

A numerical investigation of the flow of nanofluids through a micro Tesla valve*

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Abstract: In this study, Al₂O₃-water nanofluids flowing through a micro-scale T45-R type Tesla valve was investigated numerically. Both forward and reverse flows were investigated based on a verified numerical model. The effects of nanofluids flow rate, temperature, and nanoparticle volume fraction on fluid separation in the bifurcated section and the pressure drop characteristics were analyzed. It was found that most of the nanofluids flow into the straight channel of the bifurcated section when flowing forward, and into the arc channel when flowing reversely. The percentage of the main flow increases with flow rate, temperature, and nanoparticle volume fraction. Additionally, the jet flow from the arc channel leads to a larger pressure drop than forward flow. Finally, the diodicity was found most affected by flow rate, and a correlation used to predict the change in diodicity with the flow rate was proposed.

Key words: Nanofluids; Tesla valve; Pressure drop; Nanoparticles; Computational fluid dynamics (CFD)
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1 Introduction

Valves are widely used in numerous engineering applications to control the flow and pressure of fluids. There have been many useful and interesting studies on specific engineering applications of valves. These studies adopted numerical (Amirante et al., 2016) or experimental methods (Erdödi and Hős, 2017) to investigate many aspects of valves, including the valve core (Jin et al., 2018a), the valve seat (Zhang et al., 2018b), and control valves (Qian et al., 2016;


Lisowski et al., 2018). The medium flowing through the valves in these studies included incompressible liquids and compressible gases (Qian et al., 2017). And the equipment which would affect the function of valves has also been investigated (Chao et al., 2018; Zhang et al., 2018a). The conclusions obtained from the investigations are of significance to engineering.

Unlike traditional valves, the passive Tesla valve invented by Nikola Tesla in 1919 does not contain a valve core. Because of its unique construction, the pressure drop of a fluid flowing forward through a Tesla valve is less than that of a fluid flowing reversely. Thus, the Tesla valve can be used to control the flow direction of a fluid, without any moving parts. This gives the Tesla valve advantages in microfluidic applications and in the design of fire-safety equipment.

Many scholars have contributed to research on the Tesla valve. For instance, de Vries et al. (2017)

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designed a new Tesla valve for promoting circulation in a pulsating heat pipe, and found that the flow and thermal performance were improved due to the addition of the valve. Thompson et al. (2011) integrated a Tesla valve into a flat-plate oscillating heat pipe to increase overall thermal performance. Compared with a flat-plate oscillating heat pipe without a Tesla valve, they found that the use of a Tesla valve could promote circulation in the desired direction, and the promotion increased with heat input. Thompson et al. (2014) investigated a multistage Tesla valve numerically, and studied the effects of the number of stages and valve-to-valve distance on diodicity. Anagnostopoulos and Mathioulakis (2005) conducted a numerical investigation to optimize the design of a Tesla valve for micropumps. They obtained an optimized Tesla valve with 50% higher diodicity than that of a standard design. Wang et al. (2014) optimized the geometric parameters of a new Tesla-type micromixer by conducting a numerical simulation and obtained a series of geometric parameters which improved mixing efficiency. Paudel et al. (2014) studied numerically the effects of the flow medium in a Tesla valve on the thermal performance and diodicity.

Choi (2009) proposed the idea of dispersing nanoparticles of metal, metal oxide or nonmetallic oxide into traditional heat transfer media, such as water and glycol, to obtain stable suspensions. Due to their better thermal conductivity than fluids, the added nanoparticles enhance the heat transfer performance of traditional heat transfer media. With excellent heat transfer performance, the nanofluids have an advantage in application to microchannel systems. There have been many studies in this field. Mirzaei and Dehghan (2013) studied numerically the flow and heat transfer characteristics of Al_2O_3 -water nanofluids flowing through a microchannel, and found that nanofluids can enhance heat transfer and augment flow resistance. Anbumeenakshi and Thansekhar (2017) conducted experiments in a microchannel heat sink to investigate the combined effects of an asymmetric heating condition and the concentration of Al_2O_3 -water nanofluids on cooling performance. The optimum heating position and nanofluids concentration were obtained for the best heat sink cooling performance. Balasubramanian et al. (2018) conducted experiments in a 31-parallel "U"-shaped microchannel heat sink to investigate the

