The application of the elastic tube with the specific cross section form in the linear peristaltic pump

Alexander Grishin[*]

Moscow Polytechnic University, B. Semenovskaya str. 38, 107023 Moscow, Russia

Abstract. The article presents a study of the tube form influence on performance of the peristaltic pump with the linearly placed tube and several pushers squeezing it in the transverse direction. The coupled numerical simulation of fluid flow and solid domain deformation was carried out using the software, based on the finite volume method. The cross sections with surface protrusions of two different types are considered for numerical simulation. The simulation results have shown that protrusions without a smooth transition at the tube walls reduce the compression ratio of the tube and therefore yield the flow rate reduce. Protrusions with s smooth transition at the tube walls on the contrary increase the flow rate in a high pressure range. Higher flow rate and pressure values achieved in the case of surface protrusions placed in the first compression region of the tube only. Comparison of pump characteristic curves shows that the use of tube surface protrusions can significantly increase the energy efficiency of the pump.

1 Introduction

The peristaltic pump is the pump which operates on the basis of the positive-displacement principle. It consists of an elastic operating element and several (or only one) squeezing elements. The fluid pumping occurs due to squeezing elements moving. The fluid displacing takes place when the elastic operating element is squeezed. On the other hand the fluid suction takes place when the elastic operating element returning to its initial form. A hose, a tube or membranes [1] can be used as the elastic operating elements in the peristaltic pump constructions. Rollers, sliding shoes, pushers, piezoelectric crystals can be used as the squeezing elements.

Compared to other pump types, peristaltic pumps are easy to maintain, able to handle slurries and provide high flow rate accuracy. Due to its advantages the peristaltic pumps are used in a wide variety of industrial applications. It is used for food transporting and dosing of spices in the food industry, for pumping acids and other aggressive fluids in the chemical industry. Peristaltic pump systems are used for blood transfusion, transport and purification of biological fluids, and for dosing drugs in medicine. In the digital textile printing industry a pressurized peristaltic pump system is used for re-circulation of ink in the inkjet printers.

---

[*] Corresponding author: foxmccloud@rambler.ru

While the industry uses large-sized peristaltic pumps designed for pressures up to 1.6 MPa and flow rates up to 80 cubic meters per hour, in medicine and laboratory research, peristaltic micro-pumps are used with flow rates less than 2000 ml per min. Almost all large-sized peristaltic pumps are designed with the U-shaped tube placing [2]. Rollers or sliding shoes compress the tube by moving along its surface. Peristaltic micropumps, on the contrary, may be designed with the linearly placed tube and its compression is carried out by pushers that move in the transverse direction. A pump with this design is commonly referred to as a linear peristaltic pump. The linear peristaltic pump provides less efficiency compared to the peristaltic pump with the U-shaped tube placing but have its own advantages. Application of pushers as the squeezing elements provides no friction to the tube surface and therefore pump's tube wears off slower. Dreckmann and al. studied proteins degradation depending on the dozing system type and by using the developed quantitative liposomal shear stress model established that shear rate level in the linear peristaltic micropump is significantly less than in the piston micropump and the radial peristaltic micropump [3].

The full elastic operating element's compression is not always possible in the peristaltic pump. Therefore the shape of the flow path has strong influence on pump performance. Yang and al. used the diffusor channel form to reduce the pressure loss between pump's membranes [4]. Cheng and al. used only one membrane and different sized inlet and outlet [5]. Shkolnikov and al. used special squeezing actuator that operates like upstream and downstream valves [6]. Porjadkov invented the tube with two lengthwise folds to avoid significant deformation and thereby extend the device lifetime [7]. Tarasov invented the hose with a wedge-shaped thickening to decrease fatigue stress in deformed walls of the hose [8]. Thus, the purpose of this article is to study the influence of tube configuration on the peristaltic pump performance.

