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Simulation Study of Energy Dissipation Efficiency of Tesla Energy Dissipation Device in High-Pressure Oil and Gas Pipeline

Yuxuan Li

School of Xi'an Petroleum University, Xi'an Shaanxi, 710065, China

Abstract

Based on the standard k-ε model and multiphase flow model, numerical simulations were used to study the effects of inlet pressure, fluid components and different numbers of cascade stages on the energy dissipation efficiency of Tesla dissipation devices in high-pressure oil and gas pipelines. The simulation results show that: In the general pressure range of high-pressure oilfield recovery fluids, with the increase of inlet pressure, the single-stage Tesla energy dissipation device's energy dissipation efficiency with the increase of inlet pressure shows a gradual increase in the trend of inlet pressure, and the larger the inlet pressure, the more obvious energy dissipation effect. In the case of a certain inlet pressure, the single-stage Tesla energy dissipation device for the different flow media from high to low energy dissipation efficiency is: oil, oil-water mixed media, water. And in the oil-water mixing medium, The greater the proportion of oil, the better the energy dissipation effect; At a constant inlet pressure, the dissipation efficiency of the Tesla energy dissipation device increases gradually with the number of stages in series, but the value of the pressure drop produced by each stage tends to decrease gradually as the number of stages of the energy dissipation device increases. Taking into account the effect of energy dissipation and economic efficiency, it is determined that the optimal number of series connection stages for energy dissipation device is 4.

Keywords

Tesla Energy Dissipation Device; Numerical Simulation; High-Pressