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A Reversible Miniaturized Tesla Valve

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Tesla valves are passive fluid diodes originally proposed in 1920 by Nikola Tesla and consist of parallel tubes with bifurcated sections that rectify flow using fluid dynamics principles. Unlike conventional Tesla valves which are fixed in shape and offer a specific preset diodicity, the novel concept presented here provides a Tesla valve with adjustable diodicity capable of reversing the flow direction to promote flow in the backward direction rather than the forward direction. This reversibility is achieved by applying external stress that changes the valve's preferential flow. Through an integrated workflow, Tesla valve diodicity is evaluated under external uniaxial compression or tension for low Reynolds numbers ranging between 10 and 300. Findings reveal that the diodicity of the valve decreases below one under sufficient uniaxial compression. These results suggest the potential for reversing the valve's functionality under specific conditions, promoting less resistant flow in the reverse direction than the forward direction. Oppositely, applying tension to the Tesla valve increases the diodicity of the valve to up to 4.38, representing an increase of 89.6% in valve's diodicity compared to the undeformed valve. Moreover, a diodicity value of 1.57 is achieved at a Reynolds number of 30 upon applying 20% strain in tension. Such a reversible valve can be made of flexible material and will provide additional potential applications for the valve where the direction of the flow needs to be fine-tuned. [DOI: 10.1115/1.4065510]

Keywords: flexible structures, fluid control systems, flexible valve, directional flow, check valve, diodicity, no-moving-part valve, Tesla valve, variable diodicity, fluid mechanics

1 Introduction

Effective control of fluid flow direction is crucial in numerous engineering, environmental, and medical applications. Examples of such applications include preventing contaminated water backflow in sewage treatment facilities [1], optimizing indoor air quality by controlling the ventilation path regardless of the changing wind direction [2], controling fluid flow within hydraulic fractures in Enhanced Geothermal Systems (EGS) [3,4] and preventing fluid reflux such as in sweat collection and wound discharge vacuum devices to ensure the efficacy and safety of medical devices [5]. These applications highlight the necessity for advanced fluid control technologies that are both efficient and adaptable to changing operational conditions.

Among the various solutions developed to control fluid flow direction, Tesla valves stand out due to their unique no-moving-parts design. These valves function as fluidic diodes by offering a passive promotion of flow in one direction over the other owing to their unique design. Their unique design enables a higher flowrate in the forward direction while significantly impeding flow in the reverse direction. This asymmetric flow resistance measured by the valve's diodicity is crucial for different applications in hydraulic systems and microfluidics where precise flow control is essential.

In hydraulic systems, Tesla valves provide a reliable alternative to traditional check valves, avoiding common failures caused by wear of moving mechanical parts that can ultimately lead to clogging issues and compromised system reliability. Tesla valves have also been applied in cooling applications such as cooling Li-ion batteries [6]. In addition, their silent operation makes them advantageous for cooling sensitive equipment. In microfluidics, miniaturized Tesla valves enable smooth flow control and mixing on chips [7]. Optimized Tesla valve geometries have been studied for lab-on-a-chip devices and nanofluidic diodes [8]. Passive flow rectification provided by Tesla valves is also useful for integrated microfluidic circuits. Novel applications continue to emerge including dialysis machines, control of gas flows in fuel cells, cryogenics, sterilization systems, intravenous therapies, and more. Ongoing research aims to improve Tesla valve designs and explore additional uses across diverse industries and technologies through computational modeling and experiments [2].

