Influence of the rotor speed of the water-ring pump on the vacuum transport unit operation

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Abstract. Vacuum transport units based on water-ring pumps are used for pumping aggressive liquids. The previously developed mathematical model of the liquid pumping process was used to assess the effect of changes in the rotor speed. The load characteristics of the ELRS-45 water-ring vacuum pump from ERSTVAK were used in the calculation. The numerical method was used to solve the system of differential equations. Increasing of the rotor speed leads to a decrease in the absolute pressure in the tank at the end of the first step. As a result, the volume of liquid pumped in one cycle increases significantly. The average performance of the unit is significantly increased. While energy efficiency decreases. The calculated parameters allow you to select the characteristics of automatic control of the system.

1. Introduction
Vacuum systems for the transport of liquids (VLTS) have a rather low energy efficiency compared to centrifugal or piston pumps [1, 2]. Therefore, they are used in special cases. For example, VLTS are used when it is necessary to ensure the pumping of liquid without its contact with various surfaces. The VLTS, which provides blood circulation during heart surgery, must create and maintain the necessary pressure drop [3]. VLTS are used to minimize damage to fish in commercial fishing [4]. VLTS are widely used in technological processes for the transportation of aggressive liquids [5]. Expensive high-vacuum pumps are generally not required for VLTS. Water-ring vacuum pumps (WVP) are used in VLTS due to many advantages [6]. WVP’s have only one moving part without mechanical contact of metal surfaces. Therefore, they are very reliable and durable. The WVP is designed for heavy duty operation. The pumped air may contain impurities in the form of droplets or solid particles.

Attempts to improve the design of WVP continue to improve performance and energy efficiency (see [7, 8] and the bibliography in them). Mathematical models of air pumping using WVP have been published in many articles. The theoretical analysis of vacuuming and its application in a viscous flow was considered in [9]. The pumping model of vacuum chambers with adsorbing walls was proposed in [10]. The method of modeling the load characteristics of WVP based on the test results was developed in [11]. The dynamics of air pumping from the working chamber using WVP was studied in [12]. The mathematical model of VLTS steps based on WVP was developed in [13]. The impact of leaks on VLTS performance has been investigated.

Modern units allow you to adjust the operation of the WVP by varying the rotor speed n [14]. An increase in the rotor speed leads to a change in the load characteristics of the WVP [15]. This should be taken into account when automating the control of such devices. The dynamics of air pumping using
WVP was studied in [16] at different values of n. However, this is only the first step of VLTS operation. The effect of n on the second step of VLTS operation was not analyzed. The purpose of this article is to study the effect of the WVP rotor speed on the performance and energy efficiency of VLTS.

2. Mathematical model

The installation scheme and mathematical models of the VLTS operation based on WVP are described in detail [13]. The elements of the model that take into account the rotor speed will be shown below.

2.1. The first step model

The first step of the system is to pump the air out of the tank using the WVP. The differential equation for pressure in the tank with the initial condition:

\[ V_0 \frac{dP}{dt} = G \cdot (k \cdot p_A - p(t) \cdot (1 + k)) \quad p(0) = p_A. \]  

(1)

where \( V_0 \) is the volume of the tank (m³), \( p \) is the pressure in the tank (Pa), \( p_A \) is the atmospheric pressure (Pa), \( t \) is the current time (s), \( G = f(p, n) \) is the empirical function that describes the effect of the rotor speed and pressure on the WVP performance (m³/s), \( k \) is the air leakage coefficient. Parameter \( k \) is equal to the ratio of the leakage flow rate to the current flow rate. It was considered constant in this paper, \( k = 0.1 \).

It is necessary to specify the dependence of the WVP performance on \( p \) and \( n \) in equation (1). The dependence of the spent power WVP on the same values will be required in the future: \( N = \phi(p, n) \). Let’s use the method of modeling the load characteristics of WVP [16]. They were calculated using the formulas (2) and (3):

\[ G \equiv f(p, n) = \begin{cases} 0, & p \leq p_V, \\ G_M(n) \cdot \frac{1 - \left( p_V / p \right)^\alpha}{1 - \left( p_V / p_A \right)^\alpha}, & p_V < p < p_1, \\ G_M(n), & p \geq p_1. \end{cases} \]  

(2)

\[ N = \phi(p, n) = \begin{cases} N_0(n), & p \leq p_V, \\ N_M(n) \cdot \left( 1 + a_1p + a_2p^2 + a_3p^3 \right), & p > p_V, \end{cases} \]  

(3)

where exponent \( \alpha = 1.0 \), \( p_V \) is the lowest pressure for this WVP series. Such a low pressure can only be achieved with a perfectly insulated tank (\( k=0 \)). The lowest pressure achievable by the system under consideration (\( k=0.1 \)) is 9.2 kPa.

