Computational Analysis of Fluid Dynamics and Heat Transfer in a Valvular Conduit Channel

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***Abstract*—The flow of fluid and thermal characteristics is computed for a channel with a Tesla valve-configured valvular conduit. Through three-dimensional simulation, we will investigate the channel's hydrodynamic performance as well as thermal performance effect of geometric parameters, flow directionality, and Reynolds number. The focus is on the flow rectification of Tesla valves and the mechanism of convective heat transfer without moving parts. The simulations of forward flow and reverse flow exhibit significant asymmetry in terms of velocity distribution, pressure drop, and heat transfer rates. Longitudinal vortices generated by forward flow stabilize the boundary layer and slightly enhance heat transfer. The reversal of flow creates transverse vortices. Turbulent structures can compress thermal layers and enhance heat transfer in geometry. Nusselt number, friction factor, and a new term measure directional difference: thermal diodicity index. The conduction angles and side channel lengths affect the valve diodicity and thermal efficiency. Heating a coil with a larger angle or volume generates more reverse flow than a circuit with a smaller angle and volume. The research also emphasizes the significance of geometrical optimization during implementation and the thermal performance pressure drop exchange. CFD models are validated with experimental data and are grid-independent. The design criteria obtained from the results allow for optimizing microchannel systems based on Tesla valve for thermal control of small heat exchangers, battery cooling and microfluidic devices. The current work enhances the comprehension of coupled fluid-thermal phenomena in valvular conduits and lays the foundation for a predictive framework 'for device design of passive flow control and heat transfer devices based on Tesla valve.**

***Index Terms*—Tesla valve, valvular conduit, heat transfer, CFD, Nusselt number, friction factor, vortex dynamics, reverse flow, numerical modeling.**

I. INTRODUCTION

As electronics cooling, aerospace, biomedical engineering and energy systems continue toward compact, efficient, high-performing thermal-fluidic systems, innovative flow control technologies are being examined for use. Recent progress in manufacturing and computer modeling have drawn attention to the Tesla valve or valvular conduit. The one-way valve, designed by Nikola Tesla in 1920 [1], is a passive flow rectifier with no moving parts that uses asymmetric internal geometry to boost one stream and resist the other. Due to its lack of mechanical components, the Tesla valve will always remain asymmetrical and thus, is very reliable and maintenance-free. Microscale thermal management is accomplished through the utilization of Mini channel and microchannel systems. They are essential for lab-on-chip systems, heat sinks for electronics, fuel cells, and microreactors. Such systems are adept in dissipating heat energy and mixing the components because they have high surface area volume ratios and short diffusion paths. In tight geometries, it is difficult to have flow control, especially for a unidirectional flow or selective heat rise. Benefits of using Tesla Valves in various industrial applications: the non-invasive valve with no moving parts provides flow rectification and thermal asymmetry without complexity or power consumption in such channels. The Tesla valve channel shape avoids flow disruption. The network of diverging and converging pathways, bifurcation junctions, and spiral side channels provides a smooth, laminar forward flow with low hydraulic resistance. A reverse flow generates multiple vortices, flow separations and zones of recirculation in certain locations along the design flow path.

The pressure drops and the thermal interactions increase in reverse flow which can be used to enhance passive heat transfer. The thermal performance difference between the two flow directions can be quantified through this innovative “thermal diodicity”. It is a key performance measure for practical thermal systems equipped with Tesla valves. Improvements in CFD, additive manufacturing and high-definition meshing have increased the popularity of Tesla valves. Mohammadzadeh et al. [2] and Piyush et al. [3] focused on the diodic nature of the single and multi-stage Tesla valves (MSTVs) whose enhancement in pressure and thermal rectification with number of stages and geometry optimization. Tesla steps numbering as many as ten weren’t the only ones that amplified disruption and thus mixing and heat transfer in reverse flow but so did moderate Reynolds numbers (Re = 25-500) when laminar flow assumptions leave and insight into how this may change has also been offered. Utilization of the Tesla valve has been explored for heat transfer modulation and flow control. According to Bao et al. [4], two other heat transfer performance metrics were suggested relative pressure drop ratio and absolute pressure drop ratio.

