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Development of calculation method of main parameters of vacuum liquid transportation system

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Abstract. The design of a vacuum pumping system based on the principle of the displacement membrane was proposed. This principle does not imply contact of the working metal surfaces with the transported liquid. This article presents a calculation method of the main parameters of the proposed vacuum fluid transportation system. As a result of the calculation, the values of the pumping speed, the dimensions of the displacement membrane, the required chamber height, the pressure drop in the chamber, required to ensure the deflection of the displacement membrane, were obtained. Based on the proposed method, a program for calculation the main parameters of a liquid transfer system based on the mathematical software MathCAD was developed.

1. Introduction

Systems for dosed transportation of liquids without allowing it to contact with various metallic surfaces of the system are required in certain areas of science and technology [1]. For example, to restore blood circulation in the damaged areas of the heart, in addition to medical treatment, reconstructive surgeries are performed [2]. If the disease is inoperable organ transplantation is performed. Thus, the creation of a system capable of creating and maintaining the required differential pressure to ensure blood circulation is a relevant problem. For determination of the required parameters of a vacuum system that provides specified characteristics, development of a calculation method is required [3, 4]. The developed method is considered in the context of the blood transportation process by heart.

2. Description of the system design for which the calculation method is developed

A schematic diagram of the proposed construction of a vacuum fluid transportation system is shown in figure 1. The principle of the system operation is the pumping of liquid by creating and maintaining a required pressure drop by a vacuum pump. The chamber is divided into two compartments: hydraulic and vacuum, using of an elastic membrane [5]. The upper hydraulic compartment of the chamber has two inputs for supply and outflow of liquid. The lower part of the chamber also has two inputs for connecting the vacuum pump and control valves. One input serves for pumping the chamber down, the other one for gas injection. After starting the vacuum pump and opening the valves in the inlet *VE2*, *VE4*, the chamber is pumped down and the elastic membrane is bent due to the pressure difference between vacuum and hydraulic compartments. At the same time, the control hydraulic valve *VE5* is opened in the upper part of the chamber, the liquid enters the chamber under the effect of pressure difference [6]. Valves *VE*, *VE3*, *VE6* are closed at this time. After closing the valves *VE2*, *VE4* and the valve *VE5*, the outlet valves *VE1*, *VE3* are opened and the gas from the pump discharge of the vacuum pump enters the chamber and, equalizing the pressure, restores the elastic membrane element into its undeformed shape that simultaneously pushes the liquid located in the upper part of the chamber. At the same time, the second hydraulic valve *VE6* is opened and the liquid is ejected from the chamber. Valves *VE2, VE4, VE5* are closed at the same time. Then the cycle repeats. The pressure in the upper and lower parts of the chamber is controlled by pressure sensors throughout the process.

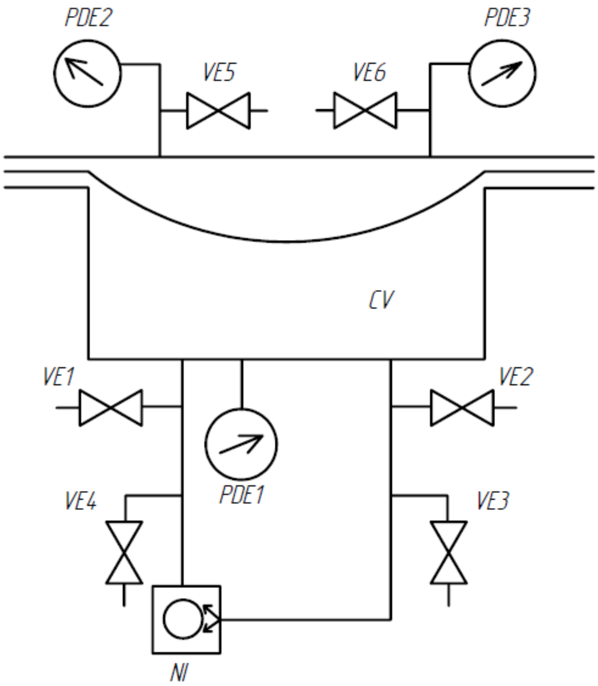

Figure 1. A schematic diagram of a vacuum fluid transportation system, where
CV – vacuum chamber;
NI – mechanical vacuum pump;
PDE1,2,3 – differential pressure sensors;
VE1-6 – solenoid valves.

