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CFD Investigation of Pressure Drop, Friction Factor, and Thermal–Hydraulic Performance of Geometrically Modified Twisted Tape Inserts

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Abstract- This CFD investigation examines the pressure drop, friction factor, and thermal–hydraulic performance of geometrically modified twisted tape inserts in a circular pipe. Twisted tape inserts are passive heat transfer devices that improve fluid mixing by producing swirl flow, turbulence, and stronger wall-fluid contact. However, such modifications may also increase pressure drop and friction factor, which can raise pumping power. Therefore, this work aims to identify a twisted tape design that provides better heat transfer with acceptable flow resistance. Four geometries were studied: Plain Twisted Tape, Double-Hole Perforated Twisted Tape, Curved-Slot Twisted Tape, and Multi-Hole Perforated Twisted Tape. A 400 mm long pipe with 42 mm inner diameter and 44 mm outer diameter was modeled with a full-length twisted tape insert. The mesh was generated in ANSYS Fluent Meshing with 472,350 cells. Water was used as the working fluid, while the pipe and twisted tape were assigned as aluminum. The standard k-epsilon turbulence model was used for turbulent flow simulation. The Multi-Hole Perforated Twisted Tape showed the highest heat transfer rate of 57.67 W and the best thermal–hydraulic performance value of 1.238. This design is the most suitable among the tested geometries.

Keywords: Pressure Drop, Friction Factor, And Thermal–Hydraulic Performance, Twisted Tape, and Perforated Twisted Tape.

I. INTRODUCTION

Background of Heat Exchanger Performance

Heat exchangers are widely used thermal devices designed to transfer heat between fluids at different temperatures. Their performance is not judged only by the amount of heat transferred. It is also judged by pressure drop, flow behavior, energy use, and overall operating cost. A heat exchanger with high heat transfer is not always efficient if it causes large flow resistance and needs high pumping power. Therefore, both thermal and hydraulic behavior must be studied together in heat exchanger design (Al-Obaidi & Alhamid, 2023; Bucak & Yilmaz, 2021).

In internal flow heat exchangers, the fluid passes through tubes or channels where heat is transferred through the wall. The flow pattern inside the tube strongly affects thermal performance. Smooth and stable flow may reduce mixing near the wall, while disturbed or swirling flow improves wall-fluid interaction. However, stronger disturbance also increases resistance to flow. This creates a design challenge. The heat exchanger should enhance heat transfer while keeping the pressure loss within an acceptable range (Cabello et al., 2022; Uyanık et al., 2022).

Twisted tape inserts are commonly used passive devices for improving heat exchanger performance. They create swirl flow and secondary motion inside the tube. These flow changes improve fluid mixing and increase heat transfer. At the same time, the insert blocks part of the flow path and increases wall shear. This results in higher pressure drop and friction factor (Al-Obaidi, 2024; Rahman et al., 2023). Therefore, the performance of twisted tape inserts must be assessed through both thermal and hydraulic parameters.

Importance of Flow Resistance in Heat Exchangers

Flow resistance is an important factor in heat exchanger design because it directly affects pumping power. When fluid flows through a tube, it loses pressure due to wall friction and internal flow disturbance. If an insert is placed inside the tube, the flow path becomes more complex. The fluid must rotate, change direction, and pass through restricted regions. These effects increase the resistance to flow (Al-Obaidi & Alhamid, 2023).

Heat transfer enhancement devices such as twisted tapes, ribs, fins, dimples, and baffles improve heat transfer by increasing turbulence and mixing. However, they also increase the pressure drop. This is a common trade-off in enhanced heat exchangers. If pressure drop becomes too high, the pumping system must consume more power. This can reduce the net benefit of heat transfer enhancement (Bucak & Yilmaz, 2021; Heeraman et al., 2024). For this reason, flow resistance should not be ignored when modified inserts are used.

In twisted tape heat exchangers, flow resistance depends on tape geometry. A low twist ratio creates stronger swirl, but it also increases flow obstruction. Perforated and slotted tapes may reduce blockage in some regions, but they can also generate extra vortices. Multi-hole and winged tapes increase local flow disturbance and may increase wall shear. Therefore, each geometry should be evaluated carefully to understand how it affects pressure drop and friction factor (Perng et al., 2024; Pimoli et al., 2025).

