Experimental study of the characteristic curves of 0.5 HP radial pump with constant speed

Estudio experimental de las curvas características de una bomba radial de 0.5 HP con rotación constante

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Artículo de investigación científica y tecnológica

***Abstract*— Radial (centrifugal) pumps are commonly used in industry and represent 22% of total consumption of the energy worldwide. The understanding of their operating conditions is important for a proper selection and use, specifically at the Best Efficient Point (BEP). This study analyzed the variation of the operating conditions of a common, small pump when the flow is regulated with a control valve at the pump discharge, keeping the rotational speed constant. The system consists in a closed loop using a turbine meter programmed in Arduino for flowrate measurement. The electric power and energy consumption were provided by an electronic Wattmeter, and the pressure at the suction/discharge of the pump was taken from Bourdon gauges. The minimum submergence of the pump intake was calculated with the Standard ANSI-HI-9.8 and the Bourdon gauges selection followed the recommendations of the Standard ASME B40.100-1998. All the measurements are part of the Energy equation for the pump-motor system (monoblock unit), whose H-Q curve is compared to manufacturer's curve with reasonable agreement that served as validation. The electric power curve is the evidence that the flow regulation method is unappropriated because the power consumption increases as the flow is regulated. At the end, the efficiency curve of the motor-pump unit was presented, with a maximum value of 12%. The shock and recirculation losses are present, but the electrical losses are evidenced through excessive heating. The test bench will have a better pump and a variable frequency drive for further studies.**

***Index Terms*—Efficient pumping systems, experimental fluid mechanics, radial pumps.**

***Resumen*—Las bombas radiales (centrífugas) son muy utilizadas en la industria y representan el 22% de la energía total consumida en Colombia. Es importante entender las condiciones de operación para una correcta selección y uso, específicamente en el punto de mejor eficiencia (BEP, por sus siglas en inglés). En este estudio se propone analizar la variación de esas condiciones en una bomba radial pequeña común al regular el caudal con una válvula en la descarga, manteniendo la rotación constante. El sistema consiste en un circuito cerrado donde el caudal se obtiene de un medidor de turbina programado en Arduino. La potencia y energía eléctrica se mide con un Vatímetro y la presión en la succión y descarga con manómetros tipo Bourdon. La sumergencia mínima en la succión fue calculada con el estándar ANSI-HI-98 y la selección de los manómetros Bourdon siguen las recomendaciones del estándar ASME B40.100-1998. Los datos medidos son parte de la ecuación de la energía planteada para el sistema motor-bomba (unidad monoblock), cuya curva H-Q fue comparada con la del fabricante, obteniendo una validación razonable. La curva de potencia eléctrica muestra que aumenta mientras el flujo es regulado, evidencia de que el método de regulación es inapropiado. Finalmente, se presenta la curva de eficiencia con un máximo de 12%. Existen pérdidas por choque y recirculación interna, pero las pérdidas eléctricas se evidencian con un calentamiento excesivo. El banco tendrá otra bomba mejor y un variador de velocidad para próximos estudios.**

***Palabras claves*—Bombas radiales, eficiencia en bombeo, experimentación en mecánica de fluidos.**

I. Introduction

THE studies of the European Commission presents statistics about the use of electric motors in industrial applications. Pumping systems has the second highest demand with 22% of the total consumption, followed by air compressors (18%), fans (16%), cooling compressors (7%) and conveyors (2%). The first place refers to other different equipment [1]. Therefore, the design of pumping systems must avoid the oversizing of pumps beyond the limits to make rational use of energy and reduce the overall costs.

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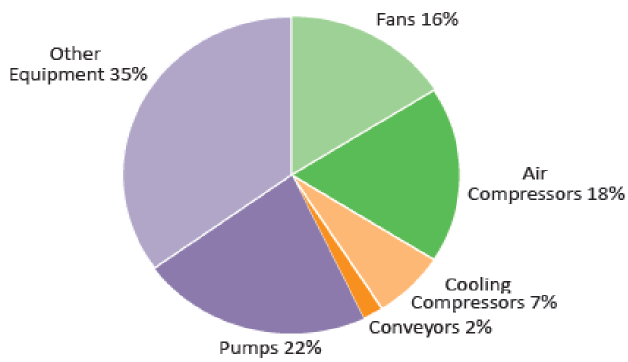

Fig. 1. Electric motor energy applications Worlwide [1].

