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Pump transients and complete pump performance characteristics

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Abstract

Pump characteristics H(Q), P(Q) and η(Q) provided by pump manufacturers in the form of test results or in situ examination results carried out by measurement companies describe pumps functioning in the "first quarter", i.e., in the pump functioning zone. They enable pump parameters to be calculated in other points of the zone for a rotational speed different than the nominal one. However, pumps sometimes function in untypical zones. This is due to failures resulting from startup with high pressure on the pump discharge flange or an existing non-zero flow (during parallel operation or with positive geometric head), when using pumps to dissipate energy (during periodical work in a serial system) or to recover energy in turbine mode. Quantitative and qualitative descriptions of those parameters for all possible functioning states are included in the universal pump characteristics. These characteristics, described in the literature, concern pumps with just a few specific speeds. This article presents characteristics of pumps with as yet unpublished specific speeds.

Keywords: pump transients, pump characteristics, pump performance

1. Introduction

Pumps make up one of the biggest groups of industrial devices. Their efficiency depends on a range of parameters, such as power, components precision, quality of materials used to produce gaskets and bearings, etc. It is estimated that fluid carriers consume about 20% of all energy produced in Poland. Around one quarter of this consumption might be caused by losses that could be avoided. Thus, even small steps toward decreasing energy consumption in such devices contribute to cutting energy consumption across industry as a whole. This could be achieved by using pumps in conditions differing from normal working states. Examples of such uses are: reversible pump-turbines working as turbines, pumps working as turbines in micro hydro power stations, and pumps working as turbines used instead of valves and/or orifice plates to recover energy (recuperate) in installations.

2. What are normal conditions?

In normal working conditions of a rotodynamic pump the fluid flows from the suction flange to the discharge flange ($Q > 0 or + Q$), the pressure inside increases ($p_t > p_s$, i.e. $H > 0$[1] or $+H$), the rotating parts revolve to the right (to the left in a pump with left impeller) when looking from the engine side ($n > 0; +n$), and engine torque M_s also turns the pump shaft in this direction. Engine torque is equal to the torque on the pump shaft (in steady-state conditions) ($M > 0; +M$) (fig. 1).

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[1] $$H = \frac{p_t - p_s}{\rho g} + \frac{c_t^2 - c_s^2}{2g} + \Delta z;\ c_t = \frac{Q}{A_s};\ c_s = \frac{Q}{A_s};\ A_t + \frac{\pi}{4}d_t^2;\ A_s = \frac{\pi}{4}d_s^2$$

