

Numerical Studies on the Influence of Surface Heating on the Flow Characteristics of a Conventional Tesla Valve

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Abstract

In this paper we study in detail the effects surface heating on the fluid flow characteristics in a conventional tesla valve. We simulate a two dimensional, laminar, incompressible flow through the tesla valve using OpenFOAM. We use buoyantPimpleFoam solver for obtaining the necessary results. The numerical study revealed that the surface heating on a vertically mounted tesla valve resulted in an increase in the diodicity of the valve. A peak in diodicity is observed at a Reynolds number of 30 and Richardson number of 0.8.

Key words: Tesla Valve, Diodicity, Richardson Number, Reynolds Number, Prandtl Number.

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INTRODUCTION

In valve-less reciprocating micro pumps, No-Moving-Part (NMP) valves are utilized to convert non-directional flow to directional flow. Micropumps in MEMS devices to move minimal quantities of fluid, cooling applications at the chip size, and pulsating heat pipes to improve heat transfer capability are some of the other applications. A Tesla valve is a typical NMP fixed-geometry passive check valve invented by Nikola Tesla. It permits fluid to flow in only one direction without the use of moving elements.

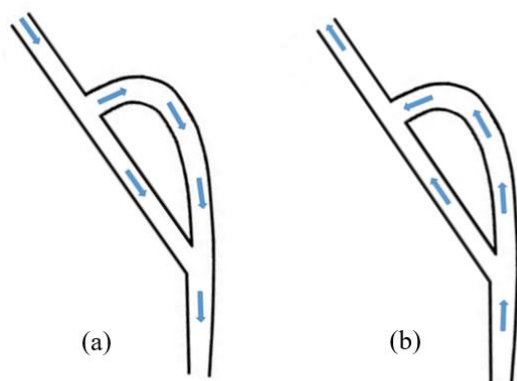


Fig. 1. Tesla microvalve; (a) in the forward direction, (b) in the reverse direction. [1]

Fig.1 shows the schematic representation of tesla valve in the forward and reverse configuration. According to fig.1(a), the majority of the fluid flows into the straight channel of the bifurcated portion during forward flow, and most fluid flows into the arc channel during reverse flow, as shown in fig.1(b). The jet flow from the arc channel greatly effects the pressure drop during reverse flow through the tesla valve, resulting in a greater pressure drop than during forward flow. [2]

At a given steady-state volume flow rate, the diodicity is the ratio of the pressure decrease in the reverse direction to that in the forward direction. [3]

$$Di = \frac{\Delta P_r}{\Delta P_f} \quad (1)$$

Where ΔP_r and ΔP_f are pressure drop in reverse and forward flow respectively.

At low Reynolds Number, the viscosity effects in microvalves are comparable to the inertia effects. Diodicity is increased by increasing the number of valves and the pressure difference, which has critical effect on flow rate [2]. The pressure loss in backward flow increases as the number of stages increases, resulting in a higher Di. Inertial losses account for the majority of the pressure loss in the Tesla microvalve. Diodicity for all arrangements increase with increase in Reynolds number and it becomes prominent at higher Reynolds number due to higher inertial losses. It has been discovered that increasing the number of stages for a particular Reynolds number improves diodicity. But this is true only up to a certain number of stages beyond which Di

does not increase much. [4]

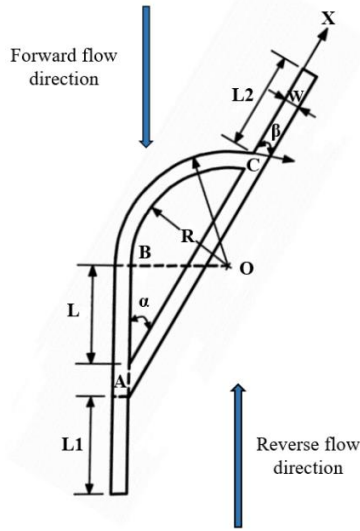


Fig. 2. Geometry of the tesla valve as specified in Truong et. al. [5]

