CONTRIBUTIONS TO SOLVING THE EQUATIONS OF THE FUNCTIONAL FEATURES OF TURBOPUMPS

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Abstract

Turbopumps are hydraulic generators that are indispensable to the pressurized and/or free level hydrotechnical systems. These are used mainly for high pumping flows. They are characterized by high velocity of the fluid in relation to the active parts and the fact that the pumped flow varies in relation to the pumping height. For accurate sizing and simulation of their functioning, we suggest a new analytical expression for the determination of the power feature for a constant rpm. Unlike the polynomial function of the second degree, present in field literature, we approximated the analytical expression for the power feature for constant rpm of the turbopump using a rational function with five coefficients. We theoretically determined the analytical expression for the loading feature for variable rpm and applied various methods of statistical processing in order to determine the actual numerical values for the coefficients of functional features of the turbopumps. We noticed that among the statistical processing methods of the experimental data, the most accurate results were achieved by our mathematical model, using the method of minimisation of the sum of the absolute values of the deviations.

Key words: functional features of turbopumps, variable rpm, statistical methods

Turbopumps are used mainly for high pumping flows and the pumped flow varies in relation to the pumping height.

At the level of irrigation networks, the equations characteristic to the function of turbo pumps that are used for the effectiveness of a system which is composed from pipes under pressure and the station of the pressure pipes (SPP), (Alexandrescu A., 2004).

The functional equations may serve to simulate the operation of the pumps within the framework of the hydro-power systems.

The main functional characteristics of the turbopumps, at variable speed are (Popescu St., 2004; Popescu St., 1993):

- the load characteristic,

$$H = f_Q(n,Q) \tag{1}$$

- the yield characteristic,

$$\eta = f_\eta(n,Q) \tag{2}$$

- the power characteristic,

$$N = f_N(n,Q) \tag{3}$$

- the feature of the dynamic load at the entry into the impeller (*the requested NPSH*),

$$NPSH = f_c\left(n,Q\right) \tag{4}$$

In all the formed expressions (1)÷(4), the speed n and flow Q are considered independent variables; when the speed presents a constant value n_0, the flow remains the only independent variable.

The actual analytic expressions of the characteristics (1)÷(3), at the speed n_0, are the following (equations 1÷4):

- the load characteristic,

$$H = f_{H0}\left(Q\right) = a_{H0}\cdot Q^2 + b_{H0}\cdot Q + c_{H0} \tag{5}$$

- the yield characteristic,

$$\eta = f_{\eta 0}(Q) = a_{\eta 0}\cdot Q^2 + b_{\eta 0}\cdot Q + c_{\eta 0} \tag{6}$$

- the power characteristic,

$$N = f_{N0}(Q) = a_{N0}\cdot Q^2 + b_{N0}\cdot Q + c_{N0} \tag{7}$$

The analytical coefficient expressions (5) ÷ (7) can be deduced by statistical processing of M couplers experimental data (obtained from measurements or, in their absence, taken from the curves provided by the supplier of turbo pumps),

$$\left(Q_{0i}, H_{0i}, \eta_{0i}, N_{0i}\right), i = 1, 2, \ldots, M \tag{8}$$

We will present each of the 3 main methods, which are differenced trough, the afferent performance criteria.

The main methods of statistical processing data (8) are: 1 the least squares method

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(M.C.M.M.P.), proposed by Gauss; 2° method of minimizing the sum of the absolute values of deviations (M.S.V.A.A.) and 3°rd mini-max method (M.M-M).

