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FUNCTIONAL ASPECTS OF PUMPS AND CENTRIFUGAL PUMP MODELS

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Abstract. This article presents the principle of operation of a centrifugal pump and the classification of impellers. The geometric and kinematic parameters of the impeller were calculated, the spiral outlet was calculated, the axial force acting on the rotor and the radial force acting on the impeller were found. The impeller was designed based on the calculation results. A strength calculation of the shaft connection with the impeller was performed. The pump drive and the centrifugal pump model were selected.

Keywords: hydraulics, centrifugal pump, aspect, component, efficiency, performance, rotation frequency, design.

Introduction. Hydraulic power engineering is the field of study and practice concerned with the transmission and control of energy (in the form of fluid under pressure) for the purpose of moving and applying forces to machine elements. This field currently employs new technologies related to hydraulic power engineering.

The amount of fluid that a pump can deliver is determined by two main parameters: the pump displacement and the drive shaft speed. The pump displacement mainly depends on the design geometry. This paper provides analytical procedures for determining the pump functions of specific positive displacement pumps [1]

Of these, centrifugal pumps are widely used in water supply systems, wastewater disposal, thermal power engineering, food industry, chemical industry, petrochemical industry, nuclear industry, aviation and rocket engineering, etc. A centrifugal pump is a mechanical device that uses a rotating impeller to create a flow inside the pump casing, thereby increasing the fluid pressure; it is commonly used for pumping liquids in various industries.

The principle of operation of a centrifugal pump is to create a centrifugal force that moves the liquid through the pump. This is achieved by the rotation of a central rotor inside the stator or by using a difference wheel, which creates a pressure difference and moves the liquid.[4] Small centrifugal pumps (e.g. aquarium pumps) are capable of developing a maximum pressure of 0.05 bar (i.e. creating a water head of up to 0.5

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meters). Some industrial positive displacement pumps (e.g. plunger pumps) are capable of developing pressures of up to 200 bar or even more. There are no seals between the suction and discharge sides of the pump. This means that centrifugal pumps are ineffective with gases and are not capable of pumping air out of the suction line when the liquid level is below the impeller. The method of regulating the performance of a centrifugal pump is to bypass a portion of the fluid being pumped from the pump outlet to its inlet through a bypass line with a regulating gate valve and a suction gate valve on the pump inlet pipe to the bypass line[11]. The simplest way to change the flow rate of a centrifugal pump is to adjust the opening of the pump outlet valve, while the pump speed remains constant (usually rated). The idea is to change the position of the pipeline characteristic curve to change the pump's operating point. Almost all centrifugal pumps will consume more power as the head decreases and the flow increases. So, if your head (pressure) decreases, your flow increases and the operating point shifts to the right of the pump curve where more power is required. The most common method of controlling the pump discharge pressure is to use a regulating valve . This valve is installed in the discharge line and is used to restrict the flow of fluid, thereby increasing the pressure[10]. Regulating valves can be manually or automatically controlled, depending on the system requirements [5].

Almost all centrifugal pumps will use more power when the head drops and the flow increases. So if your head (pressure) decreases, your flow increases, and the operating point shifts to the right of the pump curve, where more power is required. Almost all centrifugal pumps will use more power when the head drops and the flow increases. So if your head (pressure) decreases, your flow increases, and the operating point shifts to the right of the pump curve, where more power is required.[2]

Method and methodology of the research. The material uses the methods of mathematical statistics and analysis. The main components of a centrifugal pump are the impeller, casing, suction and discharge nozzles, shaft, bearings and mechanical seals.

The functional aspects of the pump are related to the performance of the layout of the elements of the hydraulic system of a given machine. In addition, how well does the pump meet the performance requirements as a converter of mechanical energy into fluid energy? If the selected pump does not satisfy the functional aspects of the

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application, there is no need to worry about how well it resists damage to the structure and the environment.

The efficiency of energy conversion by a pump is determined by its performance characteristics. Theoretically, at low pressure, the output flow of a positive displacement pump is equal to the product of the pump displacement (cc/rev, or cu. in./rev) and the shaft speed [4]. As the pressure increases and the viscosity of the fluid decreases (temperature increases), internal leakage paths in the pump lead to flow losses due to slippage, which are reduced from the output flow. Since volumetric efficiency is the ratio of actual flow to theoretical flow, the term reflects the severity of this volume loss.

