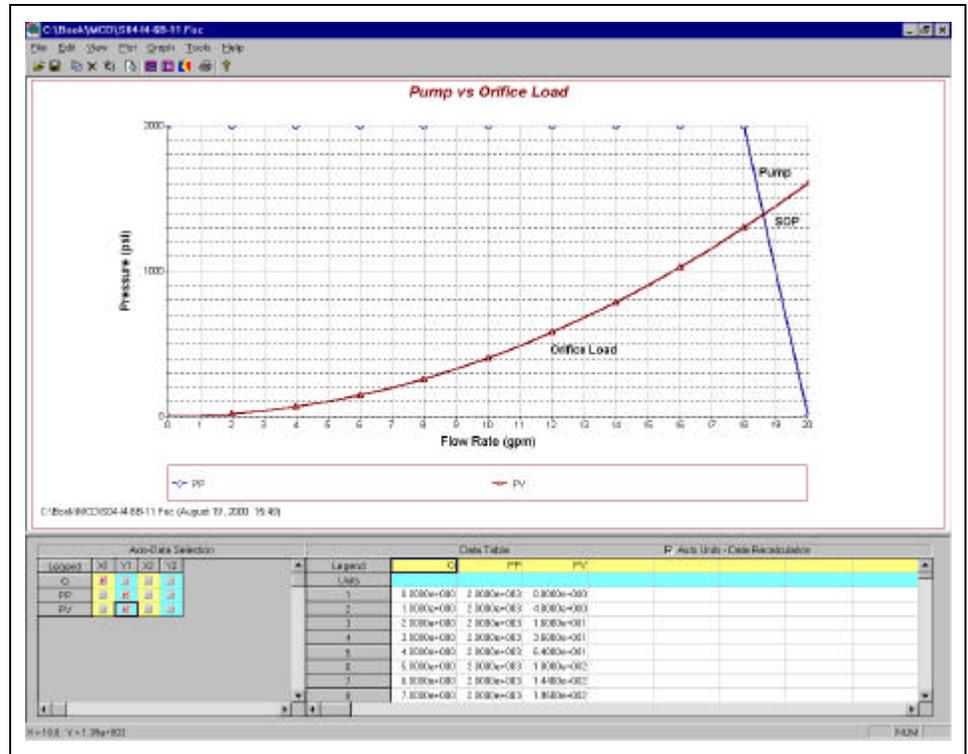
6. Draw a smooth curve through the power points to form the RPC which is also shown in Fig. 11.

The values of the operating parameters can be read directly from the SOP point where the APC intercepts RPC. It reads the pressure at the PCL node about 1400 psi and the flow from the pump as well as through the orifice around 19 gpm.

The accuracy of the values obtained in this example are based on the precision of the graphical scales used. Conventionally, there may be a limitation of applying a graphical method to obtain results demanding high accuracy. However, with the aid of a computer drawing or plotting package, such as *HyPneu Data Presentation Manager* (DPM), which can generate performance curves and read the coordinate values precisely. Figure 12 shows a screen illustrates capture from HyPneu DPM depicting the results of the above example. By pointing the cursor to the SOP point gives a coordinate reading of X (i.e., Q)  $\approx 18.6$  gpm and Y (i. e., P)  $\approx 1386$  psi, respectively. Note that this approach uses a *computer-aided-graphics* (CAG) approach. It is different from solving

problems numerically on a computer. The CAG method requires no analytical or numerical background for solving simultaneous non-linear static equations. Equipped with the precise coordinate reading capability and vivid curve presentation features, the CAG becomes a very powerful and effective tool for hydraulic professionals.

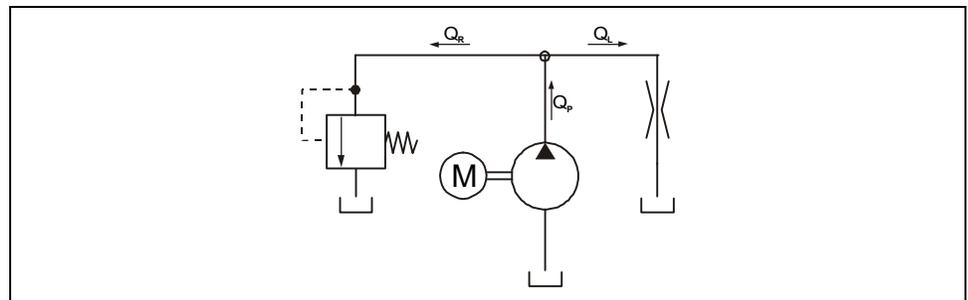
Figure 12  
Illustration of Performance Curves  
on HyPneu DPM



**Example 2**

Repeat Example S04-I4.6BX-1 but add a relief valve to limit system pressure as shown in Fig. 13. The cracking pressure is set at 1000 psi. In addition, there is a pressure override of 200 psi at a relief flow of 30 gpm. Assume that the relief valve behaves linearly under the stated conditions.