2 Research methods

The fluid flow in the peristaltic pump is strongly coupled with the solid domain. Numerical experiments require modelling both fluid flow and tube deformation. The simulation of this fluid-structure interaction problem was performed via software, in which the numerical solution of differential equations is implemented by the finite volume method. The problem is symmetric about both the vertical and horizontal planes; therefore it is possible to model 1/4 of the geometry for both solid and fluid domains. The 3D-model of elastic tube and flow path is shown in fig. 1.
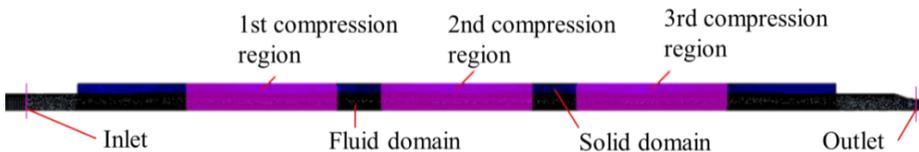

Fig. 1. The peristaltic pump model used for numerical simulation

The polyhedral mesh was generated to prepare the model. The inner diameter of the tube is 3 mm and the outer diameter of the tube is 4.8 mm. The length of each compression regions is 14 mm; the distance between the compression regions is 4 mm. The load deforming the tube was set as the force distributed over the tube surface in the compression regions. The surface of the tube was split into several boundaries, and at each boundary the force was set as a function of time (fig. 2).
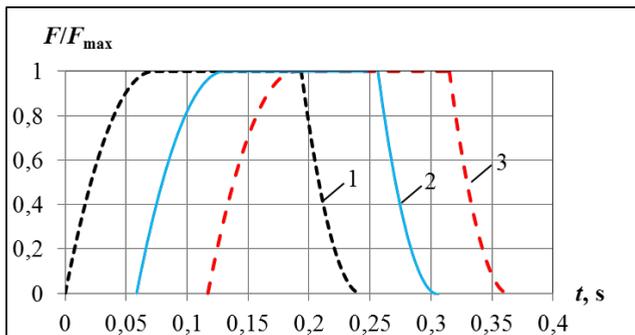
Fig. 2. The force applied to the corresponding compression regions

The force change is set so that the first squeezing element keeps the tube compressed during the actuation of the second squeezing element, and the tube is compressed by the first two squeezing elements during the actuation of the third squeezing element. It should be noted that due to software limitations, the volume of each cell of the generated must be greater than zero. Thus, the numerical simulation is possible to perform only for incomplete compression of the tube. More specifically, during compression the cross section area of the tube decreases on 65 %. Actually there is a point to operate the peristaltic pump with incomplete tube compression. In fact a much greater value of the force must be applied to achieve the complete tube compression. The simulation of only compression without fluid-structure interaction shows that for complete compression the applied force value should be 233 % greater. It is shown on fig. 3, where A is the cross section area of compressed tube with the applied force F, A_{max} is the initial cross section area of the tube and F_0 is the force value, required for the full compression.
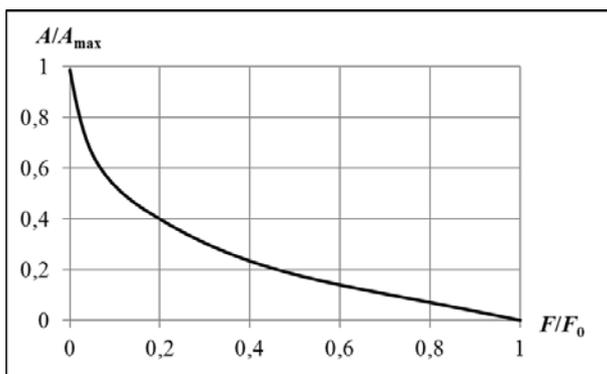
Fig. 3. The dependence of tube cross section area from the value of the applied force

Let's use the tube that has protrusions on its inner surface to increase the compression ratio of the tube without increasing the value of the compressive force. The used cross section forms are shown in fig. 4. One of the considered section forms has the simple surface protrusions with a rounding at the end (fig. 4b). Another form is characterized by a more smooth transition at the tube walls (fig. 4c), which is expected to reduce stress in this area. The tube without protrusions (fig. 4a) is also considered to compare the simulation results.
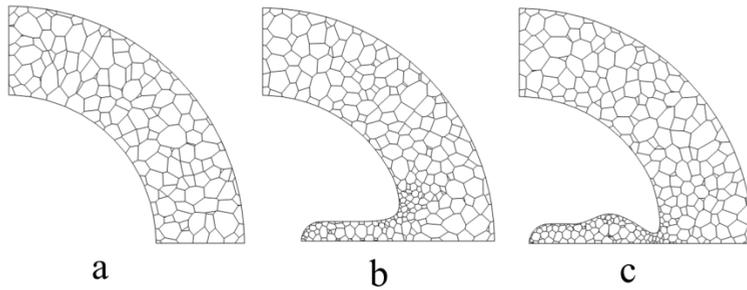
Fig. 4. The cross sections forms used for numerical simulation

Medical oil with a density of 855 kg/m^3 and a viscosity of 0.088 Pa·s was taken as the pumped liquid. In the simulation, it was assumed that the effect of fluid pressure on tube deformation can be neglected.