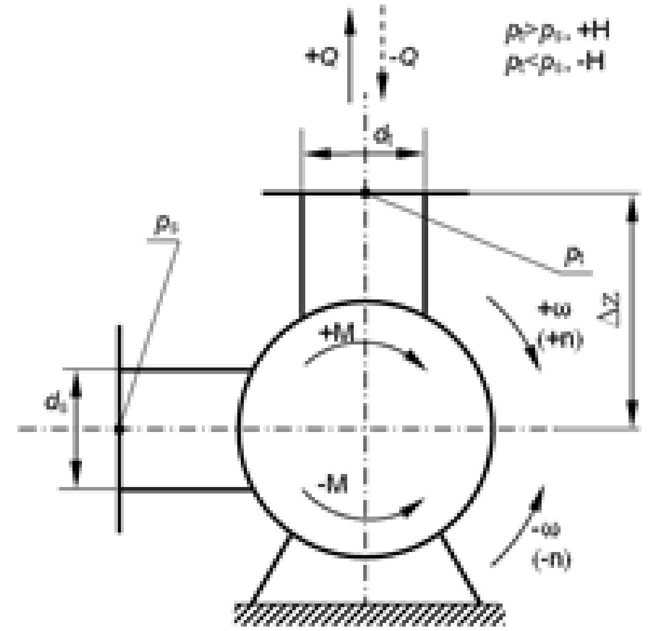

Figure 1: Positive (normal) and negative parameters of a working pump

Pump functioning can be described by four parameters: Q, H, M, n (flow intensity, pump head, shaft torque and rotational speed). When $Q > 0$, $H > 0$, $M > 0$, $n > 0$ a pump works in its normal functioning zone. Two of the four variables (Q, H, M, n) are independent. It is most convenient to choose Q and n – both of them can be positive and negative. Theoretically there are 16 possible combinations, but from the physics point of view only 8 of these are possible: 2 for pump function, 2 for turbine function, and the remaining ones for different states of energy dissipation [9]. An untypical working state could be a situation where for some reason the static pressure in an installation $\rho g H_{st} = \rho g z + p_g - p_d$ exceeds the maximum pressure $\rho g H_0$ created by the pump (fig. 2), causing the fluid to flow through the pump in the opposite direction ($Q < 0$) although all other variable relations remain true: $n > 0$, $M > 0$, $H > 0$ (e.g. starting up a water pump which cools a steam turbine condenser, when it is turned on with an open check valve, if $H_z > 0$ [4, 5]).

3. Mathematical description

In order to clearly describe pump functioning in untypical working states, it is convenient to use di-

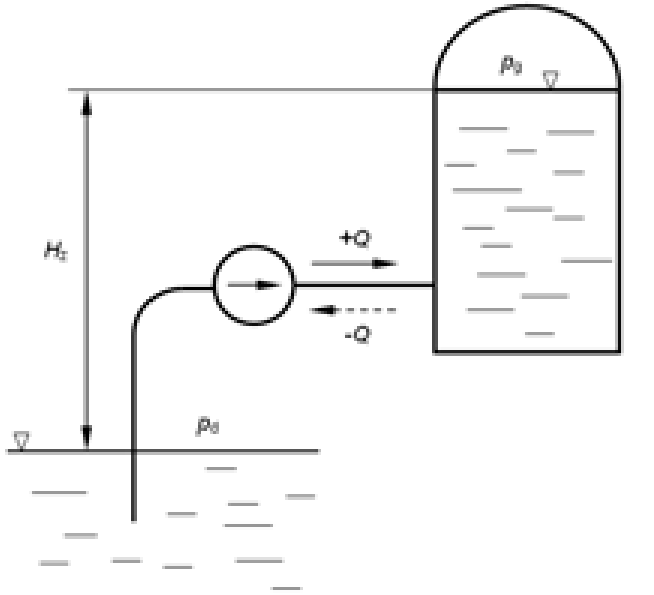

Figure 2: Possibility of creating untypical working conditions

mensionless coordinates:

$$\alpha = \frac{n}{n_n};\ q = \frac{Q}{Q_{opt}} \tag{1}$$

$$h = \frac{H}{H_{opt}};\ m = \frac{M}{M_{opt}}$$

where α_{opt}, H_{opt}, M_{opt} are parameters corresponding to the maximum pump efficiency η_{max} achieved at nominal rotational speed n_n.

There are three ways of representing pump performance characteristics. The “first representation” uses coordinates (q, α), with marked curve sets h = idem and m = idem [9]. The limiting curves h=0 and m=0 are straight lines, while h=idem and m=idem are evenly distributed over all plane quadrants (q, α). The straight lines h=0 and m=0 as well as Q and n axis divide the plane into eight parts marked with letters A...H, and each part describes different working conditions (fig. 3):

A(+ Q, + H, + M, + n) – normal pump functioning,

C(- Q, + H, + M, - n) – pump functioning as a turbine,

E(+ Q, + H, + M, - n) – “reverse pump” – rotating in the direction opposite to the calculated direction (e.g. due to a wrong connection of phases to a 3-phase engine; working with considerably lower Q, H and η),