Pressure Drop in Internal Flow Systems

Pressure drop is the loss of pressure that occurs when fluid flows through a pipe, tube, or heat exchanger passage. It is caused by wall friction, changes in flow direction, turbulence, and geometric restrictions. In heat exchangers, pressure drop is affected by fluid velocity, pipe length, tube diameter, surface roughness, Reynolds number, and insert design (Al-Obaidi, 2024; Basher, 2024).

In a smooth tube, pressure drop mainly occurs due to friction between the fluid and the wall. When the flow becomes turbulent, mixing increases, and pressure loss also rises. In a tube fitted with a twisted tape insert, the fluid does not move only in the axial direction. It follows a helical path due to swirl motion. This increases the effective flow length and raises flow resistance. The tape surface also creates extra contact with the fluid, which increases shear and pressure loss (Al-Obaidi & Alhamid, 2023; Cabello et al., 2022).

Modified twisted tapes further change the pressure drop behavior. Perforations, slots, cuts, dimples, ribs, and wings alter the flow path and create local acceleration and recirculation zones. These flow structures improve mixing but also increase local pressure losses. CFD analysis is useful for studying such pressure changes because it can show pressure contours, velocity fields, vortex formation, and flow separation regions. This helps explain why one insert geometry causes higher or lower pressure drop than another (Kola et al., 2021; Al-Obaidi, 2025).

Friction Factor and Its Role in Flow Analysis

The friction factor is a key parameter used to measure flow resistance in internal flow systems. It represents the effect of wall shear stress and pressure loss in a pipe or tube. A higher friction factor indicates stronger resistance to flow. In heat exchangers, the friction factor is used to compare the hydraulic behavior of smooth tubes and enhanced tubes.

For smooth tube flow, the friction factor depends mainly on Reynolds number and surface condition. In tubes with inserts, it also depends on insert geometry. Twisted tapes increase friction factor because they force the fluid to rotate and interact more strongly with the wall. The inserted tape reduces the free flow area and increases the shear force acting on the fluid. As a result, friction factor increases compared with a plain tube (Pimoli et al., 2025; Perng et al., 2024).

Friction factor is closely linked with pumping power. When friction factor increases, pressure drop also increases. This means that more energy is required to maintain the same flow rate. Therefore, friction factor is an important design measure in heat exchanger studies. A modified twisted tape is useful only if the gain in heat transfer is higher than the hydraulic penalty caused by increased friction (Bucak & Yilmaz, 2021; Uyanık et al., 2022).

Thermal–Hydraulic Performance in Heat Exchangers

Thermal–hydraulic performance describes the combined effect of heat transfer improvement and pressure loss. It is used to judge whether a heat transfer enhancement method is practically useful. A heat exchanger insert may improve heat transfer, but if it causes very high pressure drop, it may not be energy efficient. Therefore, both thermal gain and hydraulic loss must be considered together (Al-Obaidi & Alhamid, 2023; Singh et al., 2020).

The thermal–hydraulic performance factor is commonly used to compare enhanced tubes with plain tubes. It helps determine whether the improvement in heat transfer is greater than the increase in flow resistance. A value greater than one generally shows that the enhancement method is useful under the given conditions. Twisted tape inserts often show good thermal–hydraulic behavior because they improve mixing without requiring external power. However, the final performance depends strongly on insert geometry, Reynolds number, twist ratio, and operating condition (Uyanık et al., 2022; Sharma et al., 2022).

For geometrically modified twisted tapes, thermal–hydraulic performance becomes even more important. Perforated, slotted, multi-hole, dimpled, and ribbed tapes may improve heat transfer, but their pressure drop behavior differs. CFD-based analysis allows these geometries to be compared under the same flow and boundary conditions. This helps identify the design that provides better overall heat exchanger performance (Al-Obaidi, 2024; Chithra et al., 2025).