transient flow boiling performance and critical heat flux estimation of Al_2O_3 -water nanofluids. They found that the nanofluids enhanced the critical heat fluxes by up to about 15% compared with water, and the response time to reach steady state was reduced. Jung et al. (2009) investigated experimentally the heat transfer coefficient and flow resistance coefficient of Al_2O_3 -water nanofluids flowing through a microchannel with a rectangular cross section. Under a laminar flow condition, the heat transfer coefficient of nanofluids was 32% higher than that of deionized water, and without extra loss due to friction. Malvandi and Ganji (2015) and Malvandi et al. (2016) analyzed theoretically the effects of a series of nanofluids conditions on flow and heat transfer characteristics. Rostami and Abbassi (2016) investigated the heat transfer performance of Al_2O_3 -water nanofluids flowing through a wavy microchannel. Abdollahi et al. (2017) carried out a systematic study on the flow and heat transfer characteristics of several kinds of nanofluids, and found that under specific conditions, SiO_2 -water nanofluids had the best heat transfer performance. Gómez-Villarejo et al. (2018) prepared nanofluids by dispersing commercial Ag nanoparticles and synthesized Au nanoparticles in a base fluid composed of diphenyl oxide and biphenyl. Theoretical analysis and experiments were conducted to study the interactions between the metals and the molecules. The results showed that the addition of Ag nanoparticles to the base fluid improved thermal properties significantly. Mojarrad et al. (2013) conducted a numerical simulation to investigate the convective heat transfer of nanofluids, and developed a new model. They carried out the investigation with single-phase and two-phase models. The results showed that the single-phase dispersion model predicted the nanofluids convective heat transfer most accurately despite its simplicity, so their new model was based on this model. Buschmann (2017) investigated nanofluids heat transfer in a laminar pipe flow with twisted tape, in which the experimental data were ordered by three different scaling methods. He found that a description of laminar nanofluids pipe flow based on a combination of Reynolds and Prandtl numbers was sufficient. Yoo et al. (2018) reported that the transient hot-wire method was widely used to measure the conductivity of an object. They analyzed test cell size, the temperature coefficient of resistance,

and the sampling number in detail to improve the accuracy of the measurement.

There have been many studies of the use of nanofluids in valves. Wannapakhe et al. (2009) and Bhuwakietkumjohn and Parametthanuwat (2015) investigated the heat transfer performance of silver nanofluids in an oscillating heat pipe with check valves. Shedid (2015) investigated the reliability of the valve loss and torque coefficients in designing butterfly valves when the fluids were Al_2O_3 -water nanofluids. Using numerical simulation, he found that these two coefficients were unreliable in this particular case. Nasrin et al. (2012) conducted a transient numerical study to investigate the transport mechanism of forced convection in a valve in which the medium were CuO-water nanofluids. They found that over a long time period, the heat transfer rate reduced.

Thanks to previous investigations, the Tesla valve and nanofluids are well understood. However, the understanding of nanofluids flowing through a micro-scale Tesla valve is still lacking, so in this study we aimed to determine the flow characteristics of Al_2O_3 -water nanofluids flowing through a micro-scale T45-R type Tesla valve. The results may provide a useful reference for others interested in this field.

2 Numerical model

2.1 Geometric model

The valve used in this study was a micro-scale single T45-R type Tesla valve (Truong and Nguyen, 2003; Jin et al., 2018b). A 3D model and its geometric parameters are shown in Fig. 1. A T45-R type Tesla valve is made up of three parts: an entrance section, a bifurcated section, and an export section. The entrance section and the export section are interchanged when the flow direction changes. The bifurcated section consists of a straight channel and an arc channel. When a fluid enters a T45-R type Tesla valve from the channel which is collinear with the straight channel of the bifurcated section, we call it forward flow; when a fluid enters from the other end, we call it reverse flow. In this study, the cross section of the micro-scale T45-R type Tesla valve was a square with a side length of $100\ \mu\text{m}$. To eliminate the entrance effect, the lengths of entrance/export sections were $1200\ \mu\text{m}$,

which was 12 times the length of the equivalent diameter of the channel. For the arc channel, the inner side arc radius was $228\ \mu\text{m}$, the length of the straight section, tangent to the arc, was $235\ \mu\text{m}$, and the angle at the bifurcations was 45° .

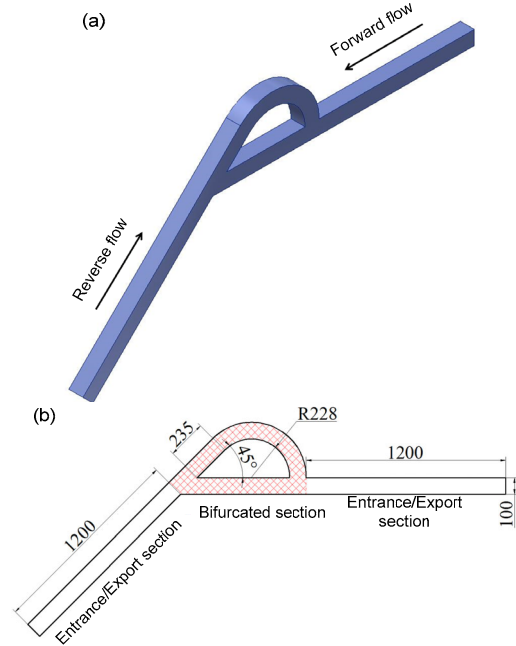


Fig. 1 Geometric model of a T45-R Tesla valve

(a) 3D model of a T45-R type Tesla valve; (b) Geometric parameters of the micro-scale T45-R type Tesla valve (unit: μm)