The empirical constants \( a_1, a_2, a_3 \) and the functions \( G_M(n), N_0(n), N_M(n) \) were found by comparing the calculation results with the test data [14]. These functions depend linearly on the rotor speed:

\[ G_M = V_C \cdot n, \]  

(4)

where \( V_C \) is the volume of air pumped per revolution of the rotor at atmospheric pressure.

The ELRS-45 pump was selected as an example in the range of rotor speed variation from 472 to 740 rpm. ELRS-45 has the value \( V_C = 0.105 \text{ m}^3\text{/rev} \). In Figures 2 and 3, the dots represent the test results [14]. The error of direct measurements did not exceed one percent. The instability of the flow measurement results was noted at low pressures. The lines were obtained by calculating using formulas (2) and (3). Digital symbols: \( 1 - n = 472 \text{ rpm} \quad (G_M = 49.6 \text{ m}^3/\text{min}) \); \( 2 - n = 590 \text{ rpm} \quad (G_M = 62.0 \text{ m}^3/\text{min}) \); \( 3 - n = 740 \text{ rpm} \quad (G_M = 77.7 \text{ m}^3/\text{min}) \). The results of calculations are in good agreement with the experimental data in figures 2 and 3. The air flow rate (pumping speed) is given under suction conditions. Increasing of the rotation speed leads to an increase in both performance and power consumption of the WVP. The power-pressure relationship has a maximum at about 40 kPa: \( 1 - N_M = 57.94 \text{ kW} \); \( 2 - N_M = 78.66 \text{ kW} \); \( 3 - N_M = 106.43 \text{ kW} \).
2.2. The second step model

The working tank is filled with liquid during the second step under the influence of a pressure drop. This pressure drop will decrease over time according to the formula:

$$
\Delta p(t) = p_A - p(t) = p_A - p_0 \cdot V_0 / V(t),
$$

where $p_0$ is the absolute pressure in the working tank after the first step (Pa); $V(t)$ is the air volume at time $t$ (m$^3$).

The flow of the liquid will be non-stationary in accordance with the formula (5). The Bernoulli equation for a smooth non-stationary flow of the liquid is used as in [13]:

$$
L \frac{dW}{dt} = \frac{1}{\rho} \left( p_A - p_0 \frac{V_0}{V(t)} \right) - gH_0 - \frac{W^2}{2} \cdot (1 + \zeta), \quad W(0) = 0.
$$

where $W$ is the fluid velocity in the pipeline (m/s), $H_0$ is the height of liquid rise in the unit (m), $L$ is the length of pipeline (m), $\rho$ is the fluid density (kg/m$^3$), $g$ is gravitational acceleration (m/s$^2$), $\zeta$ is the generalized coefficient of hydraulic drag:

$$
\zeta = \lambda \cdot L/d + \Sigma \zeta_M,
$$

where $\lambda$ is the coefficient of friction losses; $d$ is the inner diameter of the pipe (m); $\zeta_M$ is the coefficient of local hydraulic losses. The method of design calculations was applied in this article. The value of $\lambda L/d$ increases by 10% instead of taking into account each local resistance.

The well-known Altschul formula was used to calculate the hydraulic losses along the pipeline:

$$
\lambda = 0.11 \cdot (\delta + 68/Re)^{0.25}, \quad Re = Wd/\nu, \quad \delta = \Delta/d,
$$

where $\Delta$ is the absolute roughness of the pipe wall; $\nu$ is the kinematic viscosity coefficient of the pumped liquid.

The movement of the liquid will continue until the pressure in the tank increases to the value $p_2$. The process of compressing the air in the tank can be considered isothermal. The volume of air in the tank will be the smallest at this point:

$$
p_2 = p_A - \rho \cdot g \cdot H_0, \quad V_{min} = p_A - p_0 \cdot V_0 / p_2.
$$

The volume of liquid that enters the working chamber in one cycle is equal to

$$
V_1 = V_0 - V_{min} = V_0 (1 - p_0 / p_2).
$$

Differential equation for the volume of air in the tank:
\[
\frac{dV}{dt} = -Q(t), \quad W(t) = \frac{Q(t)}{S}, \quad V(0) = V_0,
\]

(11)

where \(Q(t)\) is the volume flow rate of the liquid in the pipeline (m\(^3\)/s); \(S = \pi d^2/4\) is the cross-sectional area of the pipeline (m\(^2\)).

### 3. Results of the simulation

Mathematical modeling of the unit operation was performed for the ELRS-45 vacuum pump with the following parameter values: \(V_0 = 6\) m\(^3\), \(L = 100\) m, \(H_0 = 2\) m, \(d = 0.2\) m, \(\Delta = 0.2\) mm; \(p_v = 3.3\) kPa. Sulfuric acid (94%) was accepted as the pumped liquid at 20°C: \(v = 1.303 \times 10^{-5}\) m\(^3\)/s; \(\rho = 1781\) kg/m\(^3\).