We will present each of the three principle methods that are differentiated by performance related criteria, in the specific case of the load characteristic (equation 5):

- The data (equation 8) value pairs are selected for load flow,

$$\left(Q_{0i}, H_{0i}\right), i = 1, 2, \ldots, M \quad (9)$$

- The introduction of set values (9) in equation (5) is generated following string of errors (deviations):

$$\delta_i = a_{H0} \cdot \left(Q_{0i}\right)^2 + b_{H0} Q_{0i} + c_{H0} - H_{0i}, i = 1,2 \ldots M \quad (10)$$

where deviations δ_i are dependent on the coefficients of the (equation 5),

$$\delta_i = \delta_i\left(a_{H0}, b_{H0}, c_{H0}\right), i = 1,2,\ldots,M \quad (11)$$

- Performance criteria for M.C.M.M.P it consists of minimizing the sum of squares of errors (equation 10).

$$\min\left[\sum_{i=1}^{M}\left(\delta_i\right)^2\right] = \min\left\{\sum_{i=1}^{M}\left[a_{H0} \cdot \left(Q_{0i}\right)^2 + b_{H0} \cdot Q_{0i} + c_{H0} - H_{0i}\right]^2\right\} \quad (12)$$

- Performance criteria for M.S.V.A.A. consists in minimizing the sum of the absolute values of the deviations (equation 10),

$$\min\left[\sum_{i=1}^{M}\left|\delta_i\right|\right] = \min\left\{\sum_{i=1}^{M}\left|a_{H0} \cdot \left(Q_{0i}\right)^2 + b_{H0} \cdot Q_{0i} + c_{H0} - H_{0i}\right|\right\} \quad (13)$$

- Performance criteria for M.M-M consists of minimizing the deviation of the sequence (equation 10) with maximum absolute value,

$$\min\left\{\max_{i=1,2,\ldots,M}\left|\delta_i\right|\right\} \Leftrightarrow \min\left\{\max_{i=1,2,\ldots,M}\left|a_{H0} \cdot \left(Q_{0i}\right)^2 + b_{H0} \cdot Q_{0i} + c_{H0} - H_{0i}\right|\right\} \quad (14)$$

These three methods in MATLAB can be directly applied using standard functions relating to:

- for M.C.M.M.P., for polynomial relations, polyfit.m;
- forM.M-M., fminimax.m;
- for M.V.A.A., fminsearch.m.

MATERIAL AND METHOD

A new analytical expression for power at constant speed feature.

It has been found the pump power (equations 1,3):

$$N = \gamma \cdot \frac{Q \cdot H}{\eta} \quad (15)$$

where γ it represents the specific gravity of water.

Introducing in (equation 15) the expressions (5) and (6), the resulting expression are:

$$N = \gamma \cdot \frac{Q \cdot \left(a_{H0} \cdot Q^2 + b_{H0} \cdot Q + c_{H0}\right)}{a_{\eta 0} \cdot Q^2 + b_{\eta 0} \cdot Q + c_{\eta 0}}$$

that with notations:

$$a_{N0} = \gamma \cdot \frac{a_{H0}}{a_{\eta 0}}, b_{N0} = \gamma \cdot \frac{b_{H0}}{a_{\eta 0}}, c_{N0} = \gamma \cdot \frac{c_{H0}}{a_{\eta 0}}, d_{N0} = \frac{b_{\eta 0}}{a_{\eta 0}}, e_{N0} = \frac{c_{\eta 0}}{a_{\eta 0}}$$

will become:

$$N = f_{N0}(Q) = \frac{Q\left(a_{N0} Q^2 + b_{N0} Q + c_{N0}\right)}{Q^2 + d_{N0} \cdot Q_{N0} + e_{N0}} \quad (16)$$

The coefficients of the (equation 16) can be determined with high precision by direct statistical processing of pairs of experimental values:

$$\left(Q_{0i}, N_{0i}\right), i = 1, 2, \ldots, M \quad (17)$$

values that are retrieved from the data set (equation 8).

Deductions on theoretical equation load variable speed feature.

For (equation 1), corresponding load characteristic speed *n* is considered an expression of the form (equation 5),

$$H = f_{Hn}\left(Q, n\right) = a_{Hn} Q^2 + b_{Hn} Q + c_{Hn} \quad (18)$$

but with coefficients a_{Hn} ,b_{Hn} and c_{Hn} that depend on speed n.