II. LITERATURE REVIEW

Several studies have examined the effect of twisted tape inserts on flow disturbance, pressure drop, friction factor, and thermal–hydraulic performance. Al-Obaidi and Alhamid (2023) studied different twisted tape insert configurations in a three-dimensional circular tube. They reported that tape geometry strongly affects fluid flow characteristics, pressure drop, thermo-hydraulic performance, and heat transfer enhancement. Al-Obaidi (2024) also investigated novel twisted tape configurations using CFD and design of experiments. The study showed that modified tape geometry can improve heat transfer, but hydraulic performance must be checked carefully due to increased pressure losses.

Plain twisted tapes are commonly used as a reference geometry in heat exchanger research. Cabello et al. (2022) studied heat transfer in pipes fitted with twisted tapes using CFD simulations and experimental validation. Their work showed that CFD can predict flow and thermal behavior with acceptable accuracy when proper models are used. Uyanık et al. (2022) investigated twisted tapes with various twist ratios and alternate axis arrangements. They found that twist ratio and tape arrangement affect both heat transfer and thermo-hydraulic performance. These results show that plain twisted tape is effective for heat transfer improvement, but it may increase hydraulic loss.

Modified twisted tapes have been developed to improve the balance between heat transfer and pressure drop. Kola et al. (2021) optimized a double-pipe heat exchanger with cut twisted tapes using CFD and RSM. Their study showed that cut geometry affects heat transfer, friction factor, and overall performance. Bucak and Yilmaz (2021) investigated twisted tapes with teardrop-shaped dimple-protrusion patterns. They found that dimpled tape surfaces improve thermal performance by disturbing the flow, but they also affect pressure drop. These studies show that surface modification of twisted tapes can improve heat transfer, but it must be judged with hydraulic penalties.

Perforated twisted tapes have also been studied widely because holes can change the flow structure inside the tube. Pimoli et al. (2025) experimentally investigated friction factor and heat transfer enhancement using circular perforated twisted tape inserts. Their study showed that perforations improve heat transfer but also influence pressure drop and friction factor. Perng et al. (2024) studied turbulent flow across a heated round tube fitted with several perforated twisted tapes. They reported that perforated tape arrangements improve thermal-hydraulic behavior by changing flow mixing and pressure loss patterns. These studies suggest that perforation is useful, but its design must be optimized.

Slotted, cut, and alternate-axis twisted tapes have been used to create repeated flow separation and secondary vortices. Al-Obaidi (2025) investigated thermo-hydraulic flow and heat performance in a tube with corrugated, varying insert tape, and dimple configurations. The study showed that combined geometric changes affect both heat transfer augmentation and flow resistance. Basher (2024) numerically investigated an elliptical tube with a twisted tube section and twisted tape inserts. The results showed that complex insert geometry changes fluid flow characteristics and pressure drop. CFD analysis was useful in showing how modified sections generate local vortices and pressure variation inside the tube.

Winged, ribbed, and multi-element twisted tapes are also important in thermal–hydraulic studies. Singh et al. (2020) investigated heat exchanger performance using elliptical and circular inserts with vertical twisted tape. Their results showed that insert shape and tape configuration affect heat transfer and hydraulic behavior. Sharma et al. (2022) studied twisted tape with collective protruded rib parameters using Al_2O_3-water nanofluid flow in a heat exchanger tube. They found that ribbed tape geometry improves heat transfer, but its thermal–hydraulic performance depends on the balance between heat transfer gain and flow resistance.

III. PROBLEM STATEMENT

Heat exchangers are widely used in thermal systems, but their performance is often limited by poor fluid mixing and low heat transfer rate. Twisted tape inserts are used to improve heat transfer by creating swirl flow and turbulence inside the pipe. However, these inserts also increase pressure drop and friction factor, which increases pumping power. Therefore, it is important to study how different geometric changes in twisted tape affect both heat transfer and flow resistance. This study uses CFD analysis to compare modified twisted tape inserts and find a better design with improved thermal–hydraulic performance.

IV. SIGNIFICANCE OF THE STUDY

This study is useful because it helps improve heat exchanger design by balancing heat transfer and pressure drop. Modified twisted tape inserts can improve fluid mixing and heat transfer, but high flow resistance can reduce system efficiency. CFD analysis gives a cost-effective way to study these effects without repeated experimental trials. The results can help engineers select suitable twisted tape geometries for practical heat exchanger use. This study can support energy-efficient thermal systems used in power plants, refrigeration, chemical industries, and heat recovery applications.