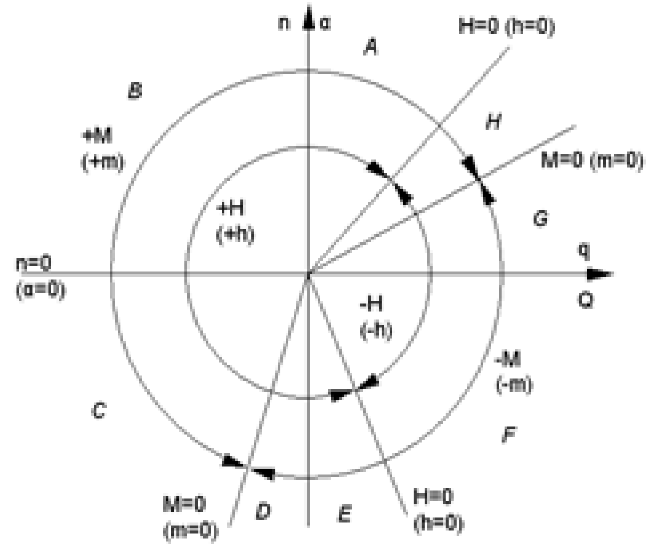

Figure 3: Possible pump functioning areas A÷H

G(+ Q, - H, - M, + n) – "reverse turbine" – working as a turbine with an opposite flow direction.

Work in the following zones: B(- Q, + H, + M, + n), D(- Q, + H, - M, - n), F(+ Q, - H, - M, - n), H(+ Q, - H, + M, + n) is accompanied by energy dispersion. The condition most frequently encountered in practice is B, as one of the stages of different transient states.

4. Untypical functioning zones

Untypical functioning conditions can have many different causes [7]. Some of the most probable are listed below. Each is characterized by sudden changes of working conditions causing short and quick changes of rotational speed n(t), efficiency Q(t), torque M(t) and shaft power P(t) as well as head H(t) of one pump or a group of pumps. Here are some of the possible situations:

1. Normal pump startup. A pump with or without a check valve, if $H_{st} = H_z + (p_g - p_d)/\rho g = 0$, H_z – geometric head; p_g, p_d – pressure in the upper (outflow) and lower (inflow) zone. The pump keeps working in normal conditions (A), the conditions of flow similarities during startup are satisfied in a short discharge pipeline system only where fluid inertia may be neglected. The approximate calculation of such startup time is shown in [9], and the numerical calculation of a big double suction pump startup is given in [6].
2. Negative flow startup (-Q). Example: a large pump of water cooling a condenser in a power plant, in an open cooling circuit where $H_z > 0$ (outflow located above inflow), no check valve, pump impeller stopped mechanically. Startup begins in (B) and ends in (A).
3. Pump startup as in b) but with the impeller rotating freely in the direction opposite to normal. Startup begins in (C), then there is a transition from (B) to (A). The numerical calculation of a big axial-flow pump startup is shown in [4, 5].
4. A sudden pressure increase to $p_g + \rho g H_z > \rho g H_0 + p_d$ in the upper tank (fig. 4; H_0 – pump head at Q=0); pump without a check valve or with a damaged check valve. The pump, working initially in (A), changes its functioning zone to (B).
5. A power cutoff occurring while the pump is working with a correctly functioning check valve or in a system where $H_{st} = 0$. The pump keeps working in normal conditions (A).
6. A power cutoff occurring for a pump connected in series with another pump and the check valve not working (fig. 4 a, c). The situation development scenario depends on whether the power cutoff occurs for pump p_1 ("smaller") or pump p_2 ("larger").
7. A power cutoff occurring for a pump connected in parallel with another pump and the check valve not working behind the "smaller" pump (fig. 4 b, c). The functioning pump will keep working in (A) with different efficiency; the pump which is not powered will start working as a water turbine (C) with the only load coming from pump system friction.
8. A power cutoff occurring in one or more circulator pumps in the primary circuit of a nuclear reactor (PWR). This situation is similar to 7, however, the parameters and properties of the pump systems are completely different.
9. Cracked discharge pipe – fast pressure drop and pump efficiency increase. The pump keeps working in (A).