The main limitation of the Tesla valve is its inability to maintain its functionality at low Reynolds numbers due to the diminished impact of fluid inertia. For instance, a diodicity of 2 has been achieved at a Reynolds number of 100, indicating that the forward flow experiences significantly less resistance compared to the reverse flow direction. However, at a lower Reynolds number, inertial effects are significantly lower; thus, a diodicity closer to 1 is expected, indicating a need for enhanced designs that maintain high diodicity across a wider range of operational conditions. The development of efficient valves with high diodicity remains an area of active research. The design parameters of the nondeformable Tesla valve and their impact on the corresponding valve diodicity are documented in the literature. Inlet and outlet lengths, channel width and depth, length of the straight segment of the side channel, angle of

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Manuscript received April 19, 2024; final manuscript received April 24, 2024; published online May 30, 2024. Assoc. Editor: Hameed Metghalchi.

the side channel, and the radius of the circular segment have been investigated [9]. A multistage Tesla valve (MSTV) consisting of multiple identically shaped Tesla valves connected in series is another optimization technique that has been reported to increase resistance in the reverse direction, thus increasing the diodicity of the valve [10–12]. However, most of the studies focused on high Reynolds number flow.

Several authors attempted to optimize the Tesla valve for low Reynolds number flow. Bohm et al. [13] presented a fabricated Tesla valve with a diodicity of 1.8 at a Reynolds number of 36. Lee et al. [14] presented a Tesla valve whose diodicity can be altered using temperature. Their results show that the valve's diodicity is reduced from an average of 1.03 to an average of 0.99 when heated from room temperature (20 °C) to 30 °C. While most studies focused on the optimization of design parameters, external disruptions to the valve performance are not well understood. This presents a bottleneck in implementing such a unique valve in applications that require fine-tuned control of fluid flow direction such as microfluidics. In addition, the fixed geometric design of the traditional Tesla valve limits its adaptability to varied operational conditions. This necessitates enhancing the flexibility and functionality of Tesla valves to increase their potential applications.

This paper addresses these limitations through the development of a novel flexible Tesla valve whose diodicity can be dynamically adjusted by applying external stress. This innovative approach not only allows customization of flow direction without the need for valve replacement, but also opens up new avenues for applications in fields requiring adaptive fluid control solutions. There is currently limited research on deformable or flexible Tesla valves. To our knowledge, no studies explored the possibility of making Tesla valves out of flexible materials like silicone rubber. Unlike traditional rigid Tesla valves, our flexible Tesla valve can deform under external stress, which allows for a reversible flow direction tailored to specific applications. This is a feature yet to be explored in existing literature.

Potential applications of the flexible Tesla valves extend into soft robotics, flexible microfluidic devices, and biomedicine. Furthermore, their deformability combined with the ability to adjust flow direction dynamically allows them to handle high pressures without damage, which introduces a groundbreaking advancement in fluid control strategies. Challenges with flexible Tesla valves include modeling the complex fluid-structure interactions as the valve deforms. The flexibility can also lead to unstable geometries and deformation which may clog the valve, so it needs to be well-adjusted. Optimizing the material properties and geometry is important to ensure that the flexible Tesla valve can withstand pressure drops without collapsing or losing its rectifying properties. Key areas for future work include new flexible valve designs, testing various materials like hydrogels or shape memory polymers (SMP) that can be fabricated to autonomously alter its shape when subjected to a certain external trigger [15], integrating flexible Tesla valves into microfluidic devices, and developing manufacturing methods for scalable fabrication.

Deformable Tesla valves are a relatively new concept still in the early stages of research for soft fluidic systems and flexible microfluidics, but this preliminary study indicates their potential for novel applications. In this study, we investigate the impact of uniaxial compression and tension on Tesla valve's diodicity using finite element methods (FEM). FEM is a robust numerical solving scheme that has been extensively used to model structural analysis. Here, we consider uniaxial compression and tension as external triggers and their impact on Tesla valve performance at a wide range of Reynolds numbers. This paper is organized as follows. First, we introduce the theoretical concept along with the governing equations. Next, we present the numerical approach based on the presented governing equations. Next, the numerical workflow is validated against experimental studies to ensure acceptable accuracy. Then, we present the numerical results of fluid diodicity under different conditions of stress at a wide range of Reynolds numbers. The outcomes of these numerical analyses would potentially reveal new potential applications of such reversible Tesla valves.