3. To determine the main parameters of the vacuum system, the following calculation algorithm was proposed

The main parameters of the developed system can be divided into performance characteristics and control parameters [7]. The control parameters include such geometric parameters of the system as:

D_{in} – internal diameter;
t_{membr} – membrane thickness;
Hydraulic compartment parameters such as:
V_{disp} – liquid volume per stroke;
Membrane mechanical properties:
E - Young's modulus of the membrane material;
μ - Poisson ratio;
σ_u – ultimate tensile strength.
The main performance characteristics are:
S_n – pumping speed;
Δp – vacuum compartment pressure difference.

The design process starts with setting the value of D_{in} based on the system's initial conditions and constraints. Finite element is conducted in order to determine the required pressure difference value whereby the displaced volume created due to membrane deflection is equal to the required volume per stroke. After that the chamber height is determined based on the vertical deflection of the membrane's centre when the required pressure difference acts upon it. The relationship between the displaced volume and the pressure difference is presented in figure 2.

It is assumed that the resistance influence of all quick coupling elements of the system reduces the pumping speed by no more than 10 % [8].

The flowchart of the algorithm for calculating the main system’s parameters is shown in figure 3.

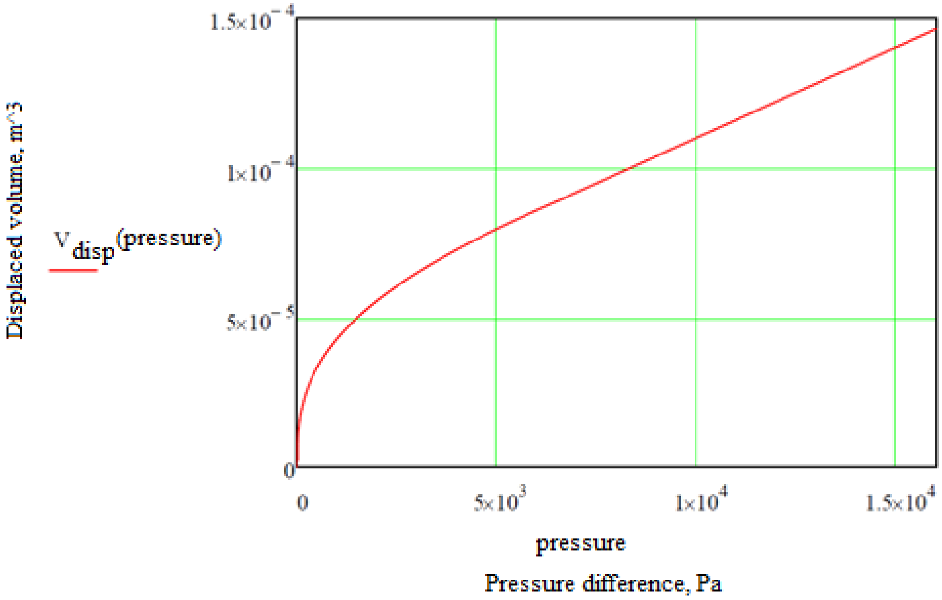

Figure 2. The relationship between the displaced volume and the pressure difference.