Mathematical description of the action of the device elements and the results of the study. The pump suffers not only volume losses but also torque losses. Torque losses occur due to the relative movement of the pump working elements, which are accompanied by energy (power) losses due to friction of the mechanical parts and fluid movement. The theoretical torque required by the pump is equal to the product of the pump working volume and the pressure difference in the pump. Obviously, the actual torque must be greater than the theoretical one to compensate for any losses occurring in the pump. Mechanical efficiency or torque efficiency is the ratio of the theoretical torque to the actual torque. The overall efficiency of the pump is equal to the product of the volumetric efficiency and the mechanical efficiency. The pump characteristics table shown in Fig. 1 illustrates the information on the type of energy conversion needed to properly match the pump to the workload. The only thing missing is a reflection of the pressure effect. In fact, three curves for each parameter should display different pressures to facilitate the pump selection process, as shown in Fig. 2.

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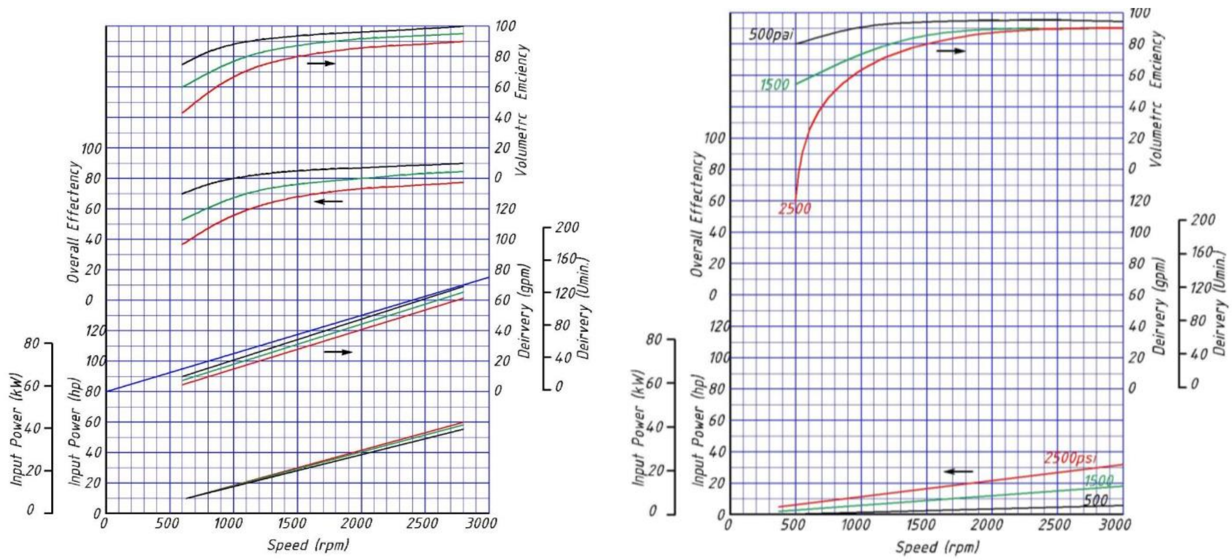

Fig. 1. Efficiency and performance graphs and the effect of discharge pressure on pump performance.

It is important to understand the penalty for poor overall pump efficiency. As shown in Figure 3, the penalty for poor efficiency can be significant. Note that a pump with 66% efficiency requires 50% more horsepower. When you translate this loss into the cost of the extra horsepower required to do the job, the results are dramatic. The type of hydraulic fluid used with a given pump can have serious consequences if the pump and fluid are incompatible. Too low a viscosity can result in excessive slippage, which can lead to inadequate lubrication.[8] Too high a vapor pressure at the pump suction can result in vapor cavitation and subsequent metal surface erosion. If the air exhaust performance is poor, pumping efficiency is greatly reduced, leading to high temperatures and the formation of a porous medium.