A proper operation of a pumping system is a compromise between the correct selection of the pump and the system (pipes and fittings). There are several recommendations to achieve this, given by international institutions, societies and committees. The designer must begin with the basic theory of radial (centrifugal pumps) to understand their conception, relevant characteristics, operating conditions and proper selection. This work is an effort to introduce students into the knowledge of pump performance, as an electromechanical device widely used in industry. For that purpose, we study the pump-motor unit as the control volume for the analysis.

For that purpose, we study de pump-motor unit as the control volume. The main goal is to replicate the original pump curve and explore its performance with by regulating the flow rate with constant speed to validate theory. The pumping system is sized for the small 372 W (0.5 HP) monoblock unit, as it is a cost-effective pump. All the components are calculated and selected according to standards to provide data for the equations. The flow is regulated with a gate valve, as usual in low-cost systems in industry. The experiments demonstrated this method is inappropriate and served for the students to be aware of it.

II. Pump Theory

Fluid machines are first classified as hydraulic and thermal machines. In the former, there are two types: turbomachines and Positive Displacement (PD) machines. Turbomachines include rotodynamic pumps (radial, mixed and axial impellers), designed using velocity triangles (Fig. 2) to obtain the Euler equation. Basically, the hydraulic power is transmitted by changing the velocity magnitude and direction of the fluid absolute velocity (c) through the impeller. The theoretical transmitted power is then [2],

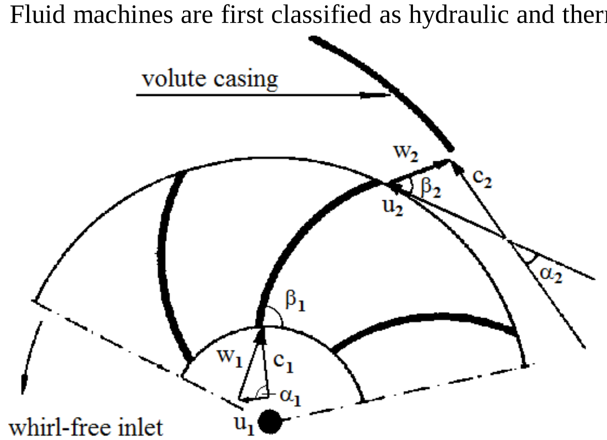

Fig. 2. Velocity triangles at blade leading and trailing edges for the Euler equation [3].

$$P = Q\rho\omega(r_2 c_2 cos\alpha_2 - r_1 c_1 cos\alpha_1) \quad (1)$$

Where Q is the flowrate, ρ is the fluid density, ω is the rotational speed (constant). Fig. 1 illustrates the radius r, the absolute velocity c and the angle α at the leading and trailing edges of the blade. For rotodynamic pumps, the Euler equation provides the theoretical specific work done to the fluid (Y).

Then, the theoretical head (H_t) is the maximum energy per unit volume [2],

$$H_t = \frac{Y}{g} = \frac{\omega}{g}(r_2 c_2 cos\alpha_2 - r_1 c_1 cos\alpha_1) \quad (2)$$

The symbol g refers to the acceleration of gravity. This head is maximum as the analysis assumes infinite blades, incompressible and potential flow; the graphic representation is the upper straight line in Fig. 3. This ideal case considers the flow passing through the impeller and casing without losses, where the angle β_1 of the relative velocity W_1 coincides with the blade angle. Note that in the analysis, the impeller geometry (β_1 and both radii) and the rotational speed (ω) are constant. However, in practice, there are internal secondary flows (circulation) that reduce the pump head. In addition, when the flow varies, the magnitude and angle of the relative velocity w_1 changes (also α_1 and α_2), and the flow does not follow the blade anymore. This refers to the shock losses, which increase with the flow rate.