2.2 Mesh and boundary condition

The structure of the micro-scale T45-R type Tesla valve is simple, so a hexahedral mesh was used to discretize the geometric model. To eliminate the influence of mesh size on the accuracy of the numerical simulation, a mesh independence check was conducted. When the total numbers of mesh were 967353 and 1043610, the relative error of diodicity was 0.88%, which indicated that 967353 meshes were sufficient for accurate simulation.

The Al_2O_3 -water nanofluids were adopted as the medium flowing through the micro-scale T45-R type Tesla valve. The average diameter of the nanoparticle was $13\ \text{nm}$, and the density of Al_2O_3 was $3890\ \text{kg/m}^3$. Based on the method of computational fluid dynamics (CFD), numerical simulations were conducted to investigate the effects of the nanofluids flow rate, temperature, and nanoparticle volume fraction on the flow characteristics of Al_2O_3 -water nanofluids

flowing through a micro-scale T45-R type Tesla valve. In the numerical simulations, the 3D double precision solver was adopted. The mixture model was chosen as the multiphase model. To reflect the effects of nanoparticles on the physical properties of the nanofluids, the method of Syamlal et al. (1993) was selected to model the kinetic part of the granular viscosity of the particles, and that of Lun et al. (1984) was used to compute the solids bulk viscosity. The flow rate ranged from 1 mL/min to 10 mL/min, and the Reynolds number was less than 2000, so a laminar model was employed. The semi-implicit method for pressure-linked equations (SIMPLE) scheme was applied to couple pressure and velocity. In relation to spatial discretization, the least squares cell-based discrete method was chosen for the gradient, the PRESTO discrete method for pressure, the first-order upwind discrete method for the volume fraction, and the second-order upwind discrete method for the momentum. The inlet boundary condition was set as the velocity-inlet, and the inlet velocity depended on the nanofluids flow rate. The outlet boundary condition was set as pressure-out with a pressure of 0 Pa. The condition of a no-slip wall was applied to other walls.

2.3 Reliability verification

Compared with a macro-scale channel, whether the continuity hypothesis is set up needs to be verified when investigating the flow characteristics of nanofluids flowing through a micro channel with a method of CFD. Topuz et al. (2018) conducted experiments to investigate the nanofluids flowing through micro-tubes with different diameters. Al₂O₃-water nanofluids were employed as the fluid media. The experiment operating conditions are listed in Table 1.

Table 1 Experiment operating conditions

Experiment No.	Tube inner diameter (μm)	Volume fraction (%)	Fluid flow rate (mL/min)
1	400	1.0	35
2	750	0.7	50
3	1000	1.0	20

For verifying the reliability of the numerical model, we used the method mentioned above to simulate the experiments with the corresponding condi-

tions. Table 2 shows a comparison of the experimental and numerical results for the pressure drop. The maximum relative error was 9.12%, which is within the acceptable range for engineering applications, indicating that the numerical method was credible.

Table 2 Comparison of experimental and numerical results for pressure drop

No.	Experimental results (MPa)	Numerical results (MPa)	Relative error (%)
1	0.2070	0.2121	2.46
2	0.0160	0.0175	9.12
3	0.0030	0.0028	-6.67

3 Results and discussion

3.1 Effects of nanofluids flow rate

The Al₂O₃-water nanofluids flowing through a micro-scale T-45R type Tesla valve with different flow rates is analyzed in this section. The nanoparticle volume fraction was set as 0.7% and the temperature as 20 °C. The nanofluids flow rate ranged from 1 mL/min to 10 mL/min.

The velocity contours of the forward and reverse flows are shown in Fig. 2, in which the nanofluids flow rate of 3 mL/min is taken as an example. We found that the nanofluids separated at the bifurcation section for both flow directions. When flowing forward through the micro-scale T-45R type Tesla valve, the nanofluids flow mainly into the straight channel. In contrast, when the nanofluids flow reversely through the Tesla valve, most of them flow into the arc channel. The flow resistance increases when the flow direction changes dramatically, so the nanofluids would enter the channel where the flow direction changes more gently at the bifurcation section.