2 Governing Equations

The deformability of the Tesla valve can be triggered by different factors such as pressure, heat, or chemical reaction. The focus of this paper is on the effect of stress which can either be exerted internally by the flowing fluid itself or externally by specific devices. The impact of uniaxial compression and tension on the valve diodicity is investigated through displacement-specified strain. While many experimental studies concerning the diodicity of Tesla valves have been carried out, numerical simulations can provide in-depth insights into how the microstructures deform, especially for micro-scale miniaturized Tesla valves. Additionally, numerical simulations offer a controllable environment where parameter variation is straightforward. This permits a thorough investigation of the impact of certain parameters on the corresponding diodicity of the valve [16]. In this paper, the valve's geometry is assumed to follow a linearly elastic behavior. Thus, the relationship between strain and stress is linear. The numerical workflow is presented below.

Diodicity (D_i) of a Tesla valve is defined as the ratio of pressure drops in the reverse direction and the forward direction at identical flowrates; i.e.,

$$D_i = \left.\frac{\Delta P_{reverse}}{\Delta P_{forward}}\right|_{q_i} \tag{1}$$

where $\Delta P_{reverse}$ is the pressure drop (Pa) in the reverse direction, $\Delta P_{forward}$ is the pressure drop (Pa) in the forward direction, and q_i is the flowrate (m^3/s). The diodicity of the Tesla valve is typically greater than unity, indicating that the preferential flow direction is the forward direction [17]. The flow in the reverse direction experiences higher resistance due to longer passage lengths, more flow direction changes, and more intense fluid jet confluence [18]. Figure 1 shows a schematic of a generic Tesla valve to aid in visualizing the concept.

Since the principle of the Tesla valve relies on the inertia of the fluid and the design of the valve, Tesla valve has a higher diodicity at high Reynolds numbers as fluid inertia is higher. As Reynolds number decreases, the inertial term diminishes, yielding a symmetric pressure drop in both directions, i.e., a diodicity closer to 1. Reynolds number is calculated at the inlet of the Tesla valve and is given as

$$\text{Re} = \frac{\rho u D_H}{\mu} \tag{2}$$

where ρ is the fluid density (kg/m^3), u is the fluid velocity (m/s), D_H is the hydraulic diameter (m), and μ is the fluid viscosity (Pa·s). The hydraulic diameter of the valve is computed as $D_H = 4A/P$, where A is the cross-sectional area of the valve (m^2), and P is the perimeter (m).

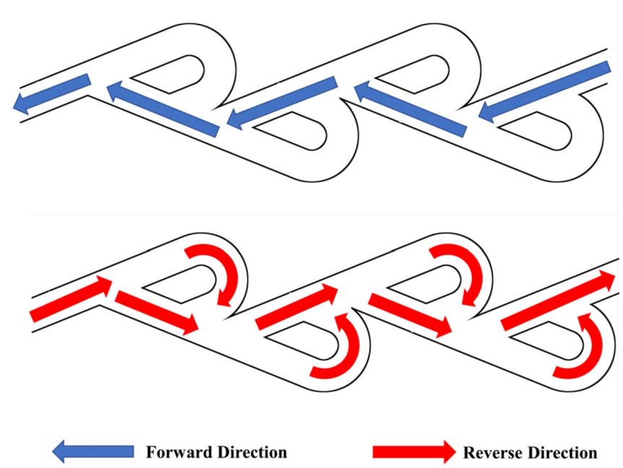

Fig. 1 Schematic of the Tesla valve concept

Mechanical deformation of the valve is simulated using implicit dynamic FEM solver, which is governed by Newton's second law of motion and linear elasticity given by

$$\nabla \cdot \sigma + F = \rho \ddot{x} \tag{3}$$

$$\varepsilon = \frac{1}{2}[\nabla x + (\nabla x)^T] \tag{4}$$

$$\sigma = C:\varepsilon \tag{5}$$

where σ is the stress tensor (N/m^2), F is the applied external force per unit volume (N/m^3), ρ is the material density (kg/m^3), $\ddot{x}$ is acceleration (m/s^2), ε is the strain tensor (dimensionless), x is the location (m), and C is the stiffness tensor (Pa). Because large deformation is anticipated, the displacement is applied slowly to avoid any inertial effects.