The new design of the Tesla valve with a tapering and broadening geometry performs better than older geometries. This indicates that geometric development of Tesla valves is still a promising study issue. As noted by Vries et al. [5], the valve in question functions effectively in pulsating heat pipes, which require a directed flow for thermal systems that rely on phase change. Due to the valve’s unequal resistances, the forward flow velocity was 25% different from the reverse flow velocity with 14% more heat dissipation. Tesla valves in their two-stage design have been a subject of research, but the heat transfer mechanisms in these valves remain poorly understood. Several investigations emphasized diodicity as the principal figure of merit, but Nusselt number (Nu), friction factor (f), and thermal diodicity (Dit) were not covered in great detail. The triplet enhances the comprehension of how valves are influencing the hydrodynamics and heat transfer, which is important for their ultimate application in thermal control systems. A numerical investigation into the fluid flow and thermal behaviour in a two-stage Tesla valve in circular conduit has been performed in this study to fill this gap. ANSYS Fluent CFD models are utilized to study heat transfer asymmetry, pressure drop, and vortex dynamics by systematically varying Reynolds numbers, geometric parameters (e.g., conduction angle, side channel length), and flow direction. The simulations are credible and validation studies show that empirical Nusselt values in laminar regime are within. We can create performance maps for real applications with Nusselt number and friction factor characteristics. The Darcy friction factor which considers the energy loss and Nusselt number convective heat transport performance. It is possible to refine the thermal management of Tesla valves by their behavior in different flow regimes. We also develop the directional comparison parameter Dit that captures the intentional use of heat transfer asymmetry. The study shows from a design point of view how angular/structural elements affect flow behaviour. The resistance to flow is high and turbulence is less when side channel lengths are more. This reduces the ability of the apparatus to transfer heat. With larger sharp conduction angles and fewer connections, vortex production and backflow mixing are encouraged, increasing Nu and pressure drop. Microfluidic heat exchangers are space-limited, so the design must be precise to remove heat without wasting energy. The most significant emphasis of the study is that the performance output of regression-based models relates geometrical attributes to realistic design. Engineers from diverse fields such as battery cooling, MEMS and renewable energy can utilize these predictive models while designing those interfaces. Mechanical valves frequently fail due to fouling, erosion, and limitations in power supply. The Tesla valve operates passively and is therefore preferred. Modern thermal-fluid systems use the Tesla valve owing to its simple structure. The non-symmetrical shape passively manages flow and more recent evidence will show improved directional heat transfer. This research employs numerical simulations, validations, and performance models to analyze the performance of the Tesla valve in compact systems. The results should enable biomedical engineers and renewable energy researchers to generate more robust, maintenance-free, energy-efficient devices.

II. RELATED WORK

In 1920, Nikola Tesla was granted a patent for the Tesla valve, which is a flow control device having no moving parts that creates greater resistance to flow in one direction than the other. Thanks to advancements in CFD, experimental visualization and 3D printing, these techniques have been revived. The demand for micro- and mini-channel designs for heat dissipation, microfluidics, and energy devices has increased interest in these geometrically complex but functionally straightforward valvular devices.

A. Historical and Foundational Studies

Mohammadzadeh et al. [11] investigated the optimum two-stage Tesla Micro-Valve (TMV) using the maximum diodicity (Di) to study one to four stage numerically. Performance does not scale linearly with number of stages, Returns decline after the second stage. Reynolds number (Re) significantly affects valve behavior, and Di clearly indicates this dependence. The hydrodynamic analysis of Multi Staged Tesla Valves (MSTVs) under laminar flow was conducted by Thompson. Research demonstrates that valve staging and tight valve-to-valve spacing greatly enhance diodicity for $Re > 50$. A power-law correlation predicted performance and assisted engineers in designs.