For both flow directions, the percentages of flow in the straight channel and arc channel of the bifurcated section are shown in Fig. 3. For the forward direction, the percentage of flow entering the straight channel increases with the flow rate. However, the percentage of flow entering the straight channel increases by only 0.90% when the nanofluids flow rate increases from 8 mL/min to 10 mL/min. That is to say, the percentage of flow entering the straight channel increases only slightly when the nanofluids flow rate is larger than 8 mL/min. For the reverse direction, the

percentage of flow entering the arc channel increases with the flow rate. The relative difference between the percentages of the flow entering the arc channel is only 0.84% when the nanofluids flow rates are 9 mL/min and 10 mL/min. In other words, in the range of the present investigation, the effect of flow rate on the nanofluids flow separation will be increasingly marginal when the flow rate is large enough.

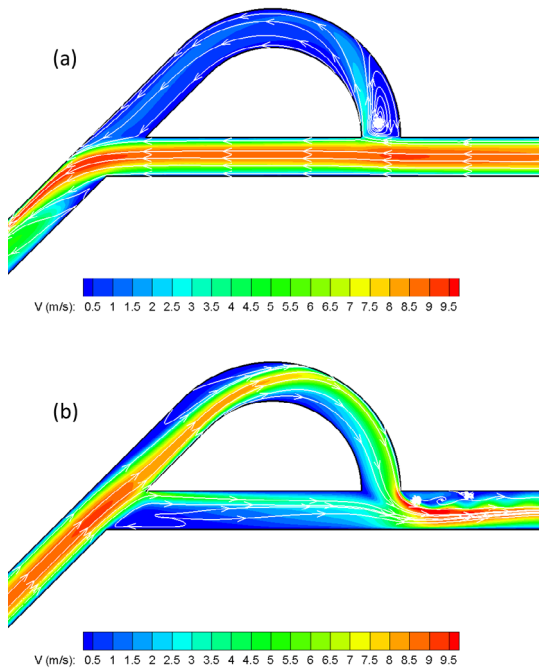
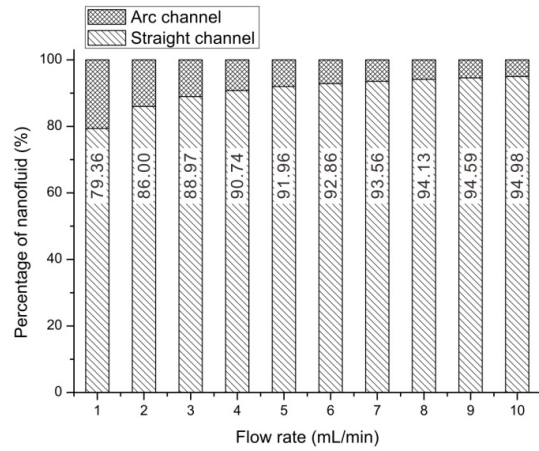


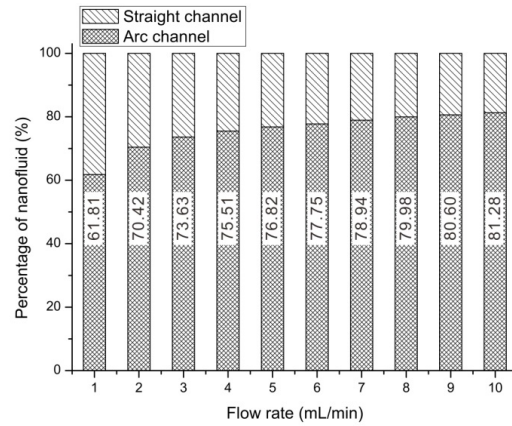
Fig. 2 Velocity contours with a flow rate of 3 mL/min (a) Forward flow; (b) Reverse flow

In this section, we investigate the pressure drop characteristics of the Al₂O₃-water nanofluids flowing through a micro-scale T-45R type Tesla valve in forward and reverse directions at different flow rates.

Fig. 4 shows the static pressure along the center line of the channel, where the forward and reverse flow with a flow rate of 3 mL/min is taken as an example. The position of the entrance is set as 0 μm, the x-axis is parallel to the straight channel of the bifurcated section, and the export direction is positive. For forward flow, the static pressure of the center line increases a little at the entrance of the bifurcated section, then decreases linearly in the bifurcated section. When the flow direction changes drastically, the static pressure of the center line decreases greatly when the nanofluids flow out of the bifurcated section. For



(a)



(b)

Fig. 3 Percentage of flow in the bifurcated section with different flow rates

(a) Forward flow; (b) Reverse flow

reverse flow, because a small amount of the nanofluids flow into the straight channel of the bifurcated section, there is a small static pressure difference between the entrance and the export of the bifurcated section. Due to the jet flow from the arc channel, the static pressure at the center line decreases dramatically, especially at the export of the bifurcated section. According to Fig. 4b, at a distance of 412 μm downstream of the bifurcated section, the static pressure decreases 31.5 kPa, and the pressure drop efficiency is 76.46 Pa/μm, which is 2.68 times the average pressure drop efficiency of the reverse flow in the micro-scale T-45R type Tesla valve. This indicates that for reverse flow, the jet flow from the arc channel has more of an impact on the pressure drop when compared with the forward flow.

