OPTIMIZATION OF TESLA VALVE GEOMETRIES FOR HIGH-EFFICIENCY PASSIVE COOLING SYSTEMS

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Introduction

The Tesla valve, invented by Nikola Tesla, controls fluid flow in one direction due to its asymmetric design without moving parts. In recent years, this mechanism has regained attention due to its direct relevance to energy efficiency. The key parameter of the valve, known as diodicity, is defined as the ratio of the pressure drop in the reverse flow to the pressure drop in the forward flow at the same flow velocity. Tesla valves in cooling systems are employed to channel coolant flow in a single direction without mechanical moving parts, improving efficiency and reliability of temperature regulation. In this study, computational fluid dynamics (CFD) is used to analyze the diodicity of various Tesla valve designs. By examining diodicity at different Reynolds numbers and varying valve width parameters, we aim to develop optimized valve designs for practical applications.

Methodology

The computational fluid dynamics (CFD) simulations were conducted using the Ansys-Fluent software package. Model validation was performed based on the existing design of the Tesla valve of the optimized GMF valve type. Following successful validation, numerical experiments were carried out for various configurations of the Tesla valve width (MSTV), with the width-to-depth ratio ranging from 1× to 4×. In both cases, the inlet and outlet section lengths were 0.6 mm, width was 0.1mm.

The numerical studies were conducted under different flow regimes, covering Reynolds numbers in low range of 100-500. This range was chosen to facilitate the analysis of laminar flow conditions, where vortex formation becomes most pronounced. These vortices play a key role in the mechanism of valve diodicity. The flow velocity was calculated based on the Reynolds number according to Equation below, while the diodicity was determined another equation presented.

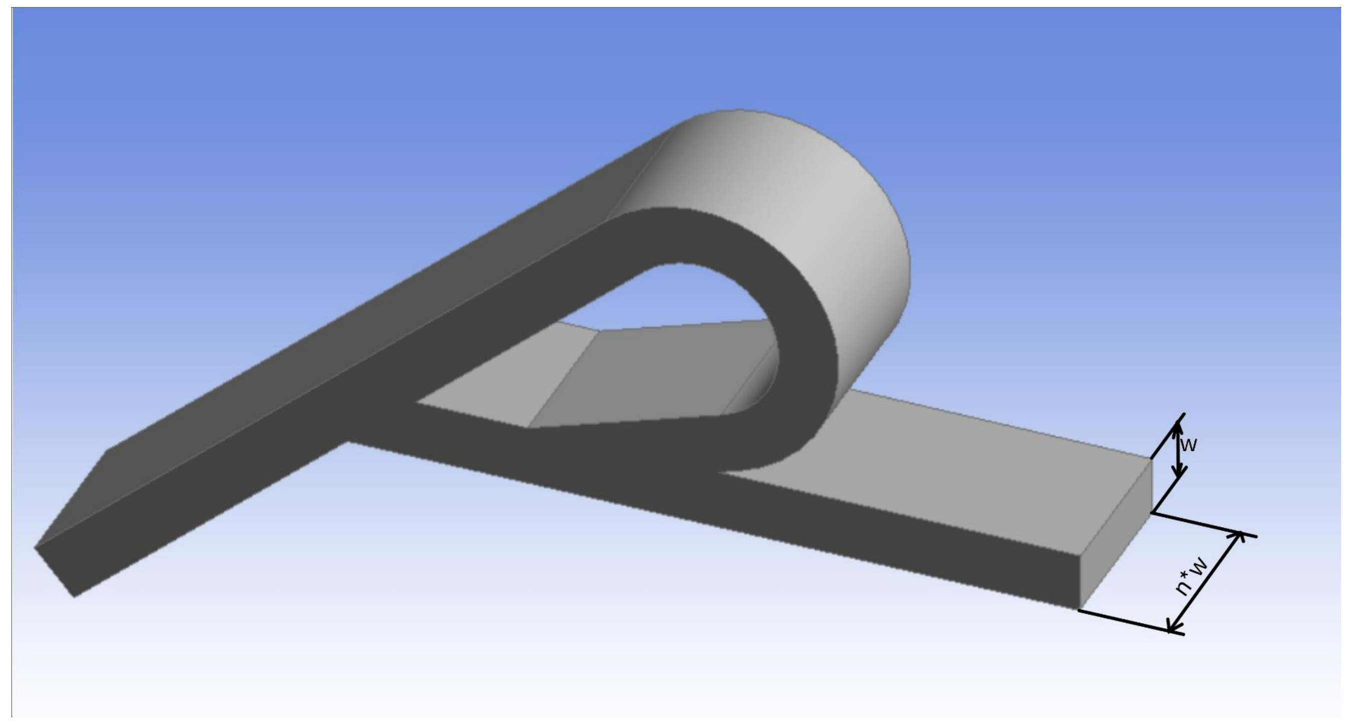

Figure 1: GMF dimensions

$$Re_i = \frac{\rho u_i d}{\mu} \qquad Di = \left.\frac{\Delta P_r}{\Delta P_f}\right|_{\dot{V}}$$