B. Thermal Performance Integration

Basil et al. [13] were among the pioneers to investigate a Tesla valve study with thermal effects and looked into heat transfer and pressure loss in MSTVs using different fluids (air, water, ethylene glycol). Their findings highlighted the valves' dual capability for heat rectification and fluid regulation. High intake temperature caused the water and glycol to reduce Di but the air increased it. Porwal et al. [14] computed thermal diodicity (Dit) as well as Nu and f using CFD. The study indicates that reverse flow promotes heat transfer because of vortex mixing and flow impingement. Micro-scale systems may use thermal modulators with esla valves.

C. Advanced Geometric Modifications and Optimization

According to the findings by Hu et al. [15], the performance of Tesla valves was greatest at condition $\theta = 70\text{-}80°$ due to the behaviour of separation bubble along with flow obstruction. Proper Orthogonal Decomposition (POD) methods were utilized to determine the dominating flow structures and energy modes in the reverse flow channel. According to Bao et al. [16], the ratio of pressure drop relative and absolute to Di is not an acceptable criterion of performance. The thermal performance based on the new widening-tapering design established that one can influence the flow dynamics through the junction design and the design of the expansion area. According to Raffel et al. [17], the numerical projections of Particle Shadowgraph Velocimetry (PSV) are proven to increase reverse flow instability as stage number increased vortex shedding. The findings supported diodic effects and underscored the significance of unstable flow events. The geometry of a Tesla valve designed for microfluidics was optimized by Sebastian et al. [18] using finite element topology optimization. The valves exhibited high Di values (~1.8) at low Re (~36), which enables their suitability for biomedical and chemical analytical systems adopting low flow rates.

D. Thermal Applications in Energy and Cooling Systems

MSTVs are proposed to improve the net power of PEMFCs. Layouts meant for magnetic stirring tapered vortexes (MSTV) generated lesser pressure loss, better oxygen distribution, and 19.89 % more net power in reverse flow relative to flow field layout.

Fan and others created a battery thermal management system with the use of PCMs and MSTVs. The hybrid technique preserved temperature stability and reduced electricity costs by up to 80%. Verifying the mandatory safety test values for EV battery cooling under varying discharge and ambient conditions. According to Lu et al. [21], a Tesla valve microchannel plate was used to study lithium-ion battery cooling. By designing both busbars and cooling jackets, the battery temperature remained below 30.5°C and the pressure drop low even at high heat flux. According to the work by Jun Du et al. [22] there is an S-type cold plate having MSTVs. The 30 mm valve spacing improves temperature uniformity affecting reverse flow vortex formation and mixing according to their calculations.

E. High-Performance System Enhancements and Noise Considerations

As proposed by Quan et al. [23], high-pressure hydrogen decompression aerodynamic noise can be mitigated through the utilization of MSTVs. It is discovered that the valve stage number, Mach number, and turbulent dissipation are directly related, which provide a design reference on hydrogen fuel system noise reduction. The Di and forward pressure loss were maximized and minimized, respectively, through the use of evolutionary algorithms and CFD. Researchers find that reducing valve-to-valve distance (G/Dh) significantly improving performance. The maximum Di is 1.811 at 173.03 Re.

F. Hybrid Systems and Emerging Applications

Lai et al. employed Tesla valve mini-channels for vertical battery heat management (2020). The study conducted in this paper has proved that the increased uniformity of the temperature at which the MSTVs can reduce the temperature spikes in the fast-discharging cycles and consequently improve the safety and cycle life of the battery system. The study investigated Tesla-type turbulators in hybrid spiral-tube exchangers. The complex design enhanced heat extraction from the fluid by inducing surface vortices to interact. Reddy and Goud explored a study involving MHD nanofluid flow between vertical Tesla-like plates. Heat recovery systems 'focus is on better thermal gradients with a lesser entropy formation. The study of Zhang et al. [28] is on the turbulent flow and its behaviour. Their results indicate surface forms of Nu and f value. Qian et al. studied Mach number variations in an MSTV Hydrodynamics system. According to them, every level must be optimized to mitigate flow-induced noise and shock wave generation.