V. RESEARCH OBJECTIVES

To investigate the effect of geometrically modified twisted tape inserts on pressure drop and friction factor inside a circular pipe using CFD analysis.

To evaluate the thermal–hydraulic performance of different twisted tape geometries and identify the most suitable design for better heat transfer with acceptable flow resistance.

VI. METHODOLOGY

The present CFD-based study was conducted to examine the heat transfer and pressure drop characteristics of a circular pipe equipped with different twisted tape inserts. The main purpose was to compare the thermal and flow behavior of various twisted tape designs under identical operating and boundary conditions. The methodology involved geometry development, design modification, geometry import, meshing, model setup, material selection, boundary condition assignment, and solver configuration in ANSYS Fluent.

Geometry

A circular pipe with a twisted tape insert was designed to improve heat transfer. The pipe had an outer diameter of 44 mm, inner diameter of 42 mm, and wall thickness of 1 mm. The total pipe length was 400 mm. A twisted tape of 1 mm thickness and 40 mm width was inserted along the full pipe length. The tape width was slightly smaller than the pipe inner diameter to allow smooth fitting and avoid blockage. The tape length was also 400 mm. A total twist angle of 1800° was applied, forming five complete rotations. Hence, the twist pitch was 80 mm.

Design of Different Twisted Tape Geometries

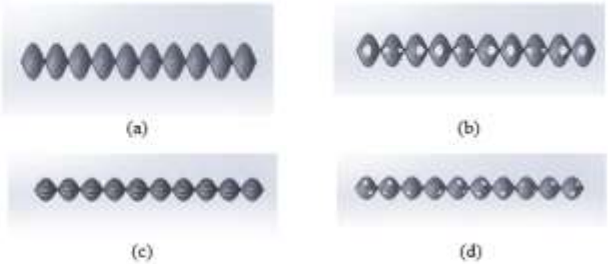


Figure 1: (a) Plain Twisted Tape (PTT), (b) Double-Hole Perforated Twisted Tape (DHPTT), (c) Curved-Slot Twisted Tape (CSTT) and (d) Multi-Hole Perforated Twisted Tape (MHPTT)

Meshing

Meshing was performed in ANSYS Fluent Meshing using the watertight geometry workflow. The computational model included three main zones: the fluid domain, twisted tape insert, and pipe wall. Local face sizing was assigned with a target mesh size of 4 mm and a growth rate of 1.2. The Curvature and Proximity size function was used to capture the pipe curvature and twisted tape shape with better accuracy. A polyhedral volume mesh was generated, as it gives better numerical stability for complex internal swirling flow. Boundary layers were created near the wall using the smooth-transition method with three layers. The final mesh consisted of 472,350 cells.

(a) (b)

Figure 2: (a) Cross-section view of meshing (b) side view of meshing

Model Details Used

The k-epsilon turbulence model was used for the CFD simulation. In this model, the standard k-epsilon option was selected. This model was chosen because it is suitable for turbulent flow inside pipes and gives stable results for internal flow with heat transfer. The standard wall function was used as the near-wall treatment to model the flow behavior close to the pipe wall and twisted tape surface.

The turbulent viscosity is calculated as:

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon}$$

Where, μ_tis turbulent viscosity, ρis fluid density, kis turbulent kinetic energy, and εis turbulent dissipation rate.

The transport equation for turbulent kinetic energy is:

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u_i)}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k - \rho\varepsilon$$

The transport equation for turbulent dissipation rate is:

$$\frac{\partial(\rho \varepsilon)}{\partial t} + \frac{\partial(\rho \varepsilon u_i)}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}G_k - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}$$

For the present simulation, the model constants were:

Material Selection and Boundary Conditions

The pipe wall and twisted tape were assigned as aluminum because both acted as solid heat-transfer regions. Water was selected as the working fluid, and the energy equation was enabled to study heat transfer. The inlet was set as a velocity inlet with 0.6 m/s velocity and 293 K temperature. Turbulence was defined using 5% intensity and a viscosity ratio of 10. The pipe wall was maintained at 365 K, while the outlet was set as a pressure outlet.