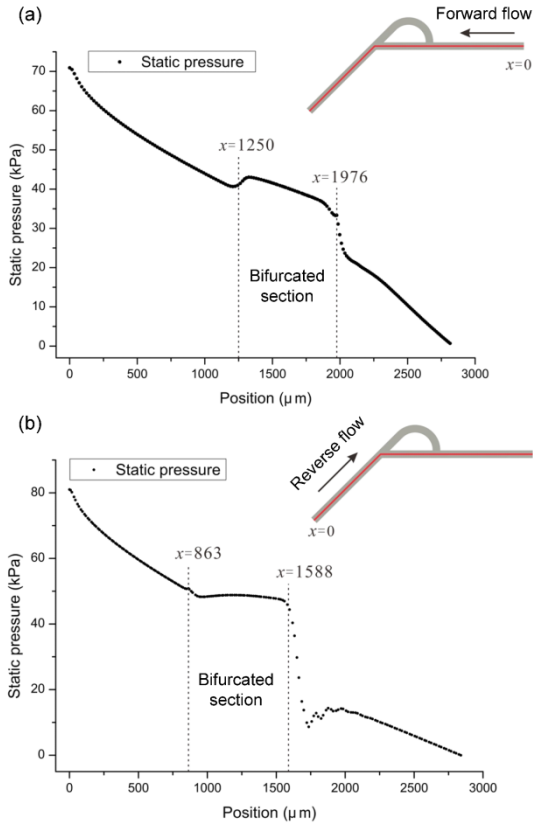


Fig. 4 Static pressure along the center line of the micro-scale T-45R type Tesla valve with a flow rate of 3 mL/min (a) Forward flow; (b) Reverse flow

Fig. 5 shows the pressure drop of forward and reverse flow with different flow rates. The forward pressure drop and the reverse pressure drop increase when the flow rate of the nanofluids increases. The reverse pressure drop increases more drastically than the forward pressure drop.

Fig. 6 shows the characteristics of diodicity, which represents the ratio of the reverse pressure drop to the forward pressure drop, and which can be derived by

$$Di = \frac{\Delta p_r}{\Delta p_f}, \quad (1)$$

where Di is the diodicity, Δp is the pressure drop, and the subscripts r and f represent the reverse flow and the forward flow, respectively. The reverse flow has a larger pressure drop than the forward flow, so the diodicity is always larger than 1. In fact, a larger diodicity means a bigger difference in pressure drop between the reverse flow and the forward flow, so that

the fluid flows through the Tesla valve with more difficulty. In other words, the Tesla valve is able to control the fluid flow direction more efficiently.

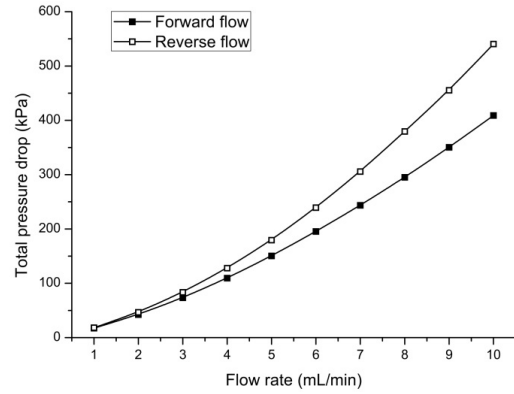


Fig. 5 Forward and reverse pressure drop with different flow rates

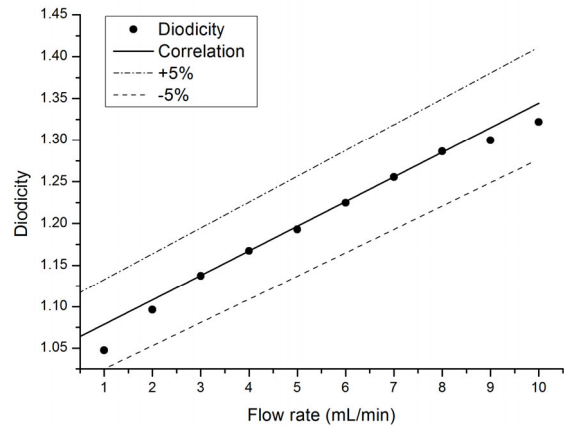


Fig. 6 Change in diodicity with flow rate

The diodicity increases with the flow rate, which indicates that with a higher flow rate, the micro-scale T45-R type Tesla valve has a better performance in controlling the flow direction of the nanofluids. In addition, a correlation is proposed to calculate the diodicity, which is expressed as follows:

$$Di = 0.0295F + 1.0493, \quad (2)$$

where F is the flow rate. The relative error between the simulated value and the correlation is within $\pm 5\%$.