G. Experimental Validation and Grid Verification

Tesla valve research prioritize validation. Simulation experiments by Paudel et al. [30] validated empirical Nu values with accuracy within 1% for Re = 50–500 thereby supporting numerical prediction methods heat transfer. Using finely graded meshes (~1 million elements) we have ensured grid independence and accurate prediction of vortex dynamics and thermal boundary layers.

H. Gaps in Literature and the Need for Comprehensive Frameworks

While earlier research assessed Di, there has been minimal scrutiny on the interdependence of the Nusselt number, friction factor, and thermal diodicity. Most studies utilized either single-stage valves or heavily tuned MSTVs with more than 10 stages. Two-stage Tesla valves are an example of intermediate designs that achieve a good trade-off between added complexity and efficiency. The effects of temperature gradients, changing flow directions, geometrical tolerances and non-Newtonian flow. This underscores the necessity of a performance framework which integrates valve geometry and operating conditions and thermal-fluid parameters to simulation and validation models.

Problem Statement

Despite being progressively employed in thermal and microfluidic systems, the dual purpose of Tesla valves in the literature is not yet well unified. Most previous studies have researched pressure diodicity, which is the valve's ability to block backflow from the downstream, but have not considered any thermofluidic interactions affecting valve performance. Focusing strictly on the aforementioned physical mechanism of closing and opening does not give consideration to flow direction, geometrical asymmetry, and vortex motion, for example, their consequence on heat transfer effectiveness, dissipation of energy, and pressure loss, in channels of valvular conduit. High-performance applications increasingly use multi-stage Tesla valve arrays. Two-stage layouts, which allow for geometrically simple designs with good performance. There is no systematic exploration of how conduction angle, side channel length, arc curvature, etc. affect thermal parameters such as Nusselt number, friction factor and thermal diodicity, and other characteristics. There is no performance model available in the literature that connects the thermal behaviour to hydrodynamic resistance for bidirectional flows. Without a comprehensive design framework, the Tesla valve design is essentially an empirical study that presents an inefficient design for micro systems like heat exchangers, battery cooling modules, and MEMS. The purpose of this paper is to carry out a thorough numerical evaluation of a two-stage Tesla valve implanted within a valvular conduit channel. This study investigates forward and reverse flow at various Reynolds numbers and establishes the relationship between geometry and flow and thermal behaviour. The objective of this research is to develop the interdependent behavior of Nu, f, and Dit to form a complete predictive design technique for passive thermofluidic systems. These types of systems will give more reliable and energy-efficient thermal management solutions.

III. NUMERICAL MODELING

In this section, the computational method for assessing the two-stage Tesla valve within the thermofluidic behaviour of a valvular conduit is discussed. The present study scrutinizes the heat transfer; pressure drop and flow characterization at different Reynolds numbers with the help of three-dimensional CFD.

A. Geometry and Boundary Conditions

In this study, a 3D model was prepared for a Tesla valve having a circular conduit cross-section. The main channel has a smooth pathway of radius 0.8 units through which fluid flows as laminar flow in the forward and backward directions. The shape is a through-channel and split arc path. Like a Tesla valve.

Table 1: Details of thermophysical properties of the material and fluid.