The deformed geometry is then used as an input to computational fluid dynamics (CFD) simulations to compute the resulting diodicity of the valve. Laminar and turbulence models including the $k-\varepsilon$ model, SST $k-\varepsilon$ model, and Reynolds stress model (RSM) have been used in different studies to simulate flow in a Tesla valve depending on the application. Thompson et al. [19] compared different turbulence models with experimental results from the study by Gamboa et al. [20]. Their results show that $k-k_L-\omega$ and SST $k-\varepsilon$ models provide the best match with the experimental results for Reynolds numbers between 500 and 2000. In this paper, Reynolds-averaged Navier–Stokes (RANS) $k-\varepsilon$ model is utilized to simulate the incompressible flow of a single-phase fluid with constant properties, which is governed by

$$\frac{\partial \bar{\boldsymbol{u}}}{\partial t} + (\bar{\boldsymbol{u}} \cdot \nabla)\bar{\boldsymbol{u}} = -\frac{1}{\rho}\nabla \bar{p} + \nu \nabla^2 \bar{\boldsymbol{u}} - \nabla \cdot \boldsymbol{\tau} \tag{6}$$

$$\nabla \cdot \bar{\boldsymbol{u}} = 0 \tag{7}$$

where $\bar{\boldsymbol{u}}$ is the mean flow velocity (m/s), $\bar{p}$ is the mean pressure (Pa), ρ is the fluid density (kg/m^3), ν is the fluid kinematic viscosity (m^2/s), τ is Reynolds stress tensor (Pa), and t is the time (s).

3 Model Validation

In this section, we validate our numerical workflow to check the accuracy of the model. We compare the results obtained numerically using COMSOL with the experimental and numerical results presented in Wang et al. [21]. The geometry used for the validation represents a two-stage Tesla valve as shown in Fig. 2. All dimensions are in mm. The cross section is a square with a side length of 2 mm. Flow of a fluid with a density of 998 kg/m^3 and a dynamic viscosity of 0.001 Pa $\cdot$ s is simulated with flowrates varying between 0.05 m/s and 0.15 m/s. The pressure drops in both the forward and the reverse directions are recorded at each flowrate and used for calculating the corresponding diodicity of the valve. Reynolds number for this validation case varies based on the flowrate and is between 100 and 300.

Figure 3 shows a comparison between the simulation results and the results presented by Raffel et al. [17] and Wang et al. [21] of Tesla valve's diodicity shown in Fig. 2. The results we obtained numerically show good agreement with the results presented in the literature. The diodicity decreases as the flowrate and Reynolds number decrease. Possible reasons for differences in the results include the number of mesh elements used in the study. This agreement verifies the adequacy of the presented approach to accurately represent the flow of water in a Tesla valve. Thus, we use the verified workflow to carry out the analysis of the geometry shown in Fig. 4.

4 Methodology

Utilizing the governing equations outlined in Sec. 2, FEM numerical solver, ABAQUS is used to simulate mechanical deformation by applying displacement-specified strain. The obtained deformed geometry is used directly for 3D fluid flow simulations. The geometry considered in the study is a two-stage Tesla valve, which is shown in Fig. 4. The geometry has a square cross section with a side length of 6 μm. The two-stage valve is made of two single-stage valves connected with the second valve flipped around the horizontal axis. The geometry shown in Fig. 4 is used for fluid flow simulations.

For mechanical simulations, a cuboid encapsulating the Tesla valve geometry is constructed. The geometry is meshed with an unstructured mesh to ensure appropriate handling of curved boundaries of the geometry for accurate FEM simulation. FEM mesh for mechanical analysis consists of 1,357,526 quadratic tetrahedral elements. Since the geometry is assumed to follow a linearly elastic behavior, the required inputs for the material properties include density, Young's modulus, and Poisson's ratio. Thus, a density of 2.65 g/cm^3, Young's modulus of 50 GPa, and Poisson's ratio of 0.25 are assigned. Figure 5 shows the mesh used for the two-stage valve for mechanical simulation in ABAQUS. To achieve a better convergence of the numerical solver, we apply uniaxial stress specified by strain. Strain is applied by imposing displacement-specified boundary conditions in the vertical direction until a strain of up to 20% is achieved in compression and tension while constraining the remaining sides of the geometry using roller-type boundary conditions. On the opposite face that the displacement is applied to, rotation in the horizontal directions (x- and z-directions in this case) is constrained. Since large deformation is anticipated, an implicit dynamic FEM solver is used. Thus, contact behavior between interacting elements is accounted for. Hard Hertzian contact is used in the normal direction while frictionless contact is applied in the tangential direction.