In addition to the situations described above, a pump can function as a turbine by definition (C),

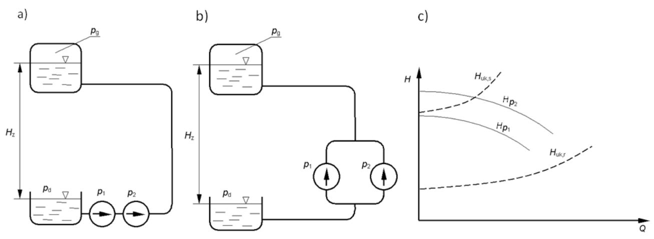

Figure 4: Two different pumps p_1, p_2($p_1 \neq p_2$connected in series (a) and in parallel (b), and pump and system characteristics (c); $H_{uk,r}$– system characteristics for pumps connected in parallel, $H_{uk,s}$– for pumps connected in series

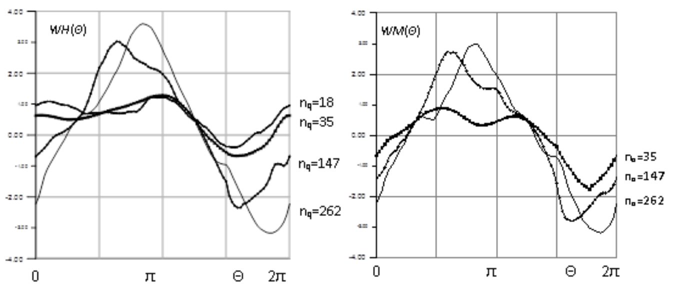

Figure 5: Third representation of complete performance characteristics a) $WH(\Theta)$ obtained using the data given in [9], [8]; b) $WM(\Theta)$ obtained using the data given in [9]

when it is used instead of valves and/or orifice plates (energy recovery) or in micro hydro power stations.[2] It can also periodically work as hydraulic resistance (e.g. in heating systems) after an intended power disconnection.

5. Research results

The relations described by formulae (**??**) and shown in the characteristics, as in fig. 3, are not convenient to use due to coordinate system ambiguity. Therefore, it is better to use the "third representation" of pump performance characteristics, as described by the (2), (3), (4), (5) and (6) formulae:

$$WH = \frac{h}{\alpha^2 + q^2} \quad (2)$$

$$WM = \frac{m}{\alpha^2 + q^2} \quad (3)$$

$$\theta' = arctg(q/\alpha) \quad (4)$$

or

$$tg\vartheta = q/\alpha \quad (5)$$

$$for\, zone\, 3 \qquad \theta = \theta' \quad (6)$$

$$for\, zone\, 1 + 4 \qquad \theta = \theta' + \pi$$

$$for\, zone\, 2 \qquad \theta = \theta' + 2\pi$$

where q, h, m, α are described by relations given in (**??**), and $\theta = \vartheta + \pi$.

Relations (2)...(6) were used to obtain $WH(\theta)$ and $WM(\theta)$ characteristics, which differ from each other considerably for pumps with different specific speeds. These characteristics are shown in fig 5.

The Institute of Heat Engineering at Warsaw University of Technology carried out tests to examine the performance characteristics for three pumps with specific speeds 11, 15 and 24 [7]. The results for two of these pumps are shown in fig. 6 and 7 (5KAN25 pump, $n_q = 11,1$) and fig. 8 and 9 (NHV50-250 pump, $n_q = 15,6$[3]It was possible to create all working conditions (A)....(H) by slightly modifying the test stand.

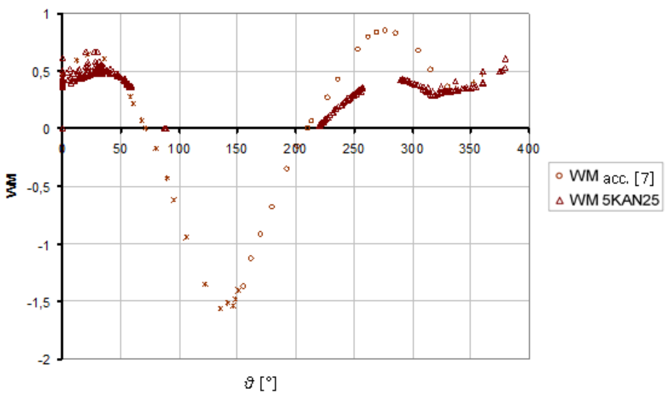

Figure 6: $WH(\vartheta)$ for 5KAN25 pump (n_q=11) against literature data (n_q=35)

[2]In these cases $Q(H, n)$, $P(Q, n)\,\eta(Q, n)$obtained by testing a particular pump are much better. If they are unavailable complete characteristics can be used.