Considering the similarity relations:

- for debits:

$$Q/Q_0 = n/n_0 \tag{19}$$

- for hydraulic tasks:

$$H/H_0 = (n/n_0)^2 \tag{20}$$

(equation 18) becomes:

$$H_0\left(\frac{n}{n_0}\right)^2 = a_{Hn}Q_0^2\left(\frac{n}{n_0}\right)^2 + b_{Hn}Q_0\left(\frac{n}{n_0}\right) + c_{Hn} \tag{21}$$

When entering the set of values (9) in (equation 21) gives the following series of errors:

According to the method of least squares, the coefficients a_{Hn}, b_{Hn} and c_{Hn} for (equation 18) and (equation 21) they are determined from the condition of maximizing the sum of squares of errors (equation 22).

$$\delta_i = \delta_i\left(a_{Hn}, b_{Hn}, c_{Hn}\right), i = 1,2,\ldots,M \tag{22}$$

$$\delta_i = a_{Hn}Q_0^2\left(\frac{n}{n_0}\right)^2 + b_{Hn}Q_{0i}\left(\frac{n}{n_0}\right) + c_{Hn} - H_{0i}\left(\frac{n}{n_0}\right)^2, i = 1,2,\ldots,M \quad (22) \tag{23}$$

where:

$$\sum_{i=1}^{M}(\delta_i)^2 = \sum_{i=1}^{M}\left[a_{Hn}(Q_{0i})^2\left(\frac{n}{n_0}\right)^2 + b_{Hn}Q_{0i}\left(\frac{n}{n_0}\right) + c_{Hn} - H_{0i}\left(\frac{n}{n_0}\right)^2\right]^2 \tag{24}$$

The necessary condition for minimizing the amount (equation 24) it depends of simultaneous cancellation of its partial derivatives in relation to each of the coefficients: a_{Hn}, b_{Hn} and c_{Hn}:

$$\min\left\{\sum(\delta_i)^2\right\} \Rightarrow \begin{cases} \dfrac{\partial}{\partial a_{Hn}}\left\{\sum(\delta_i)^2\right\} = 0 \\ \dfrac{\partial}{\partial b_{Hn}}\left\{\sum(\delta_i)^2\right\} = 0 \\ \dfrac{\partial}{\partial c_{Hn}}\left\{\sum(\delta_i)^2\right\} = 0 \end{cases} \tag{25}$$

Performing above derivation relations, we obtain the following system of equations in three unknowns a_{Hn}, b_{Hn} si c_{Hn}:

$$\begin{cases} \sum\left[a_{Hn}\cdot(Q_{0i})^2\cdot\left(\frac{n}{n_0}\right)^2 + b_{Hn}\cdot Q_{0i}\cdot\left(\frac{n}{n_0}\right) + c_{Hn} - H_{0i}\cdot\left(\frac{n}{n_0}\right)^2\right]\cdot(Q_{0i})^2\cdot\left(\frac{n}{n_0}\right)^2 = 0 \\ \sum\left[a_{Hn}\cdot(Q_{0i})^2\cdot\left(\frac{n}{n_0}\right)^2 + b_{Hn}\cdot Q_{0i}\cdot\left(\frac{n}{n_0}\right) + c_{Hn} - H_{0i}\cdot\left(\frac{n}{n_0}\right)^2\right]Q_{0i}\left(\frac{n}{n_0}\right) = 0 \\ \sum\left[a_{Hn}\cdot(Q_{0i})^2\cdot\left(\frac{n}{n_0}\right)^2 + b_{Hn}\cdot Q_{0i}\cdot\left(\frac{n}{n_0}\right) + c_{Hn} - H_{0i}\cdot\left(\frac{n}{n_0}\right)^2\right] = 0 \end{cases}$$

transcribed with next form, following general (equations 26):