Friction losses are caused by the viscous effects within the

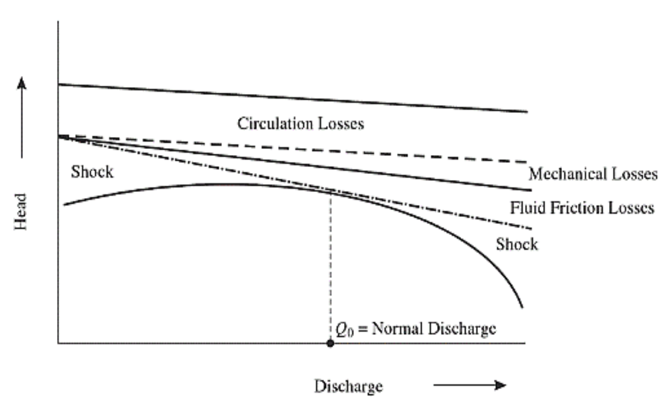

Fig. 3. Velocity triangles at blade leading and trailing edges for the Euler equation [5].

boundary layers on the internal surfaces (impeller and casing). These losses are unavoidable and reduce the efficiency as the flow rate increases due to the high velocities. Moreover, the total efficiency reduces due to the friction at mechanical seals. As a result, the pump has a Best Efficiency Point (BEP) [4], as shown in Fig. 4. The expression of the actual pump head performance can be derived from the energy equation between the pump suction and discharge (subscripts s and d, respectively) [2] as,

$$H = \frac{p_d - p_s}{\rho g} + \frac{{v_d}^2 - {v_s}^2}{2g} + (z_d - z_s) \tag{3}$$

Here, the subscripts s and d refer to the pump suction and discharge, respectively. In (3) includes the pressure terms p_d *and* p_s, the water density ρ at the operating temperature, the local acceleration of gravity g, the fluid velocities v_s and v_d, and the geodesic elevation $(z_d - z_s)$.

Fig. 4 presents the pump curves for a radial pump as a function of the flow rate, including the variation of the input shaft power (P_{shaft}), the required Net Positive Suction Head (NPSHr) and the total efficiency. The "normal" point corresponds to the Best Efficiency Point. From a control volume analysis (Fig. 5), the total efficiency is the ratio of the useful (hydrodynamic) energy input to fluid in unit time to the shaft power [6],

$$\eta = \frac{P_h}{P_{shaft}} \tag{4}$$

Where the former is defined by,

$$P_h = \rho g Q H \tag{5}$$

And the shaft power is calculated from the product between the shaft torque and rotational speed. Similarly, the total efficiency of the electric motor is defined by the ratio of the shaft power to the electric input power (measured),

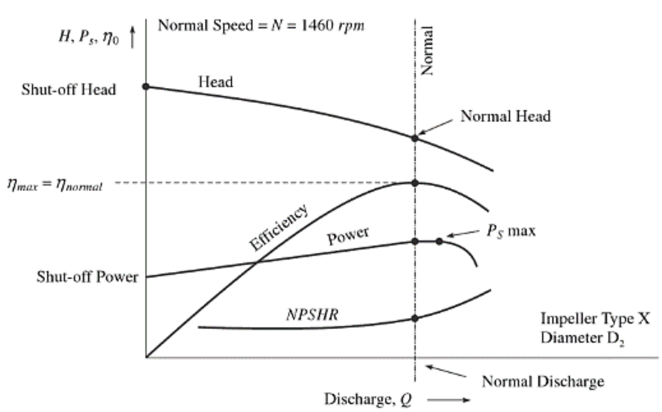

Fig. 4. Velocity triangles at blade leading and trailing edges for the Euler equation [5].

$$\eta = \frac{P_{shaft}}{P_{electric}} \tag{6}$$

If the pump-motor unit (monoblock) is considered for the control volume analysis, the overall efficiency is,

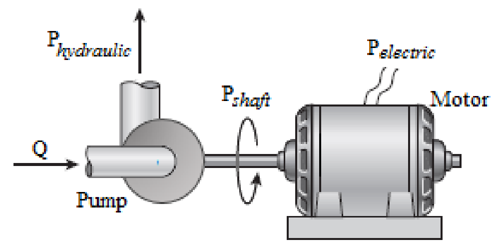

Fig. 5. Velocity triangles at blade leading and trailing edges for the Euler equation. Modified from [6].

$$\eta_{p-m} = \frac{P_h}{P_{electric}} \tag{7}$$

III. Materials and Methods

The pump was selected also by the nominal electric power of 0.5 HP, enough cost-effective size that is also used in similar test benches. In this case, the pump is the model QB60 of the company STANPROF, whose maximum head and discharge is 36 m and 32 L/min, respectively. The pump had the head vs. flow rate curve given by the manufacturer for further comparison. To analyse the pump-motor unit, the test bench consists on a closed loop circuit to avoid wasting water, as shown in Fig.6.