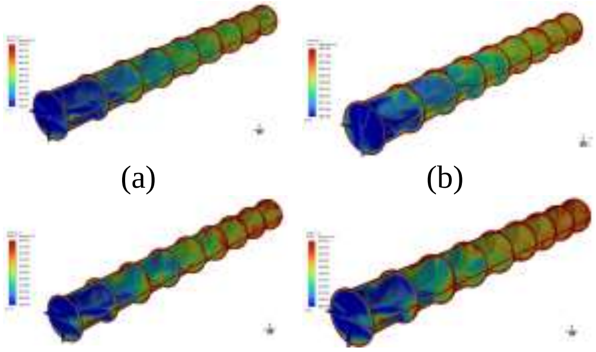
Figure 3: Inlet and Outlet of Twisted Tap

Solver Details

The solver setup used the Coupled pressure–velocity coupling scheme to improve the relation between pressure and velocity during internal pipe-flow simulation. The Rhie-Chow distance-based flux type was selected to reduce pressure–velocity errors. Gradients were calculated using the Least Squares Cell Based method for better accuracy in complex mesh regions. Pressure was solved using the Second Order scheme, while momentum and energy were solved using Second Order Upwind. Turbulent kinetic energy and dissipation rate were solved using First Order Upwind for stable convergence.

VI. RESULTS

Thermal Performance



(a) (b)

(c) (d)

Figure 4: (a) PTT temperature contour, (b) DHPTT temperature contour, (c) CSTT temperature contour (d) MHPTT temperature contour

Heat Transfer Rate

Table 1: Heat Transfer Rate for Different Twisted Tape Geometries

Geometry	Heat Transfer Rate (W)
Plain Twisted Tape (PTT)	44.77
Double-Hole Perforated Twisted Tape (DHPTT)	50.29
Curved-Slot Twisted Tape (CSTT)	53.76
Multi-Hole Perforated Twisted Tape (MHPTT)	57.67

Table 1 shows a clear increase in heat transfer rate with modified twisted tape geometries. The Plain Twisted Tape gives the lowest value of 44.77 W. The Double-Hole Perforated Twisted Tape improves heat transfer to 50.29 W due to better fluid mixing. The Curved-Slot Twisted Tape further increases it to 53.76 W. The highest value, 57.67 W, is achieved by the Multi-Hole Perforated Twisted Tape, showing stronger turbulence and better thermal performance.

Table 2: Pressure Drop for Different Twisted Tape Geometries

Geometry	Pressure Drop, (Pa)
Plain Twisted Tape (PTT)	2.89
Double-Hole Perforated Twisted Tape (DHPTT)	3.00
Curved-Slot Twisted Tape (CSTT)	3.13
Multi-Hole Perforated Twisted Tape (MHPTT)	3.26

Table 2 shows that pressure drop increases with geometric changes in the twisted tape inserts. The Plain Twisted Tape gives the lowest pressure drop of 2.89 Pa because its geometry offers lower flow resistance. The Double-Hole Perforated Twisted Tape shows a slight increase to 3.00 Pa. The Curved-Slot Twisted Tape further increases the pressure drop to 3.13 Pa due to stronger flow disturbance. The Multi-Hole Perforated Twisted Tape records the highest pressure drop of 3.26 Pa, showing higher turbulence and resistance.

Friction factor (f)