Figure 13  
A Pump-Driving-Orifice-Load  
System with a Relief Valve



**Solution**

The system now consists of a power component (i.e., the pump), a control component (i.e., the relief valve) and a load component (i.e., the orifice). The RPC will be the same as presented in Example S04-I4.6BX-1. However, the APC

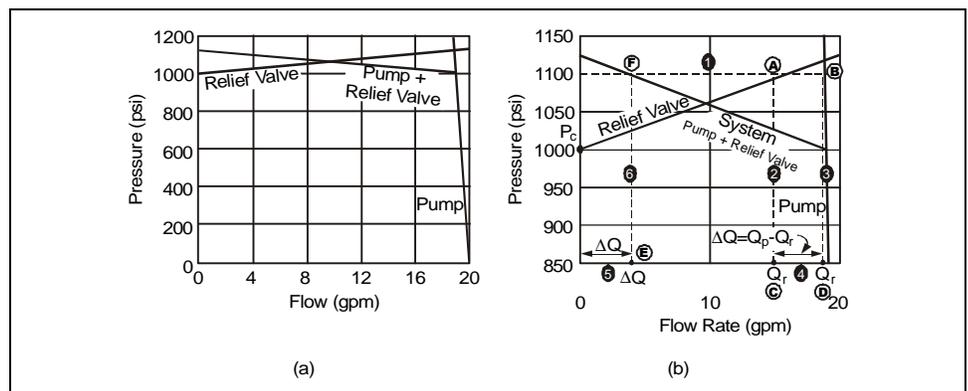
needs to consider the effect of the relief valve on the power availability to the load.

Observing the circuit configuration will find that the pump and the relief valve are in parallel. Hence, the flow delivered to the load will be the difference between the pump flow and the amount that is bypassed through the relief valve at a given system pressure. The resultant APC is obtained by the APC construction procedures shown previously. Figure 14a shows the curves of pump, relief valve, and their combination, respectively. Figure 14b illustrates a step-by-step graphical approach to obtain the APC for a power unit containing a pump and a relief valve. The procedure is as follows:

- Step 1: Draw a horizontal line from a given pressure point P greater or equal to the relief valve cracking pressure. The line will intercept the relief valve curve at point A and pump curve at point B.
- Step 2: Draw a vertical line downward from point A to intercept X-axis at point C.
- Step 3: Draw a vertical line downward from point B to intercept X-axis at point D.
- Step 4: Measure the distance between points C and D, say  $\Delta Q$ .
- Step 5: Locate an amount of  $\Delta Q$  at point E on the X-axis.
- Step 6: Draw a vertical line upward from point E to intercept the pressure line P drawn in Step 1 at point F.
- Step 7: Repeat the above steps for various pressure points to find a set of points F.
- Step 8: Connect and smooth the F points to obtain the APC for the pump and relief valve unit.

This figure shows clearly that the pump flow curve is bound by a maximum pressure that is determined by the relief valve setting. The cracking pressure  $P_c$  of the relief valve determines the point of discontinuity between the pump flow curve and the relief valve characteristics curve.

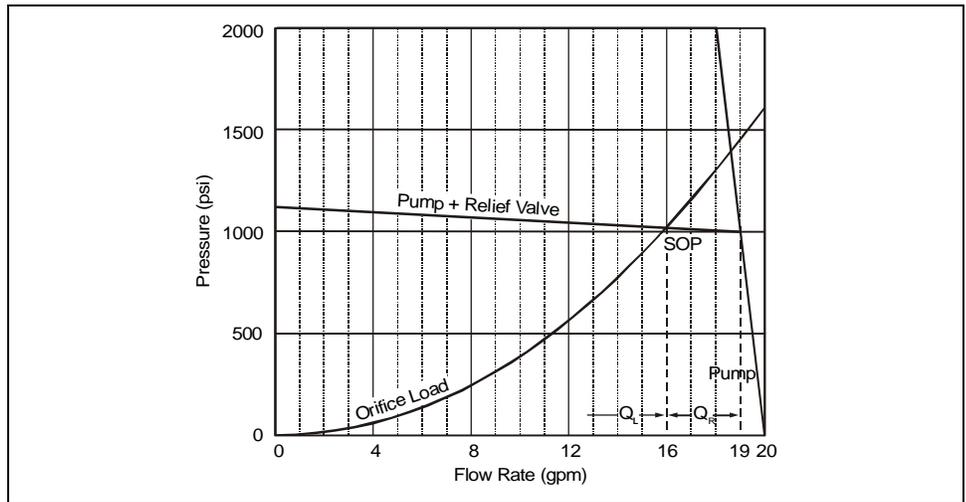
Figure 14  
The APC of a Power Unit Containing a Pump and a Relief Valve in Parallel