The strength of the pump, as reflected by the strength and burst pressure, is an important indication that the pump casing can withstand accidental overpressure without creating a safety hazard. The allowable pressure is usually 1.5 times the nominal pressure, and the burst pressure is at least 2.5 times. In some engineering circles, the working pressure is half the allowable pressure and one-quarter the burst pressure. The flow and pressure characteristics of variable displacement pumps are important for their successful application. The maximum system pressure (standby or ultimate), as shown in Fig. 4, is determined by the compensator spring setting. The slope of the curve between the initial

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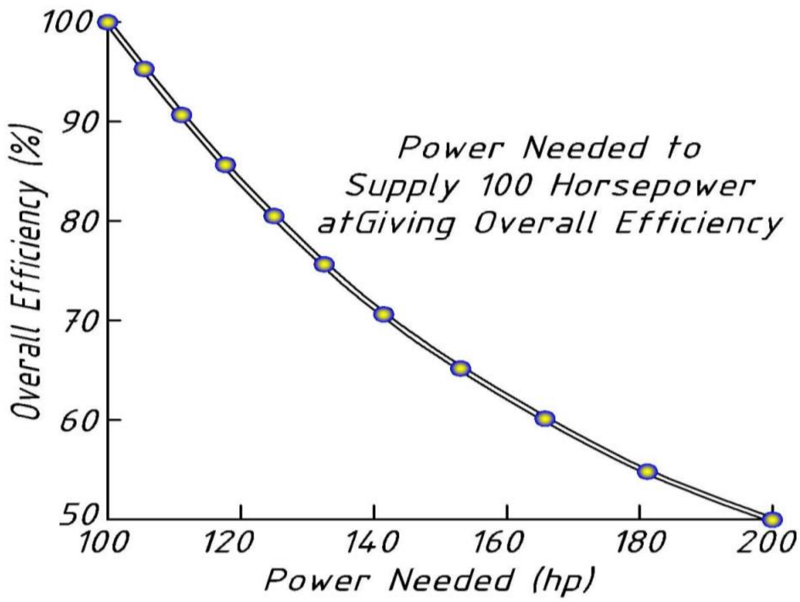

Fig.3.Reduction of energy consumption due to low efficiency of pumps.

pressure and cut-off pressure depends on the constant spring of the compensator. The flow from the pump to the full stroke condition depends on the ability of the pump to respond to the required flow, as well as on the load on the drive for acceleration. To accelerate loading, full ultimate pressure can be applied, but the volume of the delivered flow cannot exceed the load offset and leakage in the system [7]

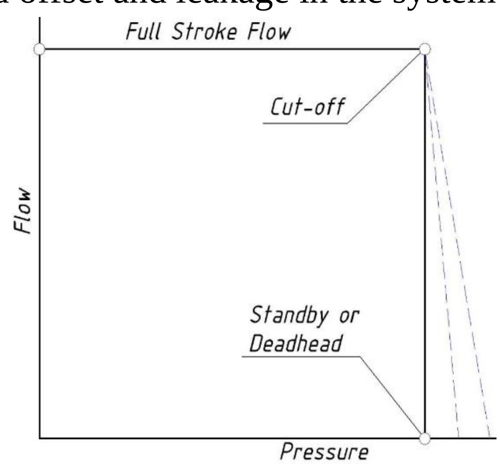

Fig. 4. Dependence of flow rate on pressure for pumps with adjustable working volume.

Another important factor in pump selection is its filling characteristics. In theory, for a positive displacement pump, the flow rate is directly (linearly) related to the pump speed. However, if sufficient fluid cannot be supplied to the pump chamber before the

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suction port closes, the chamber will only be partially filled and the pump will operate in the idle mode. This situation is illustrated in Figure 5 for a given pump, fluid, inlet temperature, and pressure, and shows that the pump speed must not exceed a certain value or the flow will be "choked off" and the pump will not operate.[6] Another way to obtain the required inlet pressure for a given pump speed is shown in Figure 5. Similarly, for a given pump, fluid temperature, and speed, the system must maintain a certain inlet pressure to avoid cavitation. The point at which deviation from linearity occurs depends on the viscosity of the fluid, the geometry of the pump inlet (restrictions), and the inlet pressure. A pump with poor filling