$$\begin{cases} a_{Hn}\cdot\left(\frac{n}{n_0}\right)^2\sum(Q_{0i})^4 + b_{Hn}\left(\frac{n}{n_0}\right)\cdot\sum(Q_{0i})^3 + c_{Hn}\sum(Q_{0i})^2 = \left(\frac{n}{n_0}\right)^2\sum(Q_{0i})^2 H_{0i} \\ a_{Hn}\cdot\left(\frac{n}{n_0}\right)^2\cdot\sum(Q_{0i})^3 + b_{Hn}\cdot\left(\frac{n}{n_0}\right)\cdot\sum(Q_{0i})^2 + c_{Hn}\cdot\sum(Q_{0i}) = \left(\frac{n}{n_0}\right)^2\cdot\sum Q_{0i}\cdot H_{0i} \\ a_{Hn}\cdot\left(\frac{n}{n_0}\right)^2\cdot\sum(Q_{0i})^2 + b_{Hn}\cdot\left(\frac{n}{n_0}\right)\cdot\sum(Q_{0i}) + c_{Hn} = \left(\frac{n}{n_0}\right)^2\cdot\sum H_{0i} \end{cases} \tag{26}$$

It can be said that the system (26) presents the coefficient matrix of the symmetric unknown variables, for solving it we applied Cramer's rule; so the system solution (equations 26) is obtained as the following determinants ratio:

$$a_{Hn} = \Delta_a/\Delta, b_{Hn} = \Delta_b/\Delta, c_{Hn} = \Delta_c/\Delta \qquad (27)$$

Where for the determinants $\Delta, \Delta_a, \Delta_b$ and Δ_c have been obtained, after elementary calculus, the next expressions (28) ÷ (31):

$$\Delta = \left(\frac{n}{n_0}\right)^3 \cdot \begin{bmatrix} \sum(Q_{0i})^4 & \sum(Q_{0i})^3 & \sum(Q_{0i})^2 \\ \sum(Q_{0i})^3 & \sum(Q_{0i})^2 & \sum(Q_{0i}) \\ \sum(Q_{0i})^2 & \sum(Q_{0i}) & N \end{bmatrix} = \left(\frac{n}{n_0}\right)^3 \cdot \Delta_1 \qquad (28)$$

$$\Delta_a = \left(\frac{n}{n_0}\right)^3 \cdot \begin{bmatrix} \sum(Q_{0i})^2 H_{0i} & \sum(Q_{0i})^3 & \sum(Q_{0i})^2 \\ \sum(Q_{0i})H_{0i} & \sum(Q_{0i})^2 & \sum(Q_{0i}) \\ \sum H_{0i} & \sum(Q_{0i}) & N \end{bmatrix} = \left(\frac{n}{n_0}\right)^3 \cdot \Delta_{1a} \qquad (29)$$

$$\Delta_b = \left(\frac{n}{n_0}\right)^4 \cdot \begin{bmatrix} \sum(Q_{0i})^4 & \sum(Q_{0i})^2 H_{0i} & \sum(Q_{0i})^2 \\ \sum(Q_{0i})^3 & \sum(Q_{0i})H_{0i} & \sum(Q_{0i}) \\ \sum(Q_{0i})^2 & \sum H_{0i} & N \end{bmatrix} = \left(\frac{n}{n_0}\right)^4 \cdot \Delta_{1b} \qquad (30)$$

$$\Delta_c = \left(\frac{n}{n_0}\right)^5 \cdot \begin{bmatrix} \sum(Q_{0i})^4 & \sum(Q_{0i})^3 & \sum(Q_{0i})^2 H_{0i} \\ \sum(Q_{0i})^3 & \sum(Q_{0i})^2 & \sum(Q_{0i})H_{0i} \\ \sum(Q_{0i})^2 & \sum(Q_{0i}) & \sum H_{0i} \end{bmatrix} = \left(\frac{n}{n_0}\right)^5 \cdot \Delta_{1c} \qquad (31)$$