Next, lay the RPC of the orifice on the APC as shown in Fig. 15. Notice that the RPC intercepts APC before it reaches the pump characteristic curve. This means that at the SOP point, the flow to the load ( $Q_L$ ) is lower than the actual pump delivery ( $Q_P$ ). The amount of flow difference ( $Q_R$ ) between  $Q_P$  and  $Q_L$  is the flow discharged through the relief valve. The approximate flow values are  $Q_P$

$\approx 19$  gpm,  $Q_R \approx 3$  gpm and  $Q_L \approx 16$  gpm, individually. The pressure at the PCL node is about 1020 psi.

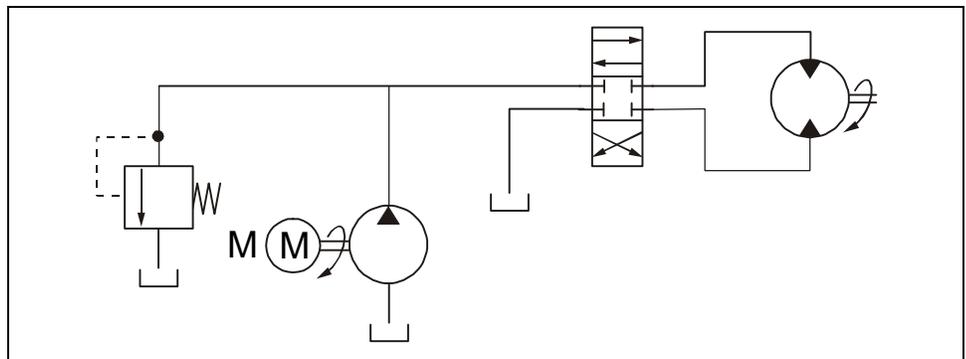
Figure 15  
The Static Performance Graph of a Power Unit Containing a Pump and a Relief Valve in Parallel



### Example 3

Repeat Example 2 but replace the orifice load with a hydraulic motor driving a constant load. In addition, add a directional control between the pump and the motor as shown in Fig. 16. The pressure-flow coefficient of the valve is  $0.5 \text{ gpm}\cdot\text{psi}^{-0.5}$  across port to port. Assume that the motor requires a pressure drop of 600 psi to drive the load.

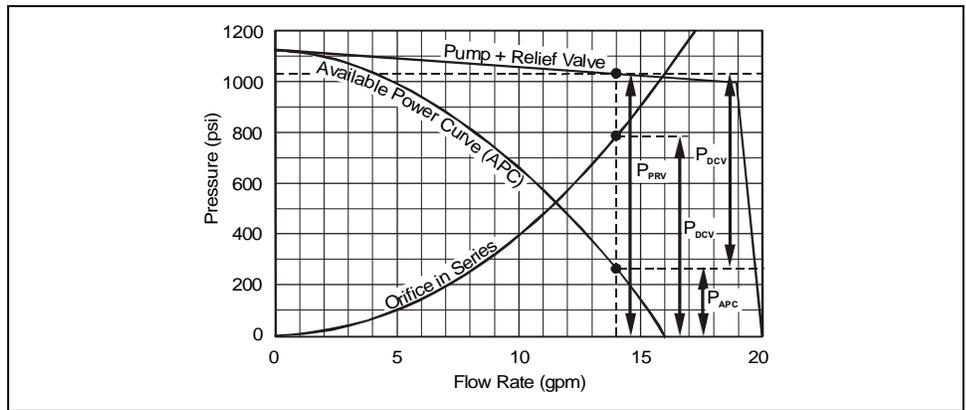
Figure 16  
A Valve Controlled Motor System