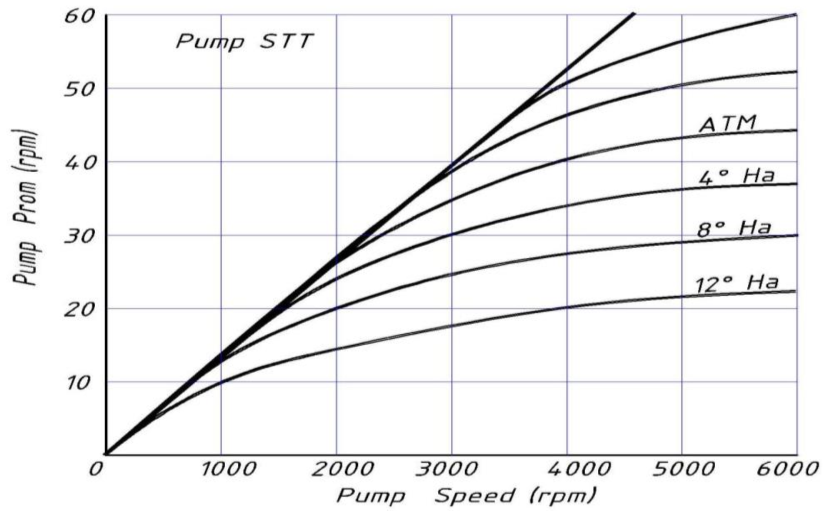

Fig.5-6. Flow rate versus pressure for pumps with adjustable displacement.

characteristics may require pressurization or at least a flooded inlet port to properly fill its pumping chambers. Most pumps have limited speed, both low and high. At low speeds, volumetric efficiency is extremely low, and the clutch and sealing characteristics of the plates, which may wear, are completely inadequate. At high speeds, mechanical efficiency may be reduced to such an extent that failure becomes inevitable. The speed characteristics of the prime mover must be taken into account in the pump specifications. The idle speed of a diesel engine or the auxiliary drive of a jet engine represent practical speed limits of importance.

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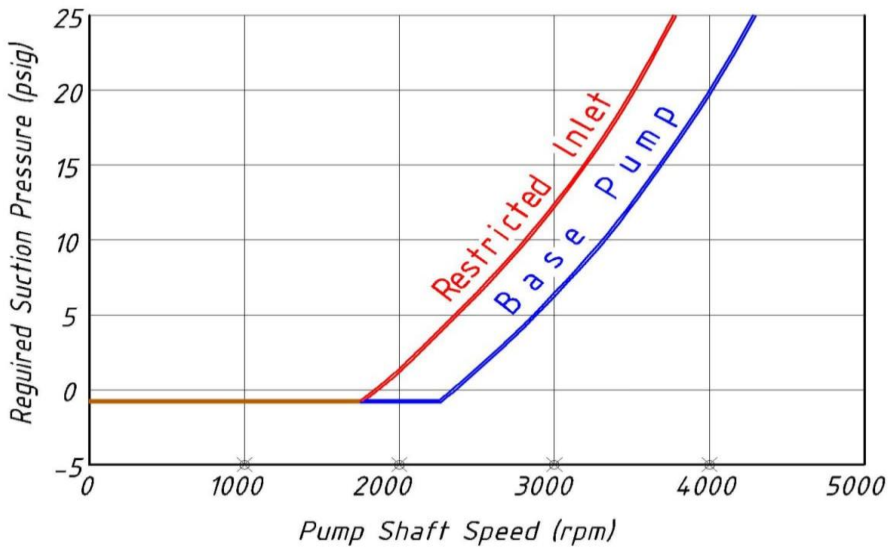

Fig. 6. Requirements for inlet pressure at a given pump speed

Serious difficulties arise when using positive displacement pumps at sub-zero temperatures. Under such conditions, the viscosity of the liquid increases significantly. This increase in viscosity leads to excessive hydraulic resistance to flow in the pipeline and increases friction forces in moving joints, makes it difficult to start the pump, disrupts the continuity of flow in the suction line, leads to incomplete filling of the pump chambers of the pump and excessive wear of the rubbing surfaces. The design features of the pump and the properties of hydraulic fluids determine the practical level of the operating temperature. Reducing the pump speed leads to a significant increase in temperature to ensure stable operation, and also increases the pumpability of working fluids compared to their viscosity level [8],

Flow or pump pulsations contribute to a variety of problems in hydraulic power systems, including:

• Noise (fluid-borne)

• Oscillations in flow meters, gauges, and controllers

• Unwanted amplification of disturbances on highly sensitive components.