The actual head (H) versus Flow rate (Q) curve is obtained with (3). Then, the pressure term p_d *and* p_s are taken from the readings of the Bourdon gauges, and the flow rate with a Arduino turbine flowmeter. The latter is installed in the upper limb of the closed loop, 10 pipe diameters (D) from both, the upstream and downstream 90° elbows. In this case, D is equal at the pump suction and discharge (25.4 mm), obtaining $v_s = v_d$. Consequently, the second term is equal to zero. The third term is just a vertical measurement between those points, obtaining 105 mm.

The power curve refers to the electric power rather the shaft power due to the complexity of measuring the torque. In fact, this is preferred in order to study the electrical issues that arise from the flow rate regulation using the valve method. Therefore, the electrical input power will be provided by a Wattmeter connected to the motor. Finally, the overall efficiency is calculated with (7) and plotted as a function of the flow rate. The minimal submerge (S) in the suction reservoir follow the standard ANSI/HI 98-1998 of the Hydraulic Institute (USA), for avoiding the free surface vortices [7],

$$\frac{S}{D} = 1.0 + 2.3F_D \tag{8}$$

Where F_D is the Froude Number, defined by,

$$F_D = \frac{V}{(gD)^{0.5}} \tag{9}$$

Thus, the pressure range at the pump inlet and discharge can be estimated using the energy equation for the minimum and maximum flow rates. First, the equation is applied between the reservoir water surface and the pump inlet. Second, the equation is applied between the pump inlet and outlet. The calculated pressure ranges must be within the suitable part of the 270 degrees dial arc span, according to the standard ASME B40.100, 2005 [8]. For all the calculations, the water temperature must be measured in the reservoir. Table I presents the measuring instruments and the accuracy. The electric system was selected accordingly to ensure the correct start/stop of the pump and safe operation, including the protections.

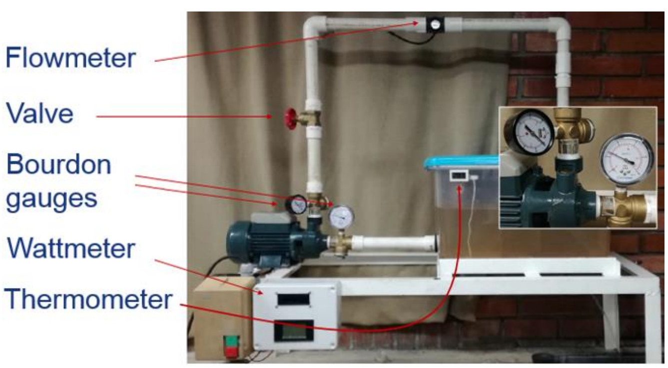

Fig. 6. Test bench at the laboratory in the Buga campus.

TABLE I
MEASURED VARIABLES AND EQUIPMENT

Variable	Quantity	Accuracy
Pressure	Bourdon gauges	± 1 mm
Flow rate	Turbine flow meter Arduino	± 3%
Electric power	Wattmeter	± 1 W
Distance	Measuring tape	± 1 mm
Temperature	Digital thermometer	± 1 °C

IV. RESULTS AND DISCUSSION

The required submergence in the suction reservoir was calculated as 149 mm. The ranges of pressure at the pump suction and discharge are, respectively 1.3 kPa < p_s < 2.5 kPa and 98 kPa < p_d < 355 kPa. Therefore, the suitable Bourdon manometers are the 4 kPa and 600 kPa, according to the standard ASME B40.100-2005. The commercially available gauges where the RiTherm of 37 mbar (3.7 kPa) and the ASTRO of 60 psi (413 kPa). Each point has two repetitions taken upscale and downscale of the flow rate range. All the fitted curves have high R^2 values. The standard error of the mean is plotted for the experimental head that covers the manufacturer's curve.