3.2 Effects of nanofluids temperature

The effects of temperature on the Al_2O_3 -water nanofluids flowing through a micro-scale T-45R type Tesla valve were analyzed. In this section, the

nanoparticle volume fraction is 0.7% and the flow rate is 3 mL/min. The temperature ranges from 15 °C to 50 °C.

As mentioned above, when flowing forward through the micro-scale T-45R type Tesla valve, most of the nanofluids flow into the straight channel, and when flowing reversely, most of the nanofluids flow into the arc channel. Fig. 7 shows the percentages of the main flow in the forward and reverse flow directions. The percentage of flow entering the straight channel increases with temperature when the nanofluids flow through the Tesla valve in the forward direction. The difference in the main flow percentages between 15 °C and 50 °C is 4.36%. It is noticeable that the increase in the main flow percentage becomes more gradual as the temperature

increases. In the reverse flow direction, the main flow percentage also increases with temperature, and the difference between the maximum value and the minimum value is 4.80%. Again, the increase becomes more gradual as the temperature increases.

Fig. 8a shows the pressure drop of forward flow and reverse flow at different temperatures. For both flow directions the pressure drop decreases as the temperature increases. The diodicity at different temperatures is shown in Fig. 8b. Diodicity increases with temperature and the increasing trend is more drastic at lower temperatures. In other words, the micro-scale T45-R type Tesla valve performs better in controlling the nanofluids flow direction at a higher temperature, but the effect of temperature diminishes as the temperature keeps increasing.

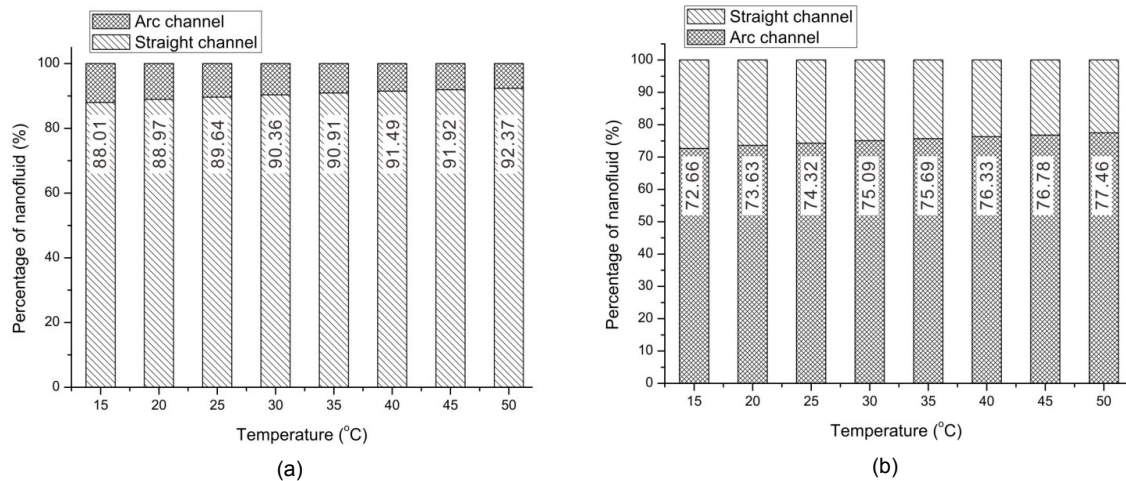


Fig. 7 Percentage of flow in the bifurcated section at different temperatures: (a) forward flow; (b) reverse flow