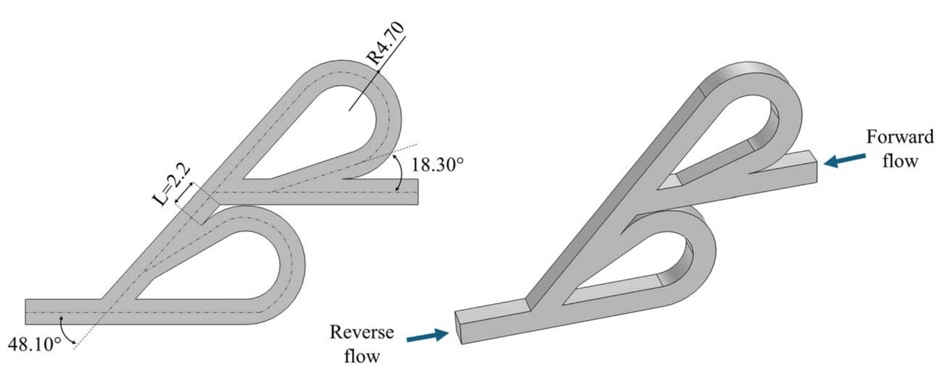

Fig. 2 A sketch of the Tesla valve geometry used for validating the workflow (dimensions are in mm).

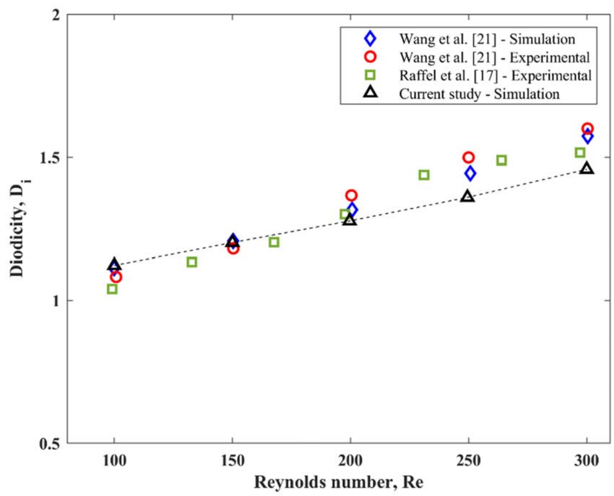

Fig. 3 Comparison between the simulation results using the presented workflow and the results found in Refs. [17,21]

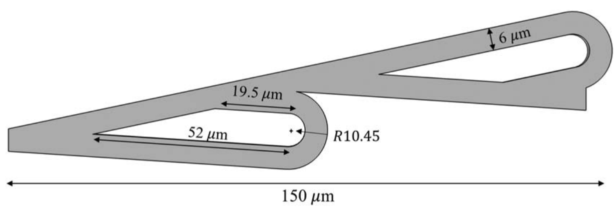

Fig. 4 The geometry used in this study of a two-stage Tesla valve (dimensions are in μm).