Thermophysical property	Steel	Water
Specific heat capacity	502.48 J/(kg.K)	4182 J/(kg.K)
Thermal conductivity	16.27 W/(m.K)	0.6 W/(m.K)
Thermal diffusivity	12.74×10^{-6} m²/s	1.4×10^{-7} m²/s
Melting point	1370°C–1510 °C	0 °C
Density	8030 kg/m²	998.2 kg/m²

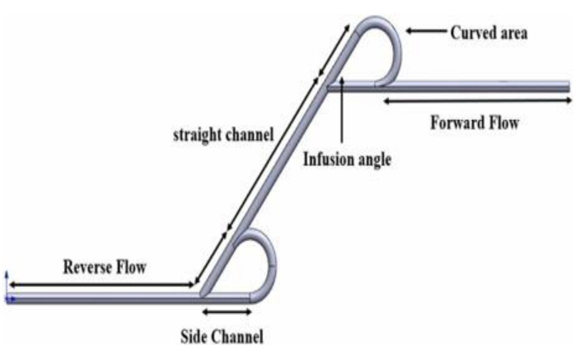

Fig 1. Schematic diagram of the Tesla valve design

The simulation of valve at steady flow yielded an entire temperature and velocity field. Application of laminar flow occurred with the increasing in the Reynolds number (Re) from 25 to 500. At low moderate flow vortex generation become noticeable so therefore value was chosen to evaluate performance.

These were the conditions at the edge, or boundary conditions:

- Inlet: Uniform velocity profile corresponding to desired Re.
- Outlet: Constant pressure (zero-gauge).
- Walls: No-slip condition, with a constant wall temperature of 340 K.
- Fluid: Water, with inlet temperature set at 292 K.

B. Governing Equations

The flow of the fluid and heat transfer was defined by the Navier–Stokes equations which were momentum and energy conservation principle:

- The assumptions outlined below resulted in the governing equations.
- A Newtonian fluid is one which, under a given strain rate, has a constant viscous stress in the fluid.
- Density of fluid is constant in incompressible flow.
- The thermal conductivity, viscosity and specific heat are constant in this transportational cooling modelling.
- This paper does not consider any gravitational or radiative effects.

The equations used are:

- Continuity equation
- Momentum equations (Navier–Stokes)
- Energy equation for thermal field resolution.

The numerical methods for the equations were offered in simulation setup.

C. Simulation Setup

A well-known computational fluid dynamic (CFD) solver ANSYS Fluent was used to carry out numerical simulation. The computing domain was discretized with 1 million elements structured mesh. Choosing the mesh density for accurate resolution of vortices and boundary layer without additional computational cost. Due to the low simulated Reynolds numbers, the Laminar Flow Model was employed. SIMPLE was utilized to solve pressure-velocity coupling. To enhance the precision of the solution, the second order upwind method was employed to solve the momentum and energy equation for spatial discretization.

The simulation technique was validated based on Nusselt number results for flow in conventional circular and rectangular channels with those reported in literature. The maximum variance of the computer model was 1% which proved the model correct.

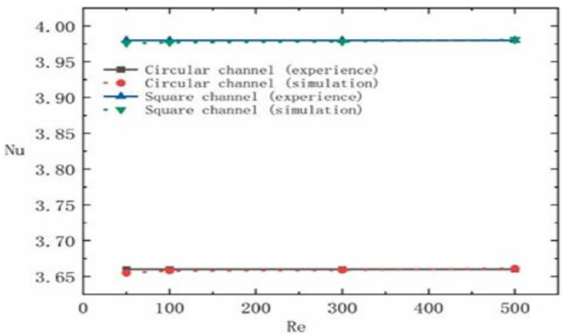

Fig. 2. Grid validity verification.

To ensure numerical stability and repeatability of the velocity and temperature fields in all simulations, the convergence criterion adopted was residual below 1x10-6.

IV. EXPERIMENTS AND RESULTS

This present section discusses the numerical data arising from the simulations of the Tesla valve at different values of the Reynolds number (Re) and the geometry. The flow, pressure, heat transfer and geometry are analysed.

A. Flow Characteristics

The speed field show the behavior of forwards and backwards flow. Essentially at Re of 25, disturbances occurring in the flow hit maximum at maximum flow streamer. As the Reynolds number (Re) increases, vortex formation intensifies at the entry and exit points of the arc channel. Vortices alter speed and disrupt flow.