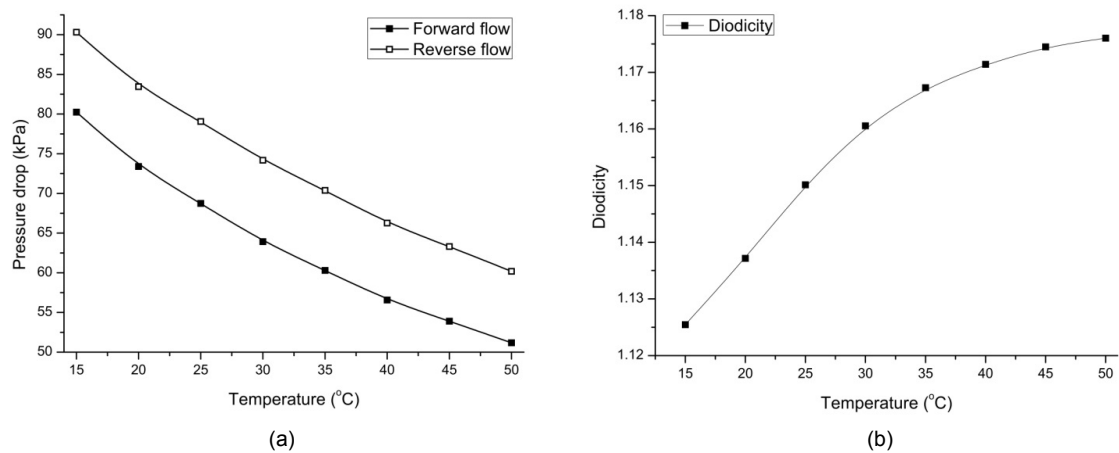


Fig. 8 Pressure drop characteristics at different temperatures: (a) forward flow and reverse flow pressure drop; (b) diodicity

3.3 Effects of nanoparticle volume fraction

In this section, the effects of Al_2O_3 nanoparticle volume fraction on the main flow percentages and pressure drop characteristics are investigated. The flow rate is 3 mL/min and the temperature is 20 °C. The nanoparticle volume fraction in this study ranged from 0 to 2%.

Fig. 9 shows the nanofluids flow percentages in the bifurcated section of forward flow and reverse flow with different nanoparticle volume fractions. The main flow percentage increases with the nanoparticle volume fraction, but the effect of nanoparticle volume fraction on the separation of nanofluids in the bifurcated section is not large. The differences between the maximum and minimum main flow percentages for the forward flow and the reverse flow

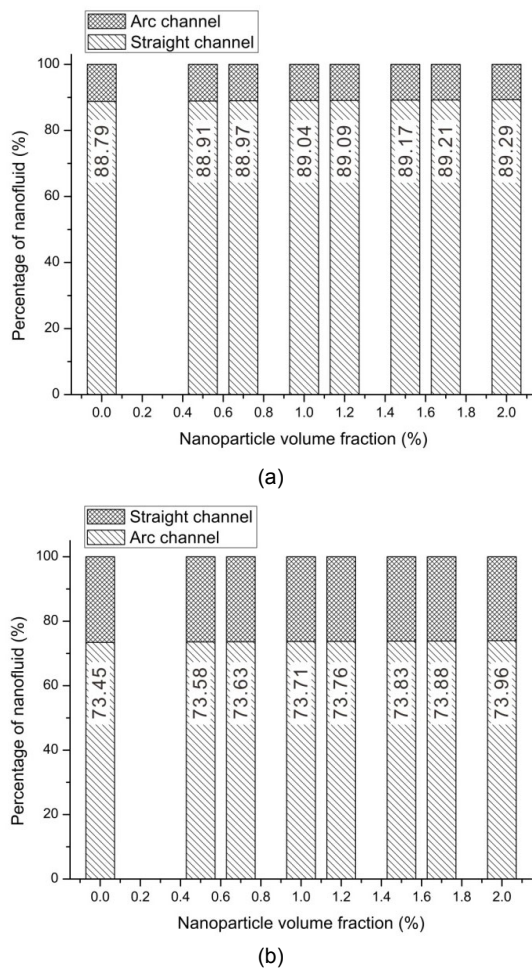


Fig. 9 Percentage of flow in the bifurcated section with different nanoparticle volume fractions (a) Forward flow; (b) Reverse flow

are 0.50% and 0.51%, respectively, which can be ignored.

Fig. 10 depicts the pressure drop of the forward flow and reverse flow with different nanoparticle volume fractions. For both flow directions, the pressure drop increases with the nanoparticle volume fraction, though the increase is minor. Furthermore, the forward flow pressure drop is more linear than that of the reverse flow.

Fig. 11 shows the diodicity with different nanoparticle volume fractions. Diodicity increases with increasing nanoparticle volume fraction, which indicates that the micro-scale T-45R type Tesla valve performs better in controlling nanofluids with a higher nanoparticle volume fraction. However, the increase rate in diodicity declines when the nanoparticle volume fraction is above 1.5%.