We have adopted the geometry from [5]. Fig.2 represents schematic diagram showing all the various parameters used in the design of tesla valve. From fig.2, channel width is W , entry and exit channel length is $L1$ and $L2$ respectively, straight segment length of side channel is L , radius of inner curve is R , α and β are the angles that the side channel makes with the main channel at A and C respectively. It was found that Di is inversely proportional to R . It is because for a fixed α and L value, a curve with smaller R value intersects $L2$ at larger angle β . In forward flow, a larger β reduces amount of flow entering side channel that reduces pressure drop. In reverse flow, a larger β helps flow in side channel to block flow in main channel more effectively thereby increasing pressure drop. [5]

Tesla valves can also be employed in heat transfer applications that require high efficiency. The performance, cycle life, and safety of Li-ion batteries used in electric vehicles are all affected by the operating temperature. Monika et. al. [6] conducted a thorough investigation of the cooling of pouch type Li-ion batteries utilising a multi-stage Tesla valve-based cold plate. It was discovered that the Multi-stage Tesla Valve (MSTV) design provides effective cooling by increasing the heat transfer rate of the small channel cold plate through fluid mixing mechanisms as compared to straight channel design. This effect is more dominant in reverse flow. It was also discovered that increasing the number of channels, stages and valve to valve distance led to an increase in heat transfer capabilities. The type of working fluid used heavily influences the diodicity and heat transfer capacity of a tesla valve [8]. For this the outlet temperature and diodicity were evaluated by varying the working fluid between air ($Pr = 0.7$), water ($Pr = 5$) and ethylene glycol ($Pr = 200$). The inlet temperature was also varied. The results

showed that when the inlet temperature rises, diodicity for water and ethylene glycol decreases significantly. In the case of air, however, the trend was in the opposite direction. MSTV performance was observed to increase with temperature in the case of air. Another application of the Tesla valve is in pulsating heat pipes, where it was discovered that when compared to an identical PHP without valves, it reduced thermal resistance by roughly 14%. [10].

The present work explores the potential of manipulating diodicity favourably by introducing heating and also by orienting the tesla valve in a vertical fashion. This paper is a numerical investigation of the effects of varying Reynolds number, Richardson number and Prandtl number on the diodicity and performance of tesla valve mounted vertically.

PROBLEM DEFINITION

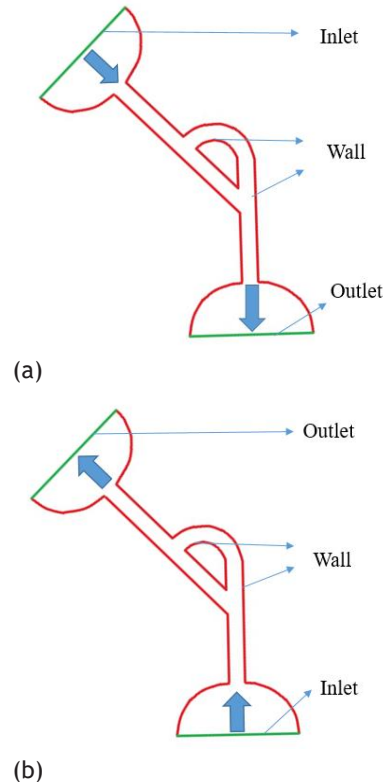


Fig. 3. Schematic for tesla valve. a) Forward flow. b) Reverse flow

We have taken a tesla valve with characteristic diameter 114 mm. The valve is oriented in a vertical manner. Our major goal is to investigate the fluid's flow behaviour when surface heating is brought into the equation. A CFD analysis is performed on the Tesla Valve. The fluid flow is considered to be two dimensional, laminar and incompressible. In order to analyse the flow characteristics, we mainly study the variation of pressure diodicity by varying the Richardson number ($0 < Ri < 1$) and for a fixed value of Prandtl number ($Pr = 0.7$). We have chosen a fixed value of $Re = 30$. The

various parameters used in the problem and their definitions are given below.

$$Re = \frac{\text{Inertial force}}{\text{Viscous force}} = \frac{\rho u_{\infty} L}{\mu} \quad (2)$$

$$Ri = \frac{\text{Buoyancy force}}{\text{Shear force}} = \frac{Gr}{Re^2} \text{ where } Gr = \text{Grashoff Number.} \quad (3)$$

$$Pr = \frac{\text{Viscous diffusion rate}}{\text{Thermal diffusion rate}} = \frac{\nu}{\alpha} \quad (4)$$