3 Results and discussion

The compressed tube shape and mean stress are shown in fig. 5. The maximum compressive stress achieved for the protrusions shape shown in fig. 5b. Due to this additional compressive stress, the compression ratio of the tube is slightly less than for the tube without protrusions shown in fig. 5a. The protrusions with a smooth transition at the tube walls provide much lower mean stress values (fig. 5c).
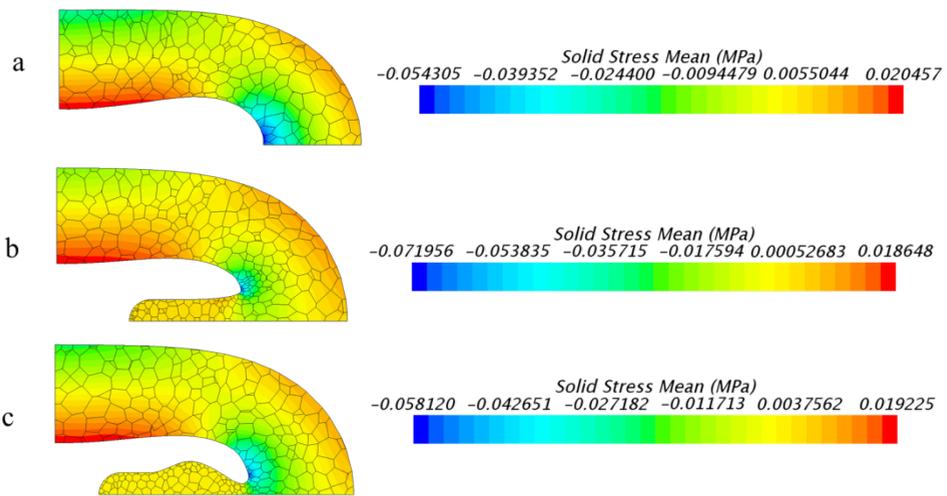

**Fig. 5.** The mean solid stress in the compressed tube region

The fluid flow was calculated both for the case when there are protrusions along the entire length of the pump tube, and for the case when there are protrusions only in the first compression region. The calculated fluid velocity changes over time at the outlet are shown in fig. 6 and fig. 7 while the pump characteristic curves are shown in fig. 8.
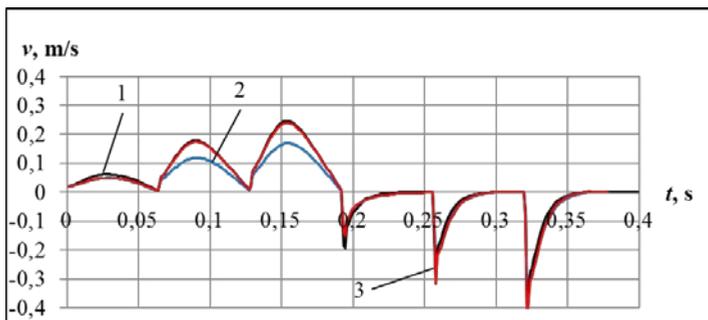
Fig. 6. The comparison of the fluid speed change over time at the outlet: 1 – tube without protrusions; 2 – simple protrusions without a smooth transition at the tube walls are along the entire length of the tube; 3 – simple protrusions without a smooth transition at the tube walls are in the first compression region only
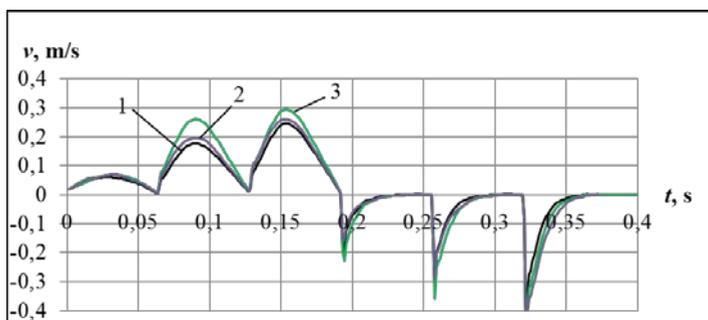
Fig. 7. The comparison of the fluid speed change over time at the outlet: 1 – tube without protrusions; 2 – protrusions with a smooth transition at the tube walls are along the entire length of the tube; 3 – protrusions with a smooth transition at the tube walls are in the first compression region only
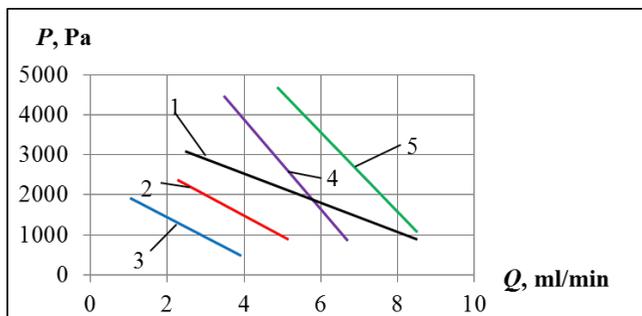
Fig. 8. Pump characteristic curve: 1 – tube without protrusions; 2 – protrusions without a smooth transition at the tube walls are along the entire length of the tube; 3 – protrusions without a smooth transition at the tube walls are in the first compression region only; 4 – protrusions with a smooth transition at the tube walls are along the entire length of the tube; 5 – protrusions with a smooth transition at the tube walls are in the first compression region only