The analysis of pressure vortices within the Tesla valve, along with comparative plots for forward and reverse flow conditions, reveals that vortex formation plays a significant role in determining the valve's diodicity. The observed vortices exhibit distinct characteristics depending on the flow direction, with more pronounced and persistent vortex structures in the reverse flow case. These vortices contribute to increased flow resistance and pressure drop, directly impacting the valve's ability to regulate unidirectional flow. The results indicate that vortex dynamics serve as a primary mechanism influencing diodicity, highlighting their importance in the optimization of Tesla valve designs for improved performance.

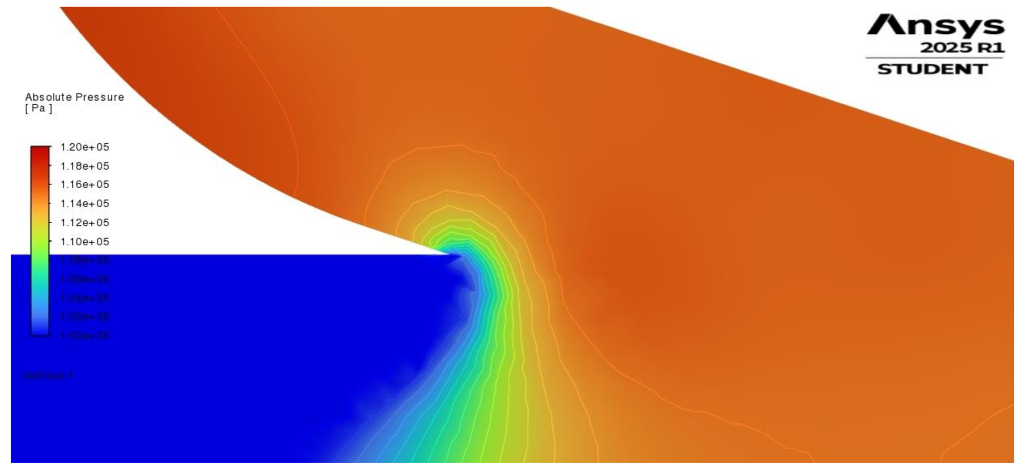

Fig 4: Pressure vortex in reverse flow

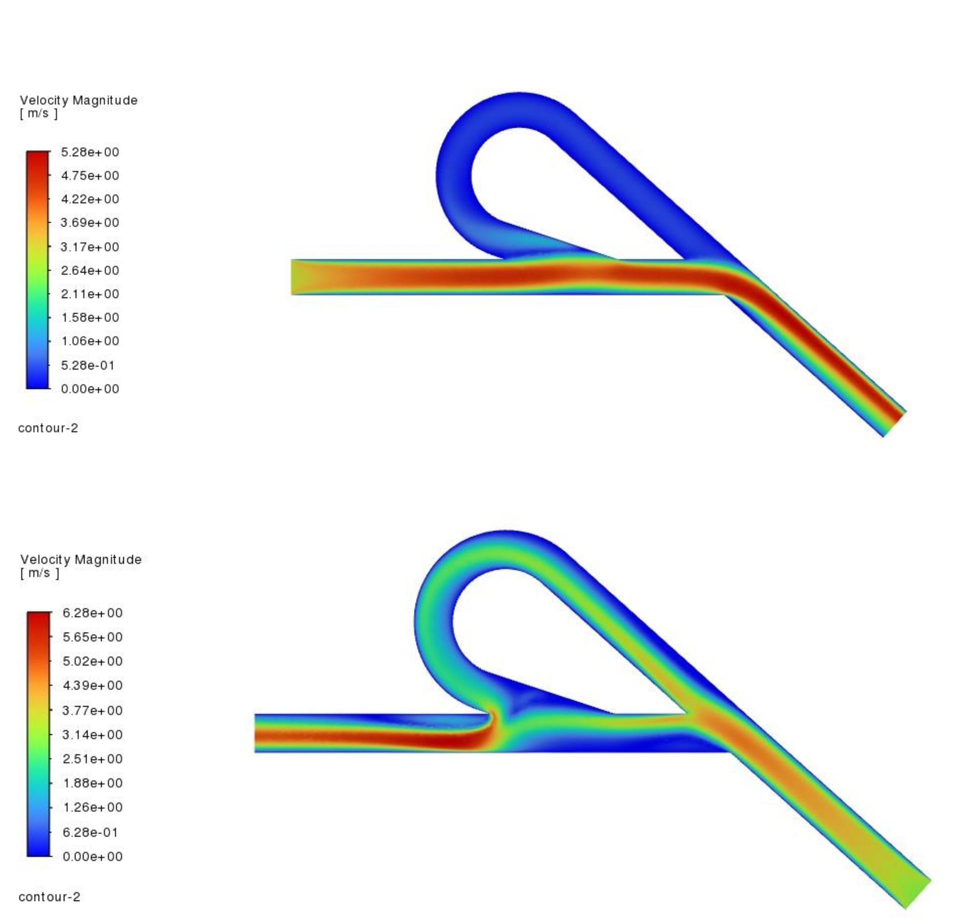

Figure 2: Forward (above) and reverse flow velocity profiles