NUMERICAL METHOD

We use *buoyantPimpleFoam* solver in the OpenFOAM package for obtaining the results. At inlet, we apply a constant velocity boundary condition and the pressure is extrapolated from the field. We also apply a constant temperature of 300 K. At outlet, we apply zero gauge pressure condition and the velocity is extrapolated from the field. At the walls, we apply no-slip condition and constant temperature (310 K). The *pimpleFoam* algorithm combines *pisoFoam* (Pressure Implicit with Splitting of Operator) and *simpleFoam* (Semi-Implicit Method for Pressure-Linked Equations). The computational method involves the solving of two-dimensional laminar incompressible Navier-Stokes equation under Boussinesq approximation which is given by:

$$\frac{\partial(\mathbf{u})}{\partial t} + (\mathbf{u} - \mathbf{w}) \cdot \nabla \mathbf{u} = -\nabla p + \frac{1}{Re} \nabla^2 \mathbf{u} \quad (5)$$

$$\nabla \cdot \mathbf{u} = 0 \quad (6)$$

$$\frac{\partial(\theta)}{\partial t} + \mathbf{u} \cdot \nabla \theta = \frac{1}{RePr} \nabla^2 \theta \quad (7)$$

Where \mathbf{u} is fluid velocity, \mathbf{w} is the mesh velocity, t is time, p is fluid pressure, Re is Reynolds number, Pr is Prandtl number, θ is dimensionless temperature and ∇ is Laplacian operator.

GRID INDEPENDENCE

TABLE 1: GRID INDEPENDENCE STUDY FOR RE = 528, RI = 0 AND PR = 0.7

Sl. No.	No. of Cells	Diodicity(Di)	% Change in Diodicity
1.	26132	1.1438	-
2.	50894	1.0230	10.56
3.	83826	1.0005	2.19
4.	103384	1.0082	0.77
5.	125090	1.0081	0.0099
6.	148964	1.0133	0.516

A rigorous grid independence study was conducted for the T45 tesla valve. The width and depth of the channel was 114 mm while Reynolds number was 528. A uniform triangular mesh was used for mesh construction. Mesh size was varied from 25000 to 175000 with an increment of 25000 cells. The diodicity value for each mesh was compared. Table 1 consolidates the results of grid independence and the grid

structure having 125090 cells (5th case) is selected as the grid independent one for rest of the simulations.

VALIDATION

TABLE 2: VALIDATION RESULTS FOR FORWARD PRESSURE, BACKWARD PRESSURE AND DIODICITY AT RE =528.

Re	P _{fwd} (Pa)	P _{bwd} (Pa)	Di _{paper}	Di _{present}
528	69.59	70.16	1.099	1.0083

The validation of our work was done in reference to Nobakht et.al. [1]. A two dimensional, laminar and incompressible flow was simulated for a Reynolds Number of 528 with the boundary conditions as discussed in section 4. Table 2 shows the result of validation. It can be seen that the results of the simulation agrees with the previous papers quite accurately.