#### 3.1. Results of the first step simulation

The Cauchy problem (1) was solved numerically at different values of the rotor speed. The calculation results are shown in figures 3 and 4. The designations in all subsequent figures are as follows: \(1 - n = 472\) rpm, \(2 - n = 530\) rpm, \(3 - n = 590\) rpm, \(3 - n = 660\) rpm.

![Figure 3](image1.png)

**Figure 3.** Pressure change in the process of pumping air at different values of \(n\).

![Figure 4](image2.png)

**Figure 4.** Mechanical work spent on pumping air at different values of \(n\).

It is known [13] that the pressure drops rapidly at the beginning of the first step, and then tends to the limit value. This limit pressure depends on the leakage coefficient and is independent of the rotor speed. The time to reach the limit pressure is less, the greater the value of \(n\). The results of the calculation according to the formula (12) of the mechanical work spent by ELRS-45 on pumping air out of the tank are shown in figure 4

\[
A_1(n) = \int_0^{T_1} q(t, p(t, n)) \, dt,
\]

(12)

where \(T_1\) is the duration of the first step.

Currently, the value of \(T_1\) is set in the VLTS control system prior to operation. The lower the \(T_1\), the less work will be spent. The duration of the first step is assumed to be \(T_1 = 10\) seconds in this article. The work of \(A_1\) increases with increasing rotor speed (figure 4). A higher value of \(n\) allows you to reduce the pressure in the chamber faster. Therefore, it is advisable to reduce the value of \(T_1\) with an increase in the rotation speed.
3.2. Results of the second step simulation

Cauchy’s task (6), (11) was also solved numerically. The calculation results for different values of \( n \) are shown in figures 5 and 6. The fluid flow rate \( Q \) increases rapidly at the beginning of the second step, and then gradually decreases. The \( Q(t) \) function has a maximum at \( t = 20.4 \) s: 1 – \( Q_M = 49.3 \text{ dm}^3/\text{s} \), 2 – \( Q_M = 52.9 \text{ dm}^3/\text{s} \), 3 – \( Q_M = 54.9 \text{ dm}^3/\text{s} \), 4 – \( Q_M = 56.6 \text{ dm}^3/\text{s} \). The initial pressure in the tank at the second step is lower, the greater the \( n \). Therefore, the flow rate of liquid in the pipeline increases.

![Figure 5. Pressure in the tank during the second step for various rotation speeds.](image)

![Figure 6. Instantaneous liquid flow at the second step for various rotation speeds.](image)

The second step of duration \( T_2 \) ends when the pressure in the tank reaches the value \( p_2 \). Useful work for the second step was calculated by the formula:

\[
A_2 = \frac{T_2}{T_1 + T_2} \int_0^T (p_A - p(t)) \cdot Q(t) \, dt .
\]

Then the efficiency coefficient is equal to \( \eta = 100 \cdot A_2 / A_1 \). Average performance per cycle \( Q_C = V_1/T_2 \), \( T_2 = T_1 + T_3 \). The energy intensity of the process (the ratio of the work spent to the volume of the pumped liquid) \( E = A_1 / V_1 \). The values of the parameters calculated for different values of \( n \) are listed in table 1.

| \( n \) (rpm) | \( p_1 \) (kPa) | \( V_1 \) (m³) | \( A_1 \) (kJ) | \( T_2 \) (s) | \( Q_C \) (dm³/s⁻¹) | \( \eta \) (%) | \( E \) (kJ/m³) |
|--------------|----------------|---------------|---------------|--------------|----------------|-------------|-------------|
| 472          | 29.4           | 3.34          | 472.0         | 91.9         | 32.8           | 41.4        | 141.1       |
| 530          | 25.3           | 3.71          | 576.3         | 93.6         | 35.8           | 39.9        | 155.1       |
| 590          | 23.0           | 3.92          | 691.2         | 94.2         | 37.6           | 36.4        | 176.2       |
| 660          | 20.8           | 4.11          | 790.8         | 94.6         | 39.3           | 34.4        | 192.2       |
| 740          | 18.9           | 4.29          | 985.4         | 94.8         | 40.9           | 29.6        | 229.8       |

4. Conclusion

Increasing the ELRS-45 rotor speed from 472 to 740 rpm led to a decrease in the absolute pressure in the tank at the end of the first step from 29.4 to 18.9 kPa. As a result, the volume of liquid pumped in one cycle increased from 3.34 to 4.29 m³. Therefore, the average performance increased from 32.8 to 40.9 dm³/s. The unit’s efficiency decreased from 41.4% to 29.6%. The energy intensity of the process has increased from 141.1 to 229.8 kJ/m³. The calculated parameters allow you to select the characteristics of automatic control of the unit. The rotor speed should be increased to the highest
possible value to increase the performance of the WVP. Increasing the energy efficiency of the WVP requires reducing the rotor speed. At the same time, the possibility of regulating the duration of the first step of WVP operation remains.

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