Introducing the expressions of determinants (28)÷(31) in solution (27), resulting (equations 32÷34):

$$a_{Hn} = \frac{(n/n_0)^3 \cdot \Delta_{1a}}{(n/n_0)^3 \cdot \Delta_1}, \; a_{Hn} = \frac{\Delta_{1a}}{\Delta_1} \qquad (32)$$

$$b_{Hn} = \frac{(n/n_0)^4 \cdot \Delta_{1b}}{(n/n_0)^3 \cdot \Delta_1}, \; b_{Hn} = \left(\frac{n}{n_0}\right) \cdot \frac{\Delta_{1b}}{\Delta_1} \qquad (33)$$

$$c_{Hn} = \frac{(n/n_0)^5 \cdot \Delta_{1c}}{(n/n_0)^3 \cdot \Delta_1}, \; c_{Hn} = \left(\frac{n}{n_0}\right)^2 \cdot \frac{\Delta_{1c}}{\Delta_1} \qquad (34)$$

Introducing of solutions (32)÷(34) in (equation 18), the expression for the loading feature for variable rpm n gets:

$$H = f_{Hn}(Q,n) = \frac{\Delta_{1a}}{\Delta_1} \cdot Q^2 + \frac{\Delta_{1b}}{\Delta_1} \cdot \left(\frac{n}{n_0}\right) \cdot Q + \frac{\Delta_{1c}}{\Delta_1} \cdot \left(\frac{n}{n_0}\right)^2 \qquad (35)$$

which is cited in the literature as (Alexandrescu A., 2004, Popescu St., 1993).:

$$H = A_0 \cdot n^2 + A_1 \cdot n \cdot Q + A_2 \cdot Q^2 \qquad (36)$$

where:

$$A_0 = \frac{\Delta_{1c}}{\Delta_1 \cdot (n_0)^2}, A_1 = \frac{\Delta_{1b}}{\Delta_1 \cdot n_0}, A_2 = \frac{\Delta_{1a}}{\Delta_1} \qquad (37)$$

In the particular case $n = n_0$, from (equations 32-34) resulting (equations 38÷39):

$$a_{H0} = \Delta_{1a}/\Delta_1, \; b_{H0} = \Delta_{1b}/\Delta_1, \; c_{H0} = \Delta_{1c}/\Delta_1 \qquad (38)$$

and

$$a_{Hn} = a_{H0}, \; b_{Hn} = \left(\frac{n}{n_0}\right) \cdot b_{H0}, \; c_{Hn} = \left(\frac{n}{n_0}\right)^2 \cdot c_{H0} \qquad (39)$$

With consideration of relations (37), expressions (36) for coefficients A_0, A_1 si A_2 become:

$$A_0 = \frac{1}{(n_0)^2} \cdot c_{H0}, A_1 = \frac{1}{n_0} \cdot b_{H0}, A_2 = a_{H0} \qquad (40)$$

The (equation 35)- the loading feature for variable rpm n may be transcribed with this form (equation 41):

$$H = f_{Hn}(Q,n) = a_{H0}\cdot Q^2 + b_{H0}\cdot\left(\frac{n}{n_0}\right)\cdot Q + c_{H0}\cdot\left(\frac{n}{n_0}\right)^2 \quad (41)$$

The (equations 39-41) are available for all the methods (M.C.M.M.P., M.S.V.A.A., M.M-M) of statistic processing of the data (9) in order to determine the coefficients a_{H0}, b_{H0} si c_{H0}.

The (equations 5÷7 and 36) are used for the determinations of the kinematic and energetic functional parameters of the turbopump, both at constant speed and variable speed.

RESULTS AND DISCUSSIONS

The theoretic recitals from the previous paragraph where applied to the radial turbopump, with double flow NDS 250-200-510 with the rotor Φ 510 mm.