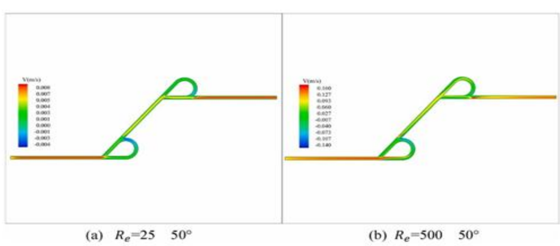

Fig. 3. Reverse flow velocity distribution.

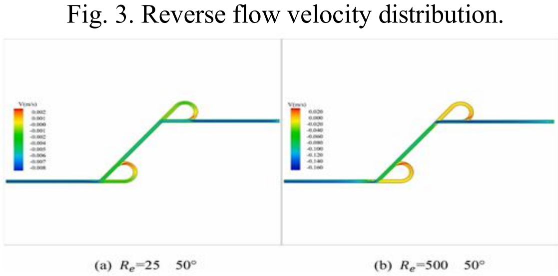

Fig. 4. Forward flow velocity distribution

Despite this, reverse flow generates more complex designs. Throughout the arc channel, vortex entrapment and recirculation zones are ubiquitous at junctions and bends. On the reverse path, these structures obstruct flow and reduce fluid velocity. With greater Re, strong vortices and reverse flow become more dissipative.

B. Pressure Distribution

The pressure distributions of the two flow directions are unequal. The streamwise motion in forward flow mitigates conduit pressure decline. Nonetheless, a rapid drop in pressure during reverse flow enhances vortex formation and flow impingement, particularly inside the arc channel.

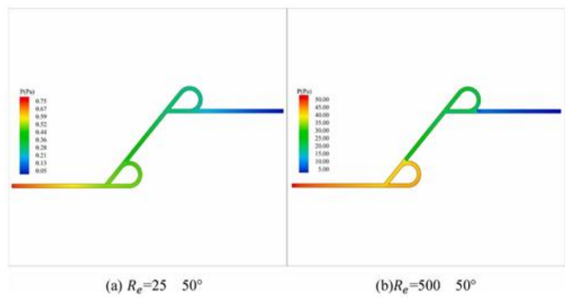

Fig. 5. Reverse flow Pressure distribution

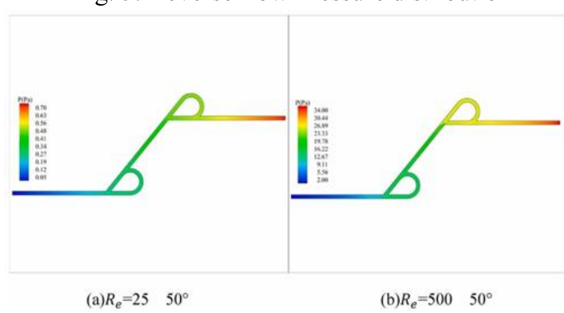

Fig. 6. Forward flow Pressure distribution

Certain arc exits exhibiting two-way pressure recovery are possibly owing to local sudden expansion and merger of flow paths. The interaction between influences of flow inertia and geometric confinement entrapment becomes vital at Re 500.

C. Heat Transfer Analysis

The dimensionless Nusselt number (Nu) measured convective heat transfer. As the conduction angle became larger, Nusselt number decreased for both forward and reverse flows. Turbulent mixing and convective enhancement can be reduced by longer and smoother paths, due to larger angles.