### Solution

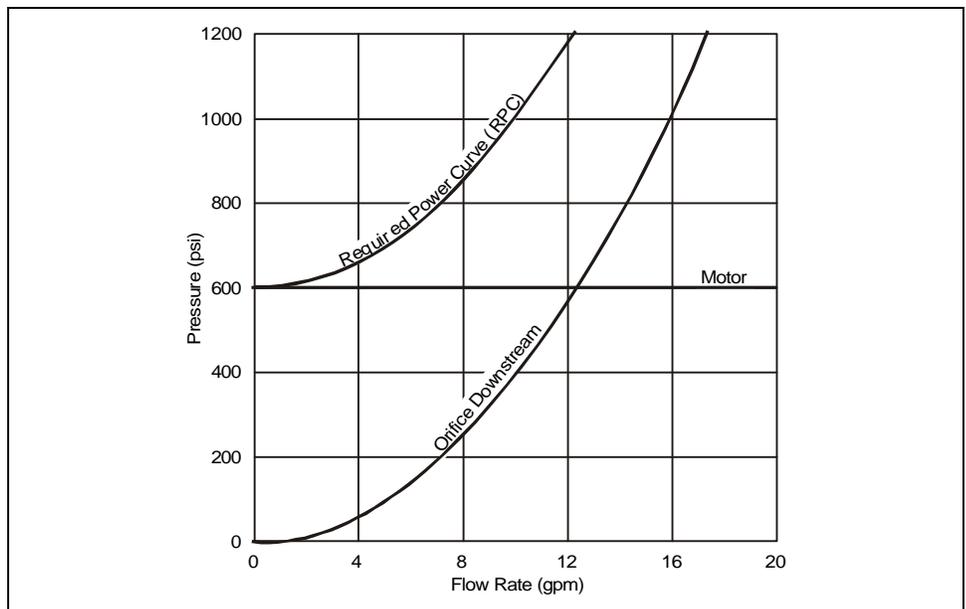
From the circuit shown, it realizes that the APC is based on the combined effect of the pump, relief valve, and the characteristics of the power to work port of the directional control valve. The resultant power curve from pump and relief is shown in the previous example and redrawn as shown in Fig. 17. Since the directional control valve is in series with the pump and relief valve, we need to apply the in series configuration procedure to construct the APC. This is done by reducing an equal amount of the pressure across the directional valve (from power port to work port) at a given flow from the power curve of the pump-relief valve unit. For example, in Fig. 17, pressure  $P_{APC}$  is equal to pressure  $P_{PRV}$  less pressure  $P_{DCV}$  at a given flow rate  $Q$ . Repeat this procedure at various flows to form a set of flow-pressure points. Drawing a smooth curve through these data points gives the APC at the PCL node, see Fig. 17.

Figure 17  
The APC of A Valve Controlled Motor System



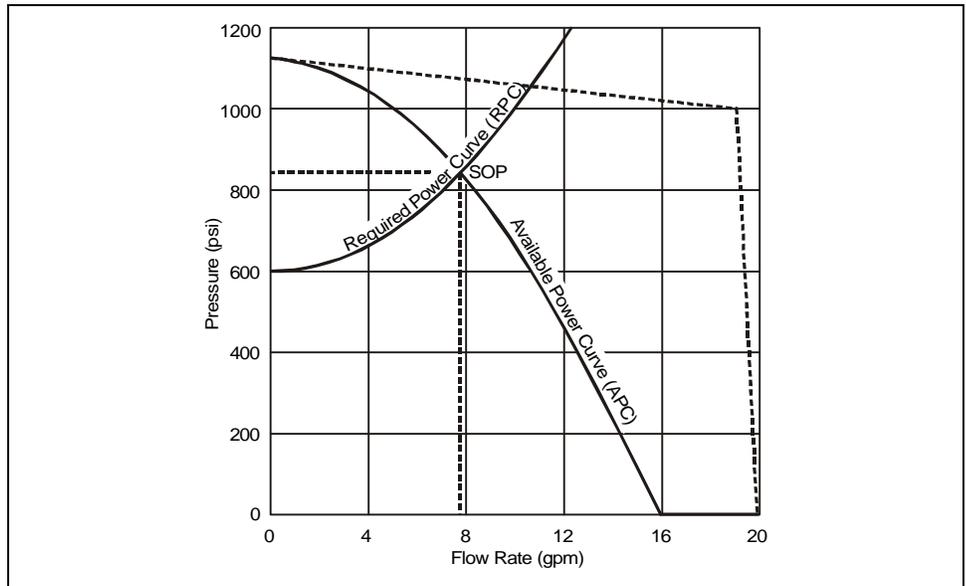
The load curve, in this case, represents the combined effect of the motor loading characteristics and the resistance created by the directional control valve downstream of the motor. Since the external load is constant, and the motor requires a 600 psi pressure drop across it to drive the load, the load curve is therefore a horizontal line of 600 psi. Moreover, the resistance is generated according to the orifice flow equation. Since the motor is in series with the restrictor, the load pressure will be increased by an amount generated by the restrictor at a given flow. The RPC of this example is shown in Fig. 18.