The set of *M* couplers of experimental data (8) were taken over from the characteristic curves provided from the pump provider and it was centralized in (*table 1).*

Table1

***M*=35 couplers values for operational parameters NDS_250_200_510, pump type at constant speed n_0=1450 r.p.m.**

No. crt., *i*	1	2	3	4	5	6	7	8	9
Q_{0i},[m³/h]	140.0	160.0	180.0	200.0	220.0	236.2	240.0	260.0	277.1
H_{0i}, [m]	95.18	95.00	94.95	94.76	94.63	94.42	94.29	94.08	93.66
N_{0i}, [kWh]	80.91	83.86	87.66	90.69	94.41	101.27	97.78	101.16	108.78
η_{0i}, [%]	42.33	46.67	50.21	53.79	56.73	60.00	59.58	62.21	65.00
No. crt., *i*	10	11	12	13	14	15	16	17	18
Q_{0i},[m³/h]	280.0	300.0	310.4	320.0	340.0	360.0	365.9	380.0	388.1
H_{0i}, [m]	93.63	93.21	92.90	92.61	92.08	91.53	91.22	90.74	90.22
N_{0i}, [kWh]	104.95	108.75	112.22	111.28	114.23	118.88	121.24	121.83	123.88
η_{0i}, [%]	64.37	66.28	70.00	68.75	70.73	71.66	75.00	73.17	77.00
No. crt., *i*	19	20	21	22	23	24	25	26	27
Q_{0i},[m³/h]	400.0	420.0	440.0	460.0	469.9	480.0	500.0	520.0	525.4
H_{0i}, [m]	89.85	88.90	87.70	86.70	85.99	85.54	84.07	82.49	82.07
N_{0i}, [kWh]	124.78	128.16	131.53	134.91	142.03	139.13	142.92	148.41	152.56
η_{0i}, [%]	74.45	75.51	76.23	76.71	77.5	76.76	76.66	75.61	77.00
No. crt., *i*	28	29	30	31	32	33	34	35	-
Q_{0i},[m³/h]	540.0	543.0	560.0	580.0	600.0	620.0	640.0	660.0	-
H_{0i}, [m]	80.81	79.86	79.02	77.08	74.98	72.61	70.04	67.09	-
N_{0i}, [kWh]	154.31	157.50	159.80	165.28	171.19	177.94	185.11	192.28	-
η_{0i}, [%]	74.13	75.00	72.71	71.17	70.00	67.11	65.00	61.71	-

The values from (*table 1)* were used in the direct representation of the afferent experimental points of the work load characteristics, of the power of the pump NDS 250-2000-510, at the constant rpm n_0=1450 r.p.m. *(figure 1),* as well as the determination trough statistic processing of the values of the ecuations coefficients and values in *(table 2)* and accurate criteria $\sum|\delta_i|$.

The functions (7) and (16), with the coefficients present in(*table 2).*, were represented in (*figure 1).*

The afferent theoretical points of the functional characteristics present the same abscissa (the values of the flow Q_{0i}) as the experimental points, but they are displayed on the respective theoretical characteristics

The graphic representation from *(figure 1)* is useful in the correction of the possible errors which can appear at the taking over of the experimental data on the characteristic curves.

Table 2

The functional coefficients characteristic of the pump NDS_250_200_510 type, at speed rpm n_0=1450 and to speed rpm n<n0.

	Characteristics	Coefficients		1	2	3	4	5	$\sum\|\delta_i\|$
1	Head (5)	symbol		a_{H0}	b_{H0}	c_{H0}	-	-	
2		value	*M.C.M.M.P.*	-1642.8038	184.9798	89.5700	-	-	11.55749
3			*M.S.V.A.A.*	-1583.5742	176.4054	89.7636	-	-	10.69400
4	Head (36)	symbol		A_0	A_1	A_2	-	-	-
5		value	*M.C.M.M.P.*	0.00004260	0.12757229	-1642.8038	-	-	11.55749
6			*M.S.V.A.A.*	0.00004269	0.12165888	-1583.5742	-	-	10.69400
7	Yield (6)	symbol		$a_{\eta0}$	$b_{\eta0}$	$c_{\eta0}$	-	-	-
8		value	*M.C.M.M.P.*	-45.106036	11.444735	0.051541	-	-	0.19694
9			*M.S.V.A.A.*	-43.914018	11.174156	0.065128	-	-	0.19230
10	Power (7)	symbol		a_{N0}	b_{N0}	c_{N0}	d_{N0}	e_{N0}	-
11		value	*M.C.M.M.P.*	2055.48508	260.06881	71.14959	-	-	57.86085
12			*M.S.V.A.A.*	332.00733	-36.93252	-20.18118	-0.2564697	-0.001576	18.69305