Flow pulsations created by hydraulic pumps are caused by three things, namely:

• The volume of fluid being pumped does not decrease at a constant rate.

For example, in a piston pump, the volume of fluid being pumped is time-dependent or a function of the angular displacement of the shaft, so the flow rate is also time-dependent.

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• Gas locks, which occur due to a restriction in the inlet flow - the outlet pressure drops rapidly when the gas lock enters the high-pressure line.

• Reverse flow (slip) from the high-pressure side of the pump to the low-pressure side is constant.

Each type of pump has its own flow pulsation characteristics and before making a final pump selection it is necessary to obtain information from the pump manufacturer or conduct actual tests[4].

In practice, the most important characteristic of a centrifugal pump is the relationship between head (or pressure) and capacity (or flow). Knowing the pressure-flow function makes the centrifugal pump model compatible with models of conventional hydraulic components. Thus, the centrifugal pump model can be integrated into any standard hydraulic circuit for simulation. Figure 7 shows the velocity components of a centrifugal pump having an inner radius r1 and an outer radius r2 and rotating with an angular velocity ω. As can be seen in this figure, there are three critical velocity components, labeled u, w and v. The quantities u and u2 represent the tangential (linear circumferential) velocities at the inner and outer ends of the blade, respectively. The quantities w1 and w2 represent the fluid velocities relative to the blade at the inlet and outlet of the impeller. The quantities V1 and V2 are the absolute velocities of the fluid at the inlet and outlet, vectorially composed of their corresponding linear and relative velocities. The velocity angles (α1, αß) and the blade pitch angles (ß1, ß2) are determined as shown in the figure. If we look at Fig. 7, these velocity values have the following relationships:

$$U_1 = \omega_1 r_1 \qquad (1a)$$

$$U_2 = \omega_2 r_2 \qquad (1б)$$

$$V_{t1} = W_1 \sin ß_1 \qquad (2a)$$

$$V_{t2} = w_1 \sin ß_2 \qquad (2б)$$

$$Vu = v_1 \cos\alpha_1 = u_1 - w_1 \cos ß_1 \qquad (3a)$$

$$V_{12} = v_2 \cos\alpha_2 = u_2 - w_1 \cos ß_2 \qquad (3ь)$$

Note that in the above equations the absolute velocities of the fluid are represented by their tangential components (V_{t1}, V_{t2}) and normal components ($V\,n_1$ and Vn_2).

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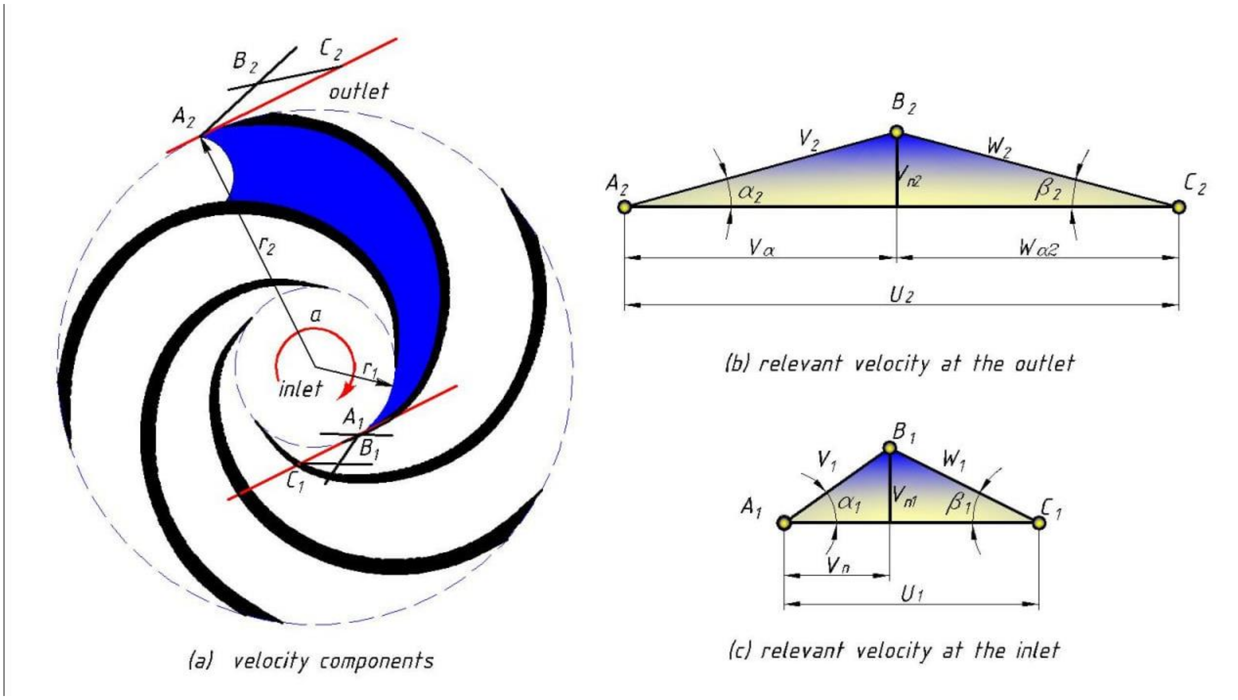