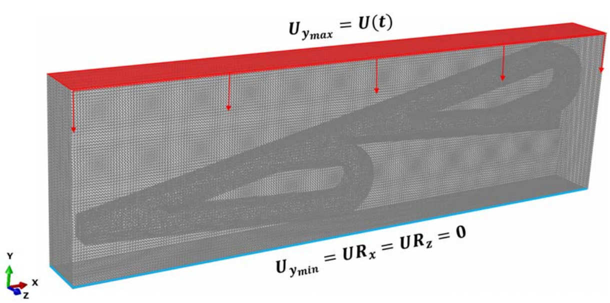

Fig. 5 FEM Mesh and the boundary conditions used for mechanical simulations are shown

Once the simulation has converged and the model has reached mechanical equilibrium, the deformed geometry is used as an input for fluid flow simulations through COMSOL. In this study, the steady-state RANS flow model is adopted to compute the resulting pressure drop across the geometry. We specifically vary the inlet velocity while keeping the outlet pressure at 0 Pa. The cross-sectional area of the original geometry at 0% strain is 36 μm^2. Flow rates are chosen between 5 m/s to 140 m/s to yield Reynolds numbers between 10 and 300. The flowing fluid considered has a density of 998.2 kg/m^3 and a dynamic viscosity of 0.002816 Pa · s.

4 Results

4.1 Diodicity Variation With Reynolds Number. Reynolds number can significantly impact the performance and diodicity of a two-stage Tesla valve. Tesla valve may extend its use to applications involving flow with high Reynolds numbers. For example, in ventilation applications where hot air is vented outside the building, the air velocity in the presence of a strong wind may reach up to

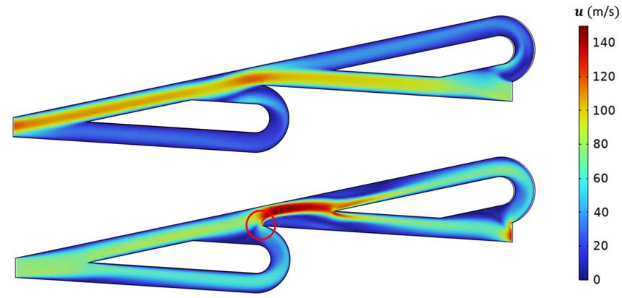

Fig. 6 Velocity field of forward (top) and reverse (bottom) flows at Re = 265

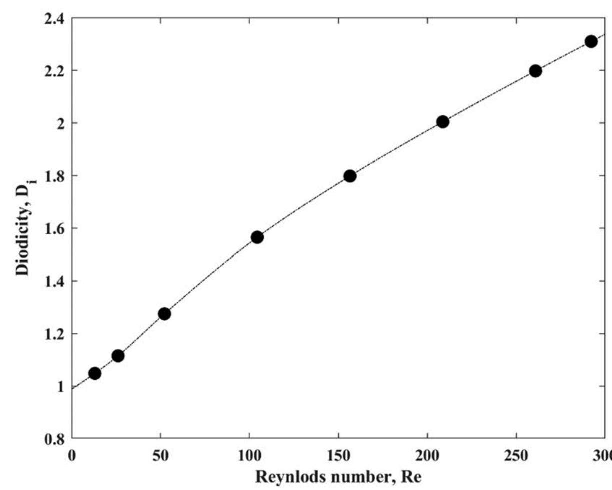

Fig. 7 Tesla valve diodicity as a function of Reynolds number is shown

6 m/s which corresponds with a Reynolds number of up to 6143 [2]. However, most studies in the literature mainly focused on Reynolds numbers less than 2000 but higher than 100. This study primarily focuses on microfluidic applications. Thus, in this section, we explore the impact of the Reynolds number on the diodicity of the two-stage Tesla valve for Reynolds numbers between 10 and 300. Figure 6 shows the velocity profile at Reynolds number 265, with 0% strain applied for the forward and reverse flow. We observe that the flow in the reverse direction is split at the bifurcated section, increasing the flow resistance and yielding a diodicity value larger than 1.

In Fig. 7, we observe a clear correlation between the diodicity of the Tesla valve and Reynolds number. The results show that as the Reynolds number increases, the diodicity increases. This is attributed to the enhanced flow resistance from a longer flowing path and the presence of multiple bifurcated sections, which divert the flow and form a vortex-like flow pattern near the bifurcated section. Notably, diodicity values of the two-stage Tesla valve exceed 2 for Reynolds numbers greater than 200, emphasizing that the flow in the forward direction is highly favored. As Reynolds number decreases, the reverse flow experiences less resistance, and the pressure drop in the reverse direction becomes closer to the pressure drop in the forward direction. Therefore, the diodicity of the valve approaches 1 as the Reynolds number decreases. This variation in the valve's diodicity with the Reynolds number presents a crucial characteristic for optimizing fluid flow in various applications ranging from industrial processes to healthcare devices that require reliable and efficient fluid flow directionality control.