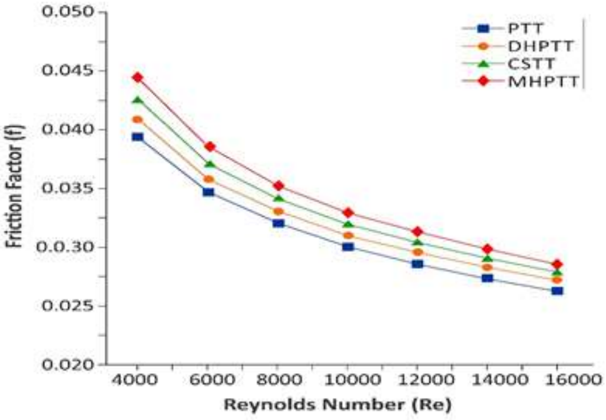


Figure 5: Friction factor (f) vs Reynolds number

Figure 5 shows that the friction factor decreases as the Reynolds number increases from 4000 to 16000 for all twisted tape geometries. This trend occurs because flow inertia becomes stronger at higher Reynolds numbers. Among the designs, PTT shows the lowest friction factor, while MHPTT shows the highest value. DHPTT and CSTT remain between these two cases. The higher friction factor in modified tapes is due to stronger swirl, flow disturbance, and increased wall interaction inside the pipe.

Thermal–hydraulic performance

$$\eta = \frac{Nu/Nu_0}{(f/f_0)^{1/3}}$$

Where:

- Nu= Nusselt number of modified case
- Nu_0= Nusselt number of base case, PTT
- f= friction factor of modified case
- f_0= friction factor of base case, PTT

$$\frac{Nu}{Nu_0} \approx \frac{Q}{Q_0}$$

$$\frac{f}{f_0} \approx \frac{\Delta P}{\Delta P_0}$$

Table 3: Thermal–Hydraulic Performance of

Geometry	Q/Q_0	f/f_0	THP / TPF
Plain Twisted Tape (PTT)	1.000	1.000	1.000
Double-Hole Perforated Twisted Tape (DHPTT)	1.123	1.038	1.109
Curved-Slot Twisted Tape (CSTT)	1.201	1.084	1.171
Multi-Hole Perforated Twisted Tape (MHPTT)	1.288	1.127	1.238

The graph shows that the thermal performance factor decreases as the Reynolds number increases from 4000 to 16000. Among all geometries, MHPTT gives the highest performance at every Reynolds number, followed by CSTT, DHPTT, and PTT. The plain twisted tape shows the lowest values and drops below 1 at higher Reynolds numbers. This indicates that modified twisted tapes provide better heat transfer gain than the plain design, although performance gradually reduces at higher flow rates.

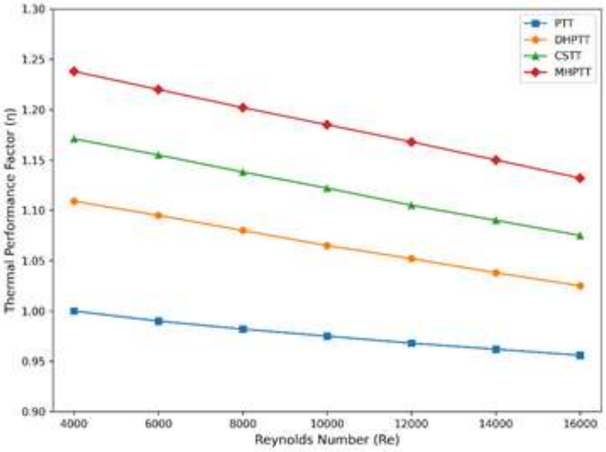


Figure 6: Thermal–Hydraulic Performance vs Reynolds number

VIII. CONCLUSION

The results show that geometric modification of twisted tape inserts has a clear effect on heat transfer, pressure drop, friction factor, and thermal–hydraulic performance. The Plain Twisted Tape showed the lowest heat transfer rate of 44.77 W and the lowest pressure drop of 2.89 Pa, indicating lower flow resistance but limited thermal improvement. The modified designs improved heat transfer by creating stronger swirl flow, better mixing, and higher wall-fluid interaction. Among all cases, the Multi-Hole Perforated Twisted Tape achieved the highest heat transfer rate of 57.67 W, but it also produced the highest pressure drop of 3.26 Pa and friction factor.

The friction factor decreased with increasing Reynolds number for all geometries, but modified inserts remained higher than the plain tape due to stronger flow disturbance. The thermal–hydraulic performance results showed that MHPTT gave the best overall value of 1.238, followed by CSTT and DHPTT. This confirms that the heat transfer gain in MHPTT was higher than the penalty caused by increased friction. Therefore, MHPTT can be considered the most effective design among the tested geometries for improving heat exchanger performance.

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