The use of protrusions with a rounding at the end along the entire tube results in a reduction of the fluid volume displacing during the tube compression by the squeeze elements. This can be explained by the fact that the surface protrusions create additional pressure losses. The flow rate is significantly higher if the protrusions are placed only in the first compression region but still lower compared to the tube without protrusions due to lesser compression ratio of the tube.

The cross section form with smooth transition at the tube walls provides higher compression ratio of the tube, therefore the flow rate in this case is higher. Similar to previous case placing the protrusions in the first compression region only provides a higher flow rate and pressure. Flow rate for the protrusions with smooth transition at the tube walls is higher than a flow rate for tube without protrusion in the high pressure range of the pump characteristic curve. Assuming that the energy consumption on the tube compression is same for all considered cross section forms, the application of protrusions similar to shown in fig. 4c in the first compression region increases the energy efficiency of the linear peristaltic twice from its original value.

4 Conclusions

Thus, it can be concluded that for the pump operating with incomplete compression of the tube, its energy efficiency can be significantly increased by using an elastic tube, on the inner surface of which there are protrusions of a special form. According to the performed numerical calculations, the effect of energy efficiency increasing is achieved if the protrusions have a smooth transition at the tube walls. The effect of energy efficiency increasing is greater if the protrusions are only in the first squeezing element's compression region of the tube.

References

1. M. Du, K. Ye, K. Wu, Z. Zhou, A Peristaltic Micro Pump Driven by a Rotating Motor with Magnetically Attracted Steel Balls, Sensors, **No. 9**, pp. 2611-2620 (2009)
2. T. Loudin, *Peristaltic Pump Evolution*, Power Engineering, v. **115(1),** pp. 58-60 (2011)
3. T. Dreckmann, J. Boeuf, I. Ludwig, J. Lümkemanna, J. Huwylerc *Low volume aseptic filling: Impact of pump systems on shear stress*, European Journal of Pharmaceutics and Biopharmaceutics, **No. 147**. pp. 10-18 (2019)
4. H.Yang, T.-H. Tsai, C.-C. Hu, *Portable Valve-less Peristaltic Micropump Design and Fabrication*, 2008 Dans Symposium on Design, Test, Integration and Packaging of Mems/Moems - Dtip, Nice, France, pp. 273-278 (2008)
5. C.-H. Cheng, C.-K. Chen, *Characteristic Studies of the Piezoelectrically Actuated Valveless Micropump*, Proceedings of the world congress on engineering 2013 **Vol. 3**, pp. 1785-1790 (2013)
6. V. Shkolnikov, J. Ramunas, J. Santiago, *A self-priming, roller-free, miniature, peristaltic pump operable with a single, reciprocating actuator*, Sensors and Actuators A: Physical, **No. 160**, pp. 141-146 (2010)
7. L.F. Porjadkov, Working tube for peristaltic pump (Patent № 2309294 RU, MPK F 04 B 43/12. req. Porjadkov L.F. 29/05/2006; pub. 27.10.2007. Bul. №30)
8. J.D. Tarasov, Peristaltic pump (Patent № 2290536 RU, MPK F 04 B 43/12. req. Saint Petersburg Mining University 04/10/2005; pub. 27.12.2006. Bul. №36)