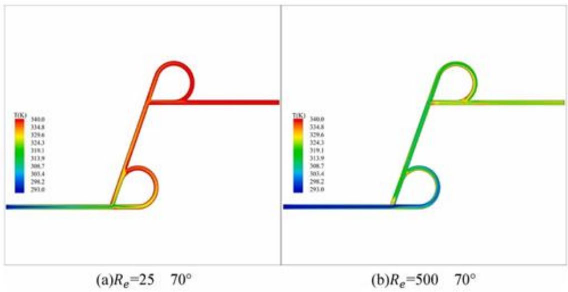

Fig. 7. Reverse flow temperature distribution

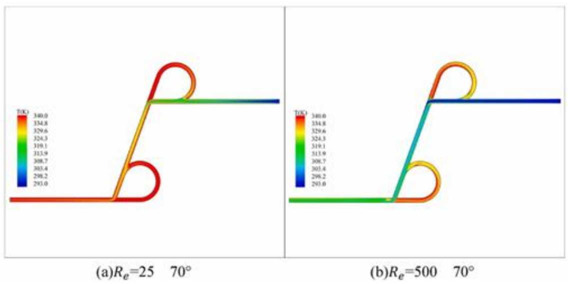

Fig. 8. Forward flow temperature distribution.

Nonetheless, the Nusselt number will always increase when the flow is reversed. Transverse vortices enhance fluid-wall contact by compressing the thermal boundary layer. Vortices augment turbulence and hinder thermal stratification, enhancing wall heat absorption.

D. Influence of Geometry

Thermal-hydraulic performance of the Tesla valve is affected significantly by geometrical changes:

- Extending the arc or side channel length leads to a decrease in friction factor and Nusselt number. Flow stability improves with smoother channels and less turbulence, but heat transfer efficiency suffers. This extended designer allows the fluid to flow smoothly around the curvature, reducing the mixing of fluids.
- The conduction angle, or guide angle, has an important impact on Dit and Nu. The larger the directing angles, the more vortex formation and thermal imbalance occur, especially at large Reynolds numbers. This angle increases the differential between forward and reverse flow heat transfer creating a strong diodic effect.

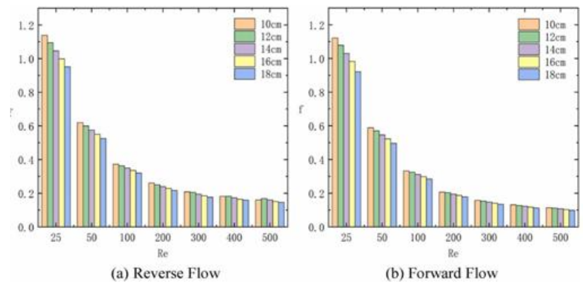

Fig. 9. Variation of the length of different side channels versus f

The performance of Tesla valves is sensitive to geometric design. Therefore, performance requires tuning the geometric parameters to achieve a good balance between flow resistance and thermal performance.

V. CONCLUSION

The fluid flow and thermal performance of a valvular conduit channel with a Tesla valve arrangement: a complete computational study Using detailed CFD models that simulate the valve shape, vortex dynamics, pressure distribution and convective heat transfer, complex interactions are studied for Reynolds numbers (Re 25-500) Results indicate that the function of the Tesla valve has directional asymmetry, while its thermal and hydrodynamic performances depend on forward and reverse flows. The main observation is that longitudinal vortices in the forward flow stabilize the boundary layer, while transverse vortices in the reverse flow compress the thermal boundary and intensify turbulence.

The increasing Nusselt numbers and thermal diodicity indices under the same shape and flow conditions indicate that these processes work in conjunction to enhance reverse flow heat transfer performance. The thermal performance and flow resistance are greatly influenced by the conduction angle and arc channel length as per the study. As the conduction angle is increased, a greater vortex is produced along with a more significant pressure drop. This shows that heat transfer is aided while energy loss is increased. With increasing side channel length, flow resistance reduces but thermal mixing decreases. The importance of geometric equilibrium in valve design has been stressed. Numerical results were compared to benchmark Nusselt data to verify simulation technique. A relative measure of thermal diodicity has been developed.

The model extends the performance evaluation and is best suited for thermal management applications when directionality of cooling and heating is key. This research refines the thermofluidic mechanics of the Tesla valve and paves the way for the optimization of energy systems, microfluidics, and compact heat exchangers. The results provided engineers with the ability to develop effective and fairly passive reliable thermal control components.

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