RESULTS AND DISCUSSIONS

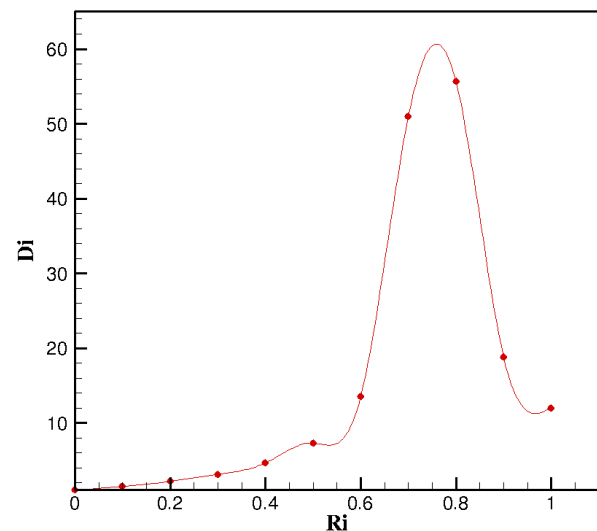


Fig. 4. Variation of Di with Ri for Re = 30

The simulations have been performed for 11 values of Richardson number (Ri) within the range 0 to 1 with an increment of 0.1. The Re is maintained at 30 for all cases of Ri. Fig 4 shows the variation of Diodicity (Di) with Richardson number (Ri) for Re 30. The results from the simulation showed that there was a steady increase in diodicity with an increase in Ri. However this trend was observed only till Ri = 0.5, following which there was a rapid increase in the value of Di from Ri = 0.5 to Ri = 0.8 followed by a drop from Ri = 0.8 to 1. Up to Ri = 0.5 there is a steady increase in Di. Fig.5 shows the pressure contours for Re = 30, Pr = 0.7 and Ri values ranging from 0.2 to 0.4 for backward flow configuration. It is evident from the pressure contours that P_{bwd} is increasing steadily as Ri increases from 0.2 to 0.4 mainly due to the increase in acceleration due to gravity. This

is predominantly because gravity acts in the opposite direction of flow in the case backward flow configuration. Consequentially as buoyancy increases (opposite to gravity)

there is higher resistance to flow which results in greater loss in fluid flow rate in the form of pressure drop.

TABLE 3: PRESSURE DROP IN FORWARD AND BACKWARD FLOW FOR VARIOUS RI.

Sl. No.	Ri	P _{fwd}	P _{bwd}	Di
1.	0	1.163	1.207	1.039
2.	0.1	1.007	1.539	1.529
3.	0.2	0.853	1.875	2.199
4.	0.3	0.699	2.209	3.157
5.	0.4	0.546	2.545	4.661
6.	0.5	0.393	2.879	7.339
7.	0.6	0.238	3.213	13.499
8.	0.7	0.065	3.328	50.992
9.	0.8	-0.069	3.880	-55.630
10.	0.9	-0.224	4.214	-18.817
11.	1.0	-0.378	4.547	-12.026