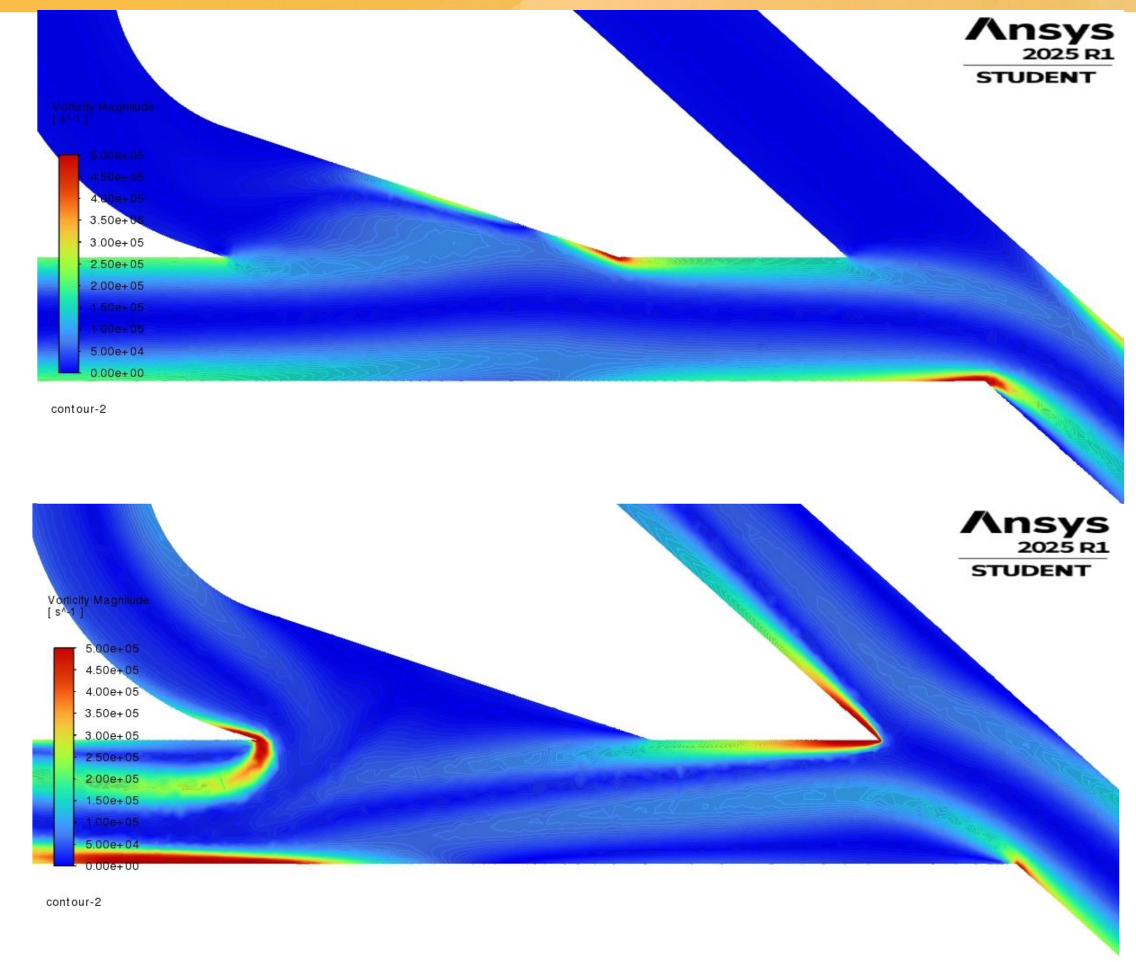

Figure 3: Forward (above) and reverse flow velocity vortices

One of the key aspects of this study is the influence of Tesla valve depth on diodicity. The results indicate that wall shear effects can significantly reduce diodicity, thereby affecting the valve's ability to regulate unidirectional flow. To investigate this phenomenon, numerical simulations were conducted for various valve depths, both with and without wall shear effects. The analysis demonstrated a clear correlation between valve depth and diodicity, as illustrated in the accompanying graph. Specifically, increasing wall shear disrupted vortex formation, leading to a reduced pressure differential between forward and reverse flow. This suggests that excessive shear effects can weaken the rectifying performance of the valve, diminishing its effectiveness in applications requiring high flow resistance in the reverse direction.