Fig. 7. Diagram of impeller speeds

This is a convenient way to obtain a pressure-flow model using these velocity components.

Assuming that the flow is steady, one-dimensional, and incompressible, the volumetric flow rate Q passing through the pump, according to the law of continuity, is

$$Q=2\pi r_1 b_1,\ \ V_{n1} =2\pi r_2 b_2, V n2 \qquad (4)$$

where: b1 (b2) - blade width at the inner (outer) end.

In the general design configuration, the arrangement of the blades results in the velocity of the fluid entering the pump having a tangential component. Since the magnitude and direction of the velocity constantly changes as the fluid passes through the impeller, the angular momentum of the fluid also changes. This creates a torque on the impeller. In other words, this is the amount of torque that must be applied to the fluid to achieve the required flow characteristics. Based on angular momentum theory and assuming an ideal system (i.e. no energy loss), the required torque T is

$$T = \rho\ Q(r_2V_{t1} - r_2V_{t2}) \qquad (5)$$

where ρ is the density of the liquid

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In addition, the power P transmitted from the shaft (=ωT) must be completely transmitted to the liquid under ideal conditions, as shown below:

$$P = \omega T = \rho g\, Q\, h_p \qquad (6)$$

where hp -pressure

$$h_1 = \frac{1}{g}(u_2 V_2 \alpha_2 \ - u_1 V_1 \cos \alpha_1) \qquad (7)$$

Equation 7 is the well-known Euler equation. Using a triangle, this equation can be rewritten as

$$h_p = \frac{u_2^2 - u_1^2}{2g} + \frac{W_2^2 - W_1^2}{2g} + \frac{V_2^2 - V_1^2}{2g} \qquad (8)$$

The first term on the right side of Equation 8 represents the pressure energy created by the centrifugal force. The second term represents the flow effect of changing the trajectory (shape and arrangement of the blades) as a function of the pressure energy. The third term represents the increase in pressure energy as a result of the increase in absolute fluid velocity.[9]

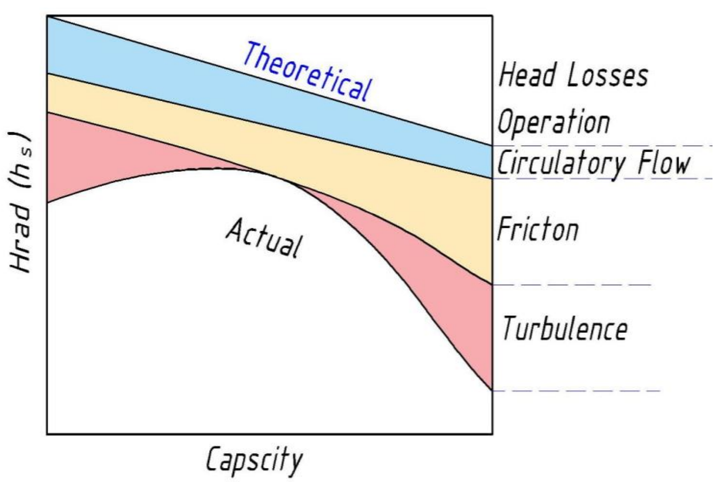

Fig.8. Curves of actual pressure dependence on productivity

If the fluid enters the impeller radially, then the angle a is equal to 90". Substituting this value into equation 8 and combining it with equations (1b), (2b), (3b) and (4) yields

$$h_F = \frac{1}{g} u_2 V_2 \cos \alpha_2 = \frac{\omega^2 r_2^2}{g} - \left(\omega \frac{\cos \beta_2}{2\pi b_2 \ g}\right) Q \qquad (9)$$