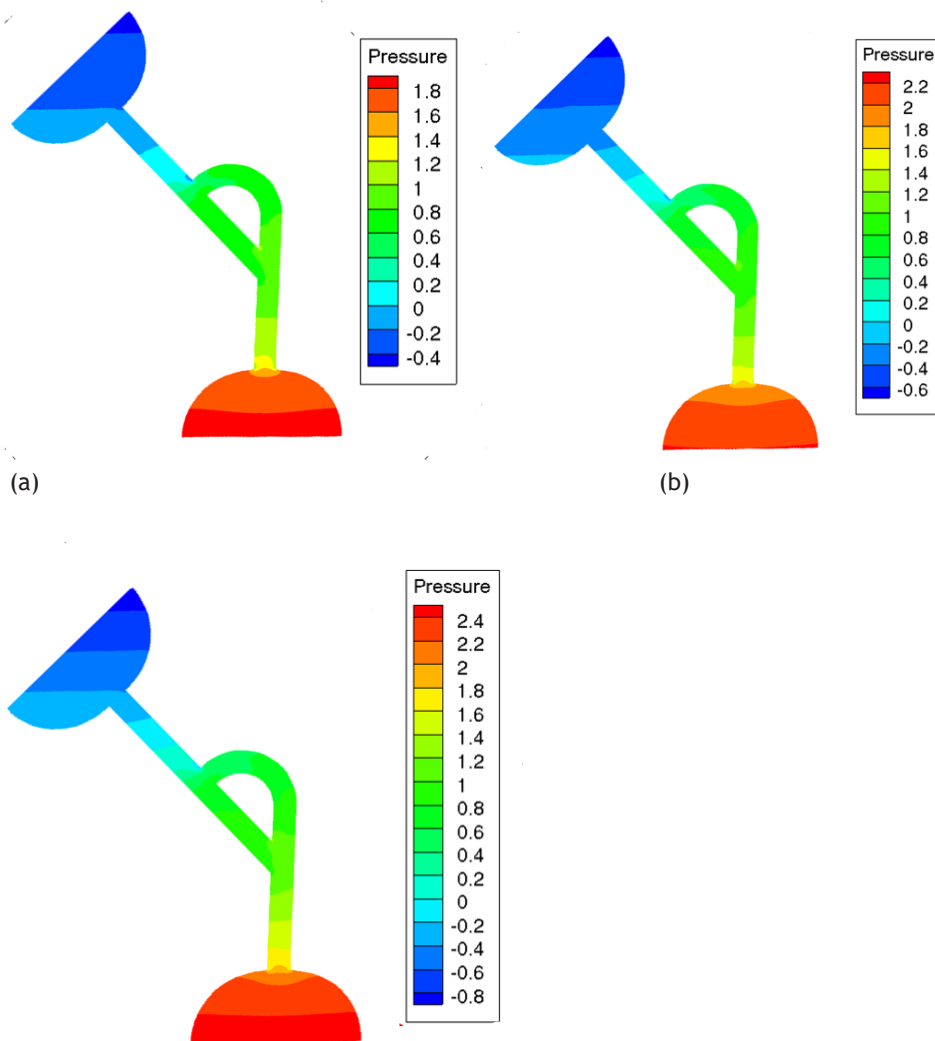


Fig. 5. Pressure contours for Re = 30, Pr = 0.7 (a) Ri = 0.2 (b) Ri = 0.3 (c) Ri = 0.4 for backward flow configurations

For Ri values from 0.5 to 0.7, the effect of g is dominant on forward flow. From table 3 it can be observed that there is a considerable decrease in P_{fwd} and simultaneously not much increase in P_{bwd} . As we know, in case of a incompressible flows, the pressure drops in a channel at the expense of increase in velocity. So as the fluid flow is along the direction of gravity, a considerable increase in fluid velocity occurs when Ri is increased. This means that pressure at inlet of the valve approaches the pressure value at the outlet, which in turn causes a steep reduction in the pressure drop. Therefore, it can be inferred that P_{fwd} mainly affects the increase in diodicity for the prior mentioned range of Ri . For Ri values from 0.8 to 1.0, following the prior mentioned principle, a further increase in flow velocity results in the pressure value at the inlet to be less than that at the outlet. As a result, there is a negative pressure difference between the input and the output, resulting in backflow.. This results in a substantial decrease in diodicity as seen in fig.4.

CONCLUSION

In this study, we investigated the impact of altering the Richardson number on the valving efficiency of the Tesla valve. A two dimensional, laminar and incompressible flow was simulated using OpenFOAM. The simulations revealed that increase in Richardson number upto a particular value had a positive effect on diodicity. This increase was uniform till $Ri = 0.5$ in the case of backward flow, because fluid was flowing in the opposite direction of gravity with respect to inlet resulting in the decrease in flow rate. As we know that, in a channel flow, a decrease in flow velocity means an increase in pressure of fluid. Therefore the inlet pressure keeps increasing as compared to the constant outlet pressure (zero gauge pressure) which leads to a significant rise in the pressure difference between inlet and outlet in the case of backward flow. After $Ri = 0.5$ there is a sharp shoot in Di values till $Ri = 0.8$ which can be attributed to the dominant effect of gravity on forward flow. In forward flow, fluid flow is along the direction of gravity with respect to outlet. As a result, increased buoyancy leads to increased flow rate. Similar to the previous case the inlet pressure starts approaching the value of outlet pressure leading to a decrease in pressure drop. After $Ri = 0.8$, in the case of forward flow, a further increase in flow velocity leads to pressure at inlet being less than that at outlet, causing the value of pressure drop to be negative and also causing backflow. This contributes to the sharp decrease in diodicity.

NOMENCLATURE

Di	Diodicity
Re	Reynolds Number
Ri	Richardson Number
Gr	Grashof Number
Pr	Prandtl Number

P_{fwd}	Pressure Drop in Forward Flow
P_{bwd}	Pressure Drop in Backward Flow
g	Acceleration due to Gravity
ρ	Density
u	Fluid Velocity
L	Characteristic Length
μ	Dynamic Viscosity
ν	Viscous Diffusion Rate
α	Thermal Diffusion Rate
∇	Laplacian Operator
w	Mesh Velocity
Θ	Dimensionless Temperature

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