[3]$n_q = n_n \cdot Q_{opt}^{1/2}/H_{opt}^{3/4}$, where n_n is the nominal rotational speed, Q_{opt}, H_{opt} are the efficiency and head corresponding to the maximum pump efficiency

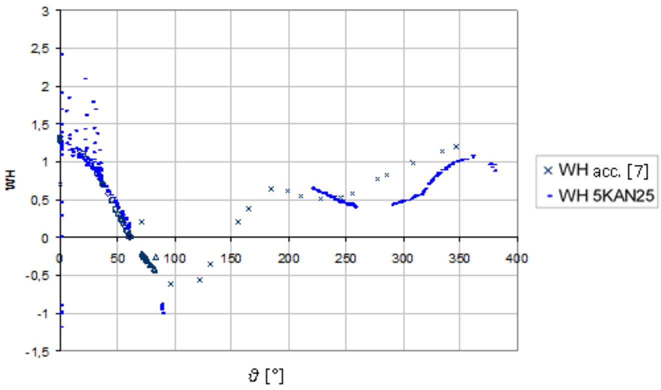

Figure 7: $WM(\vartheta)$ for 5KAN25 pump (n_q=11) against literature data (n_q=35)

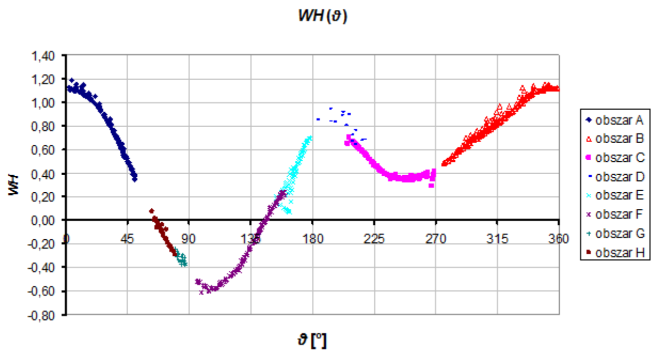

Figure 8: $WH(\vartheta)$ for NHV50-250 pump (n_q=15.6)

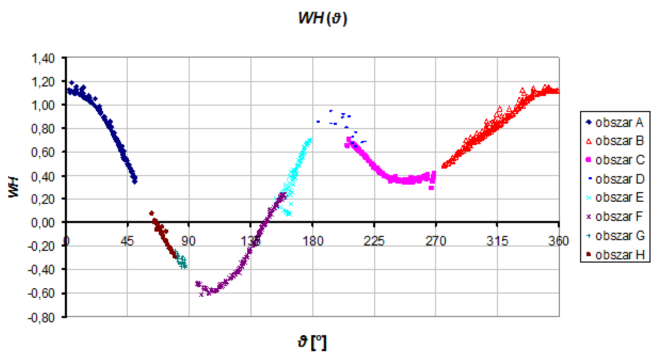

Figure 9: $WM(\vartheta)$ for NHV50-250 pump (n_q=11)

These characteristics support the literature data and at the same time enlarge the set of available data which can serve as a basis for obtaining performance characteristics of pumps with similar specific speeds.

6. Summary

In order to evaluate pumps working in untypical conditions it is essential to know the pump characteristics in such zones. Pump manufacturers usually specify the characteristics for zone A and basic rotational speed only. In very rare cases users are provided with the characteristics in the form of efficiency hill charts. Literature containing characteristics of pumps with required specific speeds could help solve the problem. However, available publications contain only a few such characteristics for just a few n_q, so when analyzing pumps with specific speeds significantly different from those described in the literature, it would be advisable to engage in some anticipation by interpolating between the "neighboring" characteristics. One should bear in mind that those characteristics were obtained a few decades ago, when technology was at a different level of development, so numerical approximation could produce non-negligible errors. Laboratory research is still being conducted to increase the number of resources containing complete characteristics. There also seems to be a need to create a numerical model of fluid flow for a pump working in untypical conditions.

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