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Therefore, for a given centrifugal pump operating under certain conditions (i.e. the quantities ω, g2, b2, ß2 are known), the two coefficients on the right-hand side of equation 9 are constant. When replacing the head h with a pressure p (= p g h), equal to 9, we get

$$p = p_0 - KQ \qquad (10)$$

where $p_0 = \rho\omega^2 r_2^2$

$$K = \rho \frac{\omega \cos \beta_2}{2\pi b_2} \qquad (11)$$

Some applications have different requirements for the pump performance. For example, the pump may need to act as a motor due to the application of negative external loads that create a backflow into the pump. Such an application may require extremely low noise levels but still operate at relatively high pressures, say 300 bar (4500 psi).

Obviously, a centrifugal pump has a linear pressure-flow relationship under the assumed conditions specified in this section.

This is because the efficiency of a conventional pump drops off at high flows. This characteristic means that two different pump flows can be used to produce the same head. Having two delivery points at the same pressure can cause instability in a pump with forward-curved vanes, so most centrifugal pumps have backward-curved vanes.

Hydraulic efficiency depends on the design of the flow path and the way the fluid passes through it. It is defined as the actual head (h) achieved compared to the ideal head (h) delivered by the pump.

Friction losses are generally proportional to the square of the outlet flow. Imperfect matching of the flow to the outlet vane angle b2 results in a circulating flow,

A centrifugal pump can be designed for a specific flow rate at a given speed when the relative velocity is tangential to the inlet vane. Turbulent losses at this optimum operating point are negligible. At other discharges, the head loss varies approximately as the square of the deviation in approach angle.

Volumetric efficiency takes into account the loss of flow due to leakage. It is the ratio of the actual flow rate (Q) delivered by the pump to the theoretical flow rate (Q) calculated using equations 4. The actual flow rate is the theoretical flow rate minus the leakage flow rate (Q)[12].

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$$\eta_{hc} = \frac{h_a}{h_s} = 1 - \frac{h_L}{h_s} \qquad (12)$$

Mechanical efficiency is the fraction of the mechanical power supplied to the pump that is used to move the fluid. It is the ratio of the input power minus the power losses (PL) to the input power (P). Mechanical power losses are mainly due to friction in mechanical components such as bearings. The general trend is for mechanical efficiency to decrease with increasing speed and flow capacity.[12]

$$\eta_{hc} = \frac{P_s - P_L}{P_s} = 1 - \frac{P_L}{\omega T} \qquad (13)$$

$$\eta_{hc} = \frac{Q_2}{Q_1} = 1 - \frac{Q_\tau}{Q_1}$$

Therefore, the overall efficiency is

$$\eta_{oc} = \eta_{hc}\eta_{vc}\eta_{mc} \qquad (14)$$

Conclusions. It was determined that a pump with an efficiency of 66% requires 50% more power. When these losses are translated into the cost of the additional power required to do the job, the results are astounding. The type of hydraulic fluid used with a given pump can have serious consequences if the pump and fluid are incompatible. Too low a viscosity can result in excessive slippage, which can lead to inadequate lubrication. Too high a vapor pressure at the pump suction can result in vapor cavitation and subsequent destruction of the metal surface.

An important factor in selecting a pump is its filling characteristics. Theoretically, for a positive displacement pump, the flow rate is directly (linearly) related to the pump speed,

However, if sufficient liquid cannot be supplied to the pump chamber before the suction port closes, the chamber is only partially filled and the pump operates in the idle mode. This situation is illustrated in the figure for a given pump, liquid, temperature and inlet pressure, and shows that a certain pump speed must not be exceeded, otherwise the flow will be "choked off" and the pump will not operate. Another way to obtain the required inlet pressure for a given pump speed. Similarly, for a given pump,

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liquid temperature and speed, the system must maintain a certain inlet pressure to avoid cavitation.

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