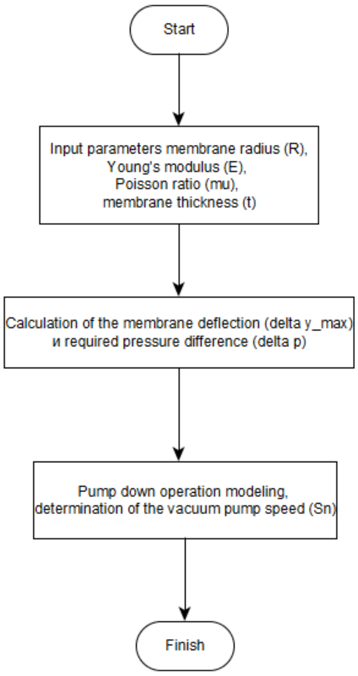

Figure 3. Flowchart of the algorithms of vacuum liquid transportation system main parameters calculation.

The chamber's volume changes caused by deflection of the membrane during pump down necessary to take into account for the pumping speed determination. The problem is solved by a numerical analysis. The whole time interval of modelling is divided into sufficiently small segments, during which it is assumed that $p = const$.

The following iterative algorithm is used:

1. Determination of the gas volume pumped down during a small time interval;
2. Determination of the pressure value at next iteration using equation (1)

$$p_{i-1} \times V_{i-1} = p_i \times (V_{i-1} + \Delta V) \quad (1)$$

3. Determination of the displaced volume caused by pressure difference $p_{hydr} - p_i$;
4. Calculation of the vacuum chamber's volume with the displaced volume taking into account

$$V_i = V_{i-1} - V_{disp} \quad (2)$$

5. Go to the next step.

The relationship between the displaced volume, the pressure difference during the stroke time (0.4 s) and the pumping speed are determined. Using this pumping model, it is possible to determine the required value of the pumping speed S_n.

The application of the proposed calculation method of main parameters of vacuum liquid transportation system based on the example of the heart, yielded the values required vacuum pumping speed: $S_n = 0{,}744$ L / min and pressure difference $\Delta p = 3.659 * 10^3$ *Pa*.

The pump down chart for two strokes (1 cycle) is shown in figure 4.

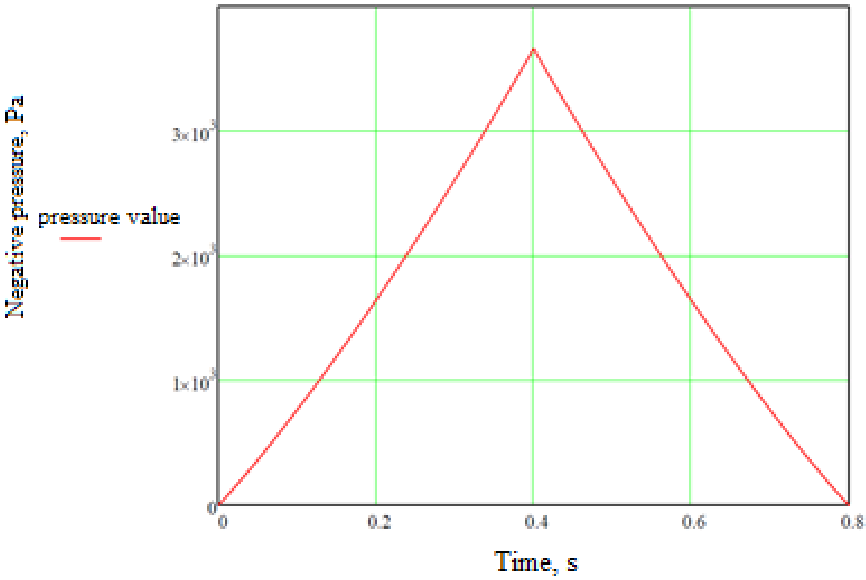

Figure 4. The pump down chart for two strokes.

4. Conclusion

The proposed calculation method allows to determine the main parameters of the vacuum system for obtaining required liquid flow rate. The future work will be devoted to the designing and manufacturing an experimental facility for the verification of the proposed calculation method.

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