4.2 Diodicity Variation With Strain. We further investigate the influence of uniaxial strain on the diodicity of the flexible

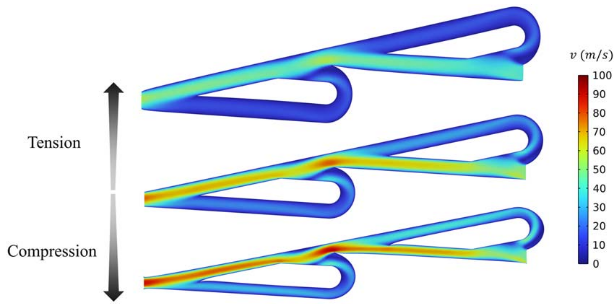

Fig. 8 Velocity field of the forward flow at Re = 100. From the top, 10% strain in tension, 0% strain, and 10% strain in compression.

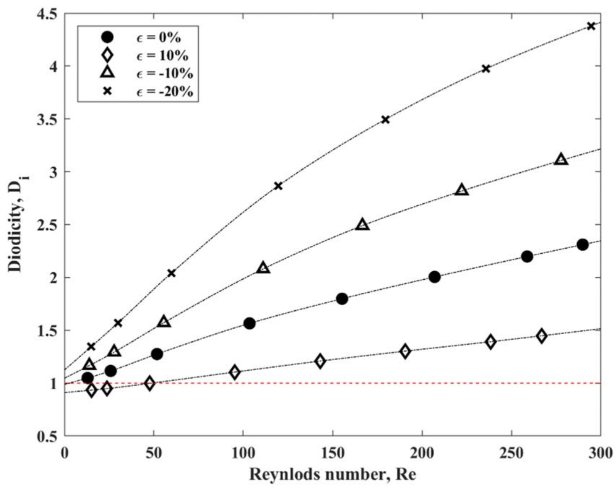

Fig. 9 Tesla valve diodicity at different values of strains as a function of Reynolds number

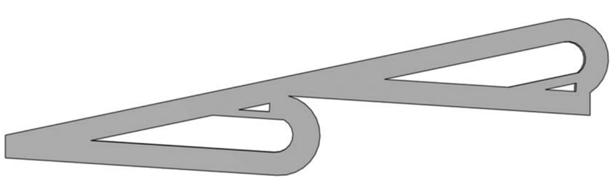

Fig. 10 A modified geometry of the Tesla valve with an added triangular obstacle

Tesla valve. The diodicity of the two-stage valve is computed at different Reynolds numbers and different strains. Applying different strain values is noticed to mainly alter the cross-sectional area available for the flowing fluid. Figure 8 shows the forward flow in the original uncompressed valve and under 10% strain in tension and compression. The flow resistance in the forward direction increases as strain increases, which reduces the cross-sectional area, decreasing the diodicity of the valve. Oppositely, applying a strain of 10% in tension widens the valve and reduces the flow resistance, thus, the fluid passes easily as shown by the reduced velocity in Fig. 8. It is important to note that the inlet and outlet cross-sectional area might be different after applying strain. Per definition, the diodicity is computed at the same flowrate for the forward and reverse directions. Thus, the inlet velocity is adjusted depending on the cross-sectional area as needed to achieve the same flowrate for both flow directions.