Figure 18  
The RPC of A Valve Controlled Motor System



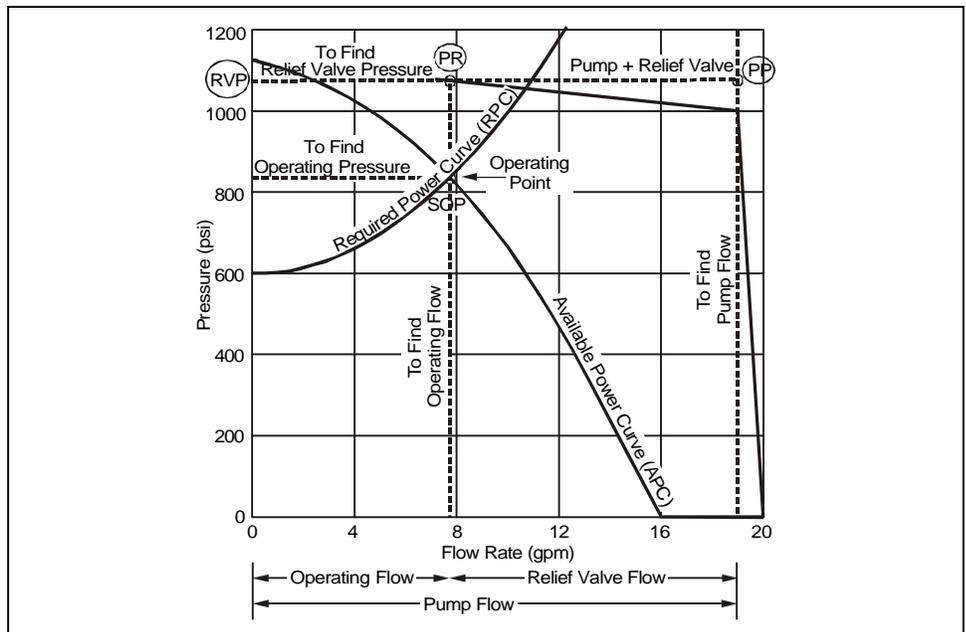
Finally, combining Figs. 17 and 18 gives the static performance graph of the valve controlled—motor system as shown in Fig. 19. An eye-ball reading of the pressure and flow at the SOP is around 840 psi and 7.7 gpm, respectively. However, if these values are obtained by the cursor using HyPneu DPM, the data will be approximately around 837 psi and 7.7 gpm which is very close to the digital simulation results (837.404 psi and 7.704 gpm) shown in a later chapter.

Figure 19  
The Static Performance Graph of A  
Valve Controlled Motor System



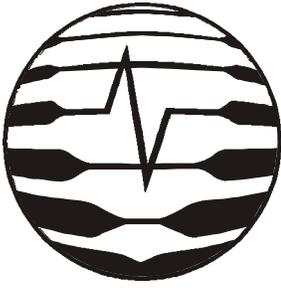
Let's further explore Fig. 19. Extend the vertical line through SOP to intercept the pump-relief valve power curve at point PR as shown in Fig. 20. Draw a horizontal line from PR to the left that intercepts Y-axis at point RVP. This is the relief pressure. The value is around 1080 psi, namely, the relief is open (cracking pressure is set at 1000 psi). Next, draw another horizontal line from SOP to the right. This time the line will intercept the pump characteristic curve at point PP. Then go vertically downward to intercept X-axis at point PQ. This is the actual pump flow at the operating condition. It reads a value of around 19 gpm.

Figure 20  
Graphical Determination of Operating  
Parameters of A Valve Controlled  
Motor System



The above example demonstrates the power and feasibility of using this graphical method to determine the operating conditions for a complicated non-linear hydraulic system. Many critical operating information can be rapidly obtained from a simple static performance graph. The simplicity and rapidity of

applying the SPG technique to obtain operating information should be taken seriously in daily hydraulic practices. However, the SPG method presented in this section is for treating stationary loads. If the hydraulic system is designed for handling periodic loads, it then requires the use of the load locus technique which in essence is an extension of the SPG technique. Since the analysis of periodic loading is very important to characterize power and motion behaviors of a hydraulic system, the load locus technique is presented later in a stand alone chapter called *Duty Cycle and Loading Analysis*.



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