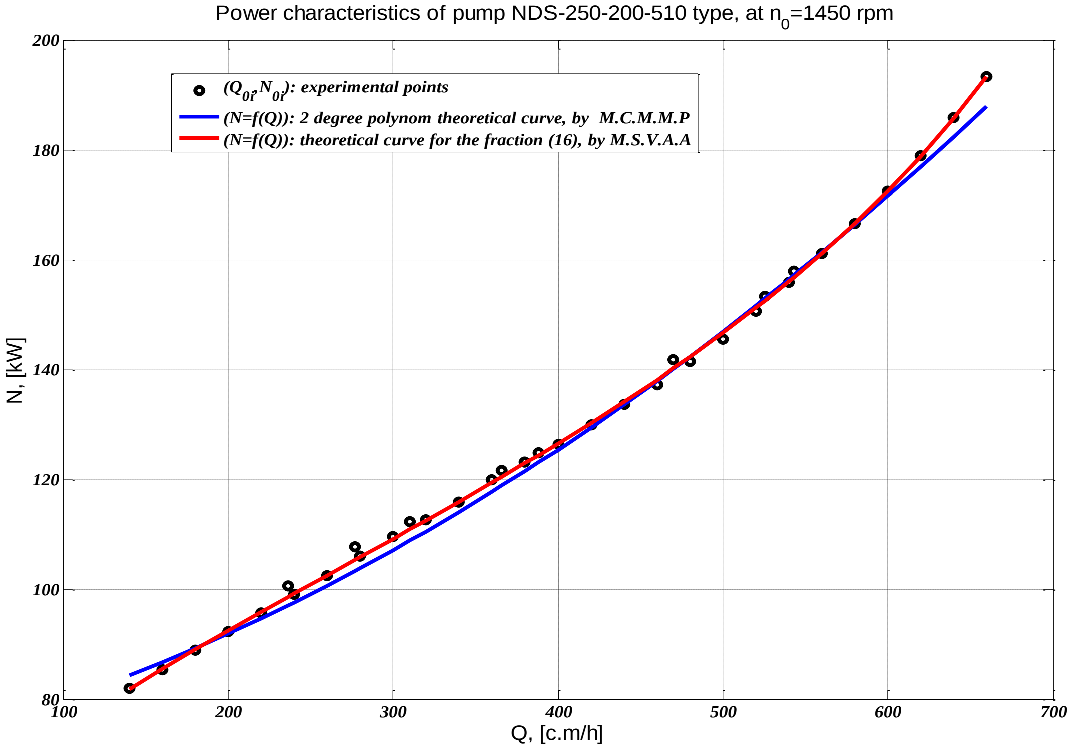

Figure 1 **Power characteristics of experimental and theoretical mission of pump type NDS-250-200-510, at speed n_0=1450 r.p.m**

CONCLUSIONS

Analytical expressions of the variable load speed, deduced by theoretical manner imply the least squares method, which means that the coefficients of a constant speed pump drives in full compliance with similar expressions cited in specialized works.

The analytical expression for the variable speed coefficient values can be entered directly to the constant speed that is not only determined by M.C.M.M.P. but also by other processing methods statistics: M.S.V.A.A., M. M.- M. etc.

Approximate analytical expression for the functional power at constant speed by rational with 5 coefficients proposed in this paper ($\sum|\delta_i| = 18.69305$) is more accurate than second - degree polynomial function, as it is cited in the specialized literature ($\sum|\delta_i| = 57.86085$).

Among the methods of experimental data, the best results were achieved by M.S.V.A.A.

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