The Head vs Flow rate curve is compared to the manufacturer's curve (Fig. 7), indicating a reasonable agreement that served as validation. The major difference (25%) is for the highest flow rate and may be due to the use of inappropriate fittings for both manometers: the 5-way brass connections shown in Fig.5. That is, only 3-way connections are needed: two for the flow passing through and the third for the pressure gauge. The 5-way fitting has two additional port, one of them has the largest diameter and it is located opposite to the pressure gauge port; at 180 degrees. Although it is blocked, there is a cavity where flow recirculates, which affected the pressure measurements at the highest flow rate. Unfortunately, only the 5-way fitting was commercially available; further experiments will include the 3-way fitting.

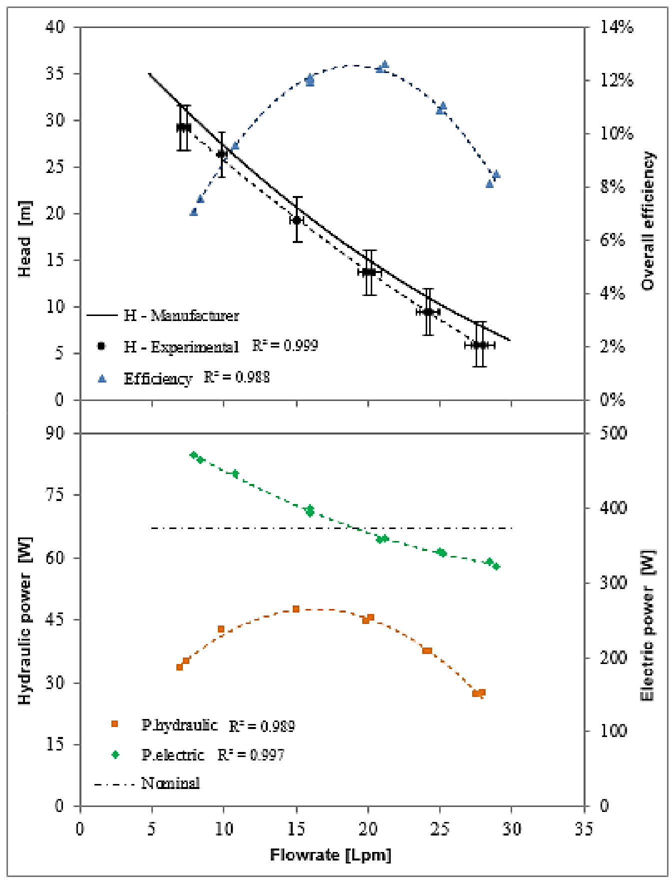

Fig. 7. Experimental characteristic curves from measurements. Above: Head and Overal efficiency vs Flow rate. Below: electric and hydraulic power vs Flow rate.

The overall efficiency of the system was very low, reaching a maximum of 12.6 percent. Mathematically, it was possible to determine the BEP flow rate by deriving the second order polynomial (R^2=0.989), obtaining 19.02 L/min. This point has the nominal electrical power of 372 W (0.5 HP). It can be seen from the electric power curve that it increases as the flow rate is regulated, which demonstrates this method is not appropriate for that purpose. Therefore, the efficiency is affected by all the losses involved; i.e. the hydraulic (shock, friction and circulation), the mechanical and even the electrical losses. When the valve is gradually closed to limit the flow rate, the pump is forced to operate with a restriction. Then, as the rotation is constant, the electric motor must provide higher torque to allow the pump to operate continuously. However, the torque is proportional to the electric current, which generated excessive heating on the motor frame due to the Joule effect. The thermal protection opened the circuit when the temperature reached 60°C.

V. Conclusion

A small, radial pump is analyzed in a test bench designed and validated at the Buga campus, Antonio Nariño University. The energy equation for the pump-motor unit (monoblock) allowed the calculation of the pump head, mainly as a function of the pressure difference at the pump suction and discharge. The electric power increases as the valve is closed, which demonstrates the inefficiency of this method to regulate the flowrate. For these small pumps the efficiency is low, reaching a maximum of 12% in this case. The explanation, besides of the expected hydraulic losses (shock, recirculation), includes the electric losses represented by the excessive heating of the motor frame (Joule effect in the stator). This test rig can be replicated to obtain the characteristic curves and best efficiency point (BEP) of similar pumps. To analyze only the pump, the shaft power must be estimated. This can be achieved by measuring the rotational speed and torque, or by using the electric power and the motor efficiency. Further studies include a centrifugal pump regulated with variable frequency drive.

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