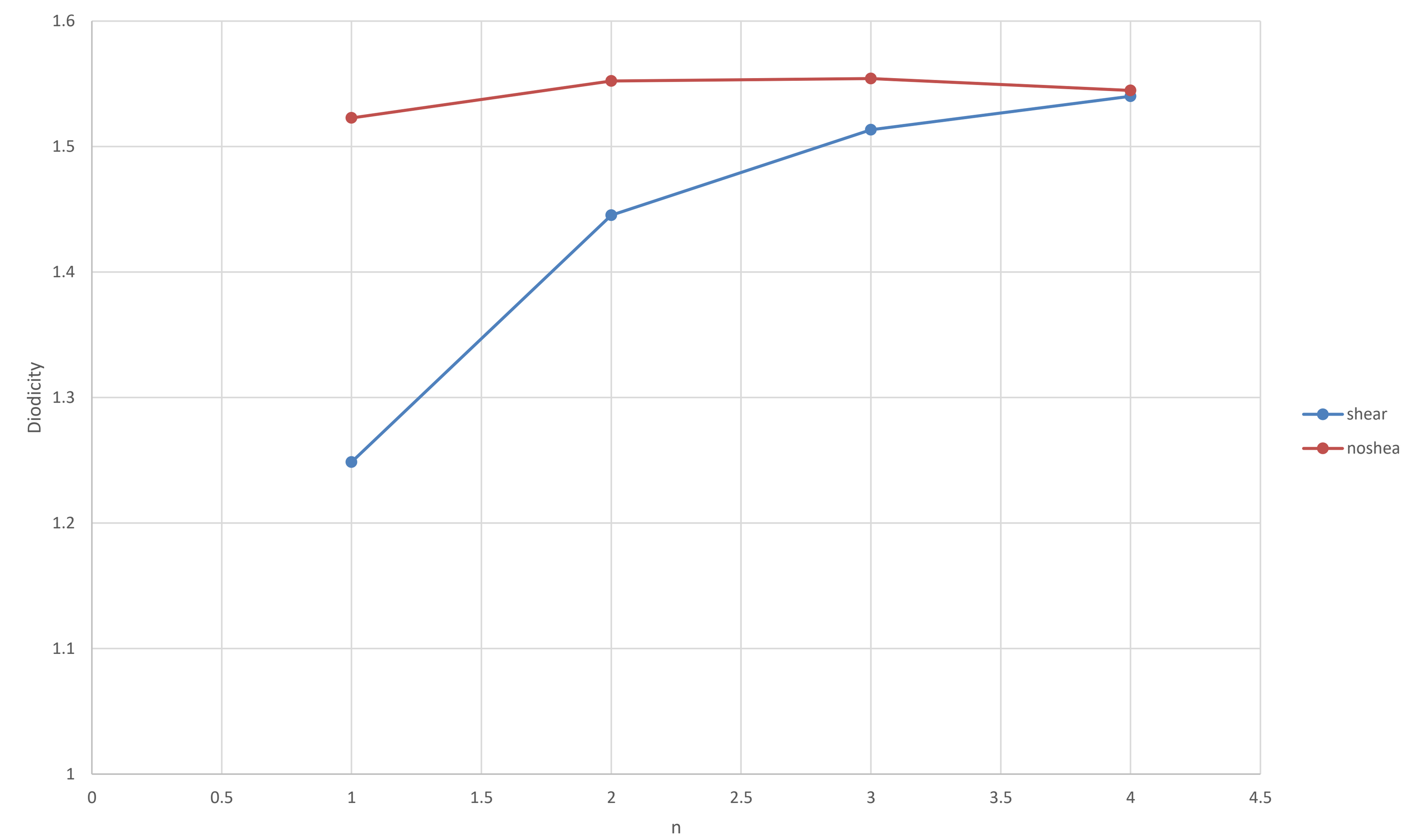

Fig 5: With/without shear stress diodicities

In the investigation of the influence of channel depth on Tesla valve diodicity, results indicate that diodicity increases with channel depth until reaching a saturation point, predominantly governed by shear stress exerted along the side walls. These findings have important implications for the design and optimization of Tesla valves in practical applications. In particular, controlling shear effects through precise geometric modifications can enhance diodicity, improving the valve's efficiency in areas such as microfluidics, passive flow control, and energy recovery systems. Based on the results, it is recommended that Tesla valve designs optimize depth-to-width ratios to minimize excessive shear while preserving the vortex structures essential for high diodicity. Future studies could further explore the relationship between wall shear and vortex stability, considering additional factors such as surface roughness and material properties. These insights contribute to the broader understanding of flow rectification mechanisms and pave the way for improved passive flow control technologies.