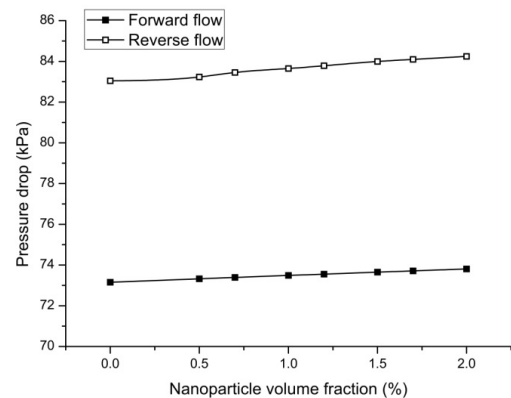


Fig. 10 Forward flow and reverse flow pressure drop with different nanoparticle volume fractions

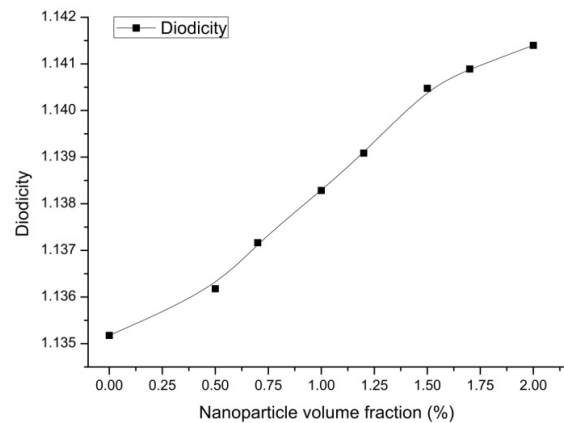


Fig. 11 Diodicity with different nanoparticle volume fractions

4 Conclusions

In this study, the flow of Al₂O₃-water nanofluids through a micro-scale T45-R type Tesla valve was investigated numerically. By investigating in detail the nanofluids flow percentages in the bifurcated section, the pressure drop of forward and reverse flows, and the diodicity, the effects of flow rate, temperature, and nanoparticle volume fraction on nanofluids separation in the bifurcated section and on pressure drop characteristics were determined. Some conclusions can be drawn as follows.

Analysis of the velocity contours showed that most of the nanofluids flow into the straight channel of the bifurcated section when flowing forward, and into the arc channel when flowing reversely. The percentage of the main flow increases with increasing flow rate, temperature, and nanoparticle volume fraction, despite its limited effect. The static pressure along the center line of the micro-scale T-45R type Tesla valve was investigated in detail. We found that when the nanofluids flow through the Tesla valve reversely, the jet flow from the arc channel influences the pressure drop significantly, leading to a larger pressure drop than forward flow. Diodicity was most affected by the flow rate. In the range of this study, the diodicity changed almost linearly with the flow rate. We proposed a correlation to predict the change in diodicity with the nanofluids flow rate, and the accuracy of the correlation was validated.

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中文概要

题目: 纳米流体在微尺度特斯拉阀中流动的数值研究

目的: 微通道以其效率高、体积小等特点在许多领域有着越来越广泛的应用。特斯拉阀是一种没有运动部件的止回阀, 在微流动控制领域有着明显的优势。大量研究表明, 将纳米流体运用到微尺度通道中可明显提高换热效率。本文将二者结合, 研究 Al_2O_3 -水纳米流体在微尺度特斯拉阀中的流动特性, 为微尺度特斯拉阀以及纳米流体的进一步研究提供参考。

创新点: 1. 将特斯拉阀应用于纳米流体的微流动控制中;
2. 研究不同的操作条件和不同的介质特性对纳米流体在微尺度特斯拉阀中流动特性的影响;
3. 研究纳米流体在微尺度特斯拉阀中不同流动方向的流体分布和压力情况, 并根据特斯拉阀的压降比(反向流动压降/正向流动压降)来分析特斯拉阀对微流动的控制效果。

方法: 1. 建立微尺度特斯拉阀的三维模型; 2. 通过有效性验证的数值方法, 在不同操作条件和不同流动介质特性的情况下, 模拟纳米流体在微尺度特斯拉阀中正反两个方向的流动; 3. 根据流体在流动过程中的分布以及压力的变化情况, 分析温度、流体流量和纳米颗粒体积分数对纳米流体在微尺度特斯拉阀中流动特性的影响。

结论: 1. 纳米流体在特斯拉阀中正向流动时, 大部分流体进入了分叉段中的直通道; 而反向流动时, 大部分流体进入了分叉段中的弧形通道, 并且随着流量、温度和纳米颗粒体积分数的增加, 主流量的百分比增加。2. 当纳米流体反向流动时, 在弧形通道出口处的射流对压降的影响非常明显, 这是导致反向流动压降大于正向流动的重要原因。3. 特斯拉阀的压降比受流量的影响最显著; 在本文的研究范围内, 压降比随着流量的增加而线性增加。

关键词: 纳米流体; 特斯拉阀; 纳米颗粒; 计算流体动力学