Figure 9 further details the variation in the valve diodicity at different strains across different Reynolds numbers for the two-stage

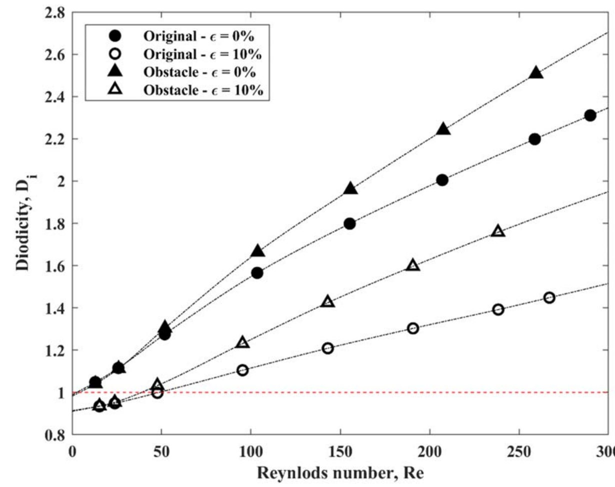

Fig. 11 Diodicity of the original and modified Tesla valves at different values of strains and different Reynolds numbers

Tesla valve. Strain is observed to inversely affect the preferential flow direction, which is a groundbreaking capability of the introduced flexible Tesla valve. The diodicity is also noticed to drop below 1, especially for Reynolds numbers less than 50, if enough strain is applied. According to Fig. 9, 10% strain is enough to reduce the valve diodicity to less than 1. This indicates that the preferential flow direction is reversed, emphasizing that the forward direction flow experiences greater resistance than the reverse direction. However, more strain is required for flows with high Reynolds numbers. Oppositely, applying tension to the geometry increases the diodicity of the valve. At a Reynolds number of 295, the diodicity reaches up to 4.38, which represents an increase of 89.6% in valve's diodicity compared to the undeformed valve. This is attributed to the geometric change in the cross-sectional area available for the flow of fluid.

Introducing an obstacle to the flow may also change the response of the Tesla valve to stress/strain. As a result, the diodicity may change as well. In this section, we introduce a triangular obstacle near the bifurcated section. The modified Tesla valve with an added obstacle is shown in Fig. 10. The cross-sectional area and the valve dimensions remain the same.

Figure 11 shows the diodicity of the modified Tesla valve (Fig. 10) compared to the original geometry shown in Fig. 4. It is observed that the modified Tesla valve yields a higher diodicity at Reynolds numbers between 50 and 300. However, at Reynolds numbers less than 50, the diodicity is identical for both designs. In addition, we observe that adding the obstacle to the geometry decreases the sensitivity of the Tesla valve diodicity to the applied stress. For example, applying a 10% strain in compression at a Reynolds number of 100 results in a 29.42% decrease in the diodicity of the original geometry while it results in a 26.01% decrease in the modified geometry. The change in the diodicity of the Tesla valve based on the strain applied is what makes the valve flexible. Understanding the response of flexible Tesla valves can aid in designing durable valves that can withstand high-pressure fluid flow.

5 Conclusion

In this paper, we present a reversible Tesla valve concept with the capability of changing the preferential flow direction based on the intended application. In specific, an integrated workflow combining FEM and CFD is used to investigate the impact of uniaxial compression and tension on the diodicity of a Tesla valve. The numerical analysis revealed that the diodicity of the valve decreases as strain increases. The diodicity reduces to less than unity when

10% strain is applied in compression at a Reynolds number less than 50. This indicates that the valve functionality has been reversed and that the reverse direction became the preferential flow path. For a Reynolds number greater than 50, higher values of strain are required to reverse the Tesla valve. In addition, the results showed that applying tension on the valve can increase its diodicity, making it more effective in controlling fluid flow direction. A strain of 20% in tension can increase the diodicity by up to 89.6%. Adding a triangular obstacle near the bifurcated section also increases the diodicity of the valves and makes the valve less sensitive to stress.

Author Contributions

Arash Dahi Taleghani: Conceptualization, Supervision, Visualization, Writing—review & editing. **Faras Al Balushi**: Formal analysis, Investigation, Methodology, Visualization, Writing—original draft.

Conflict of Interest

There are no conflicts of interest. This article does not include research in which human participants were involved. Informed consent is not applicable. This article does not include any research in which animal participants were involved.

Data Availability Statement

The authors attest that all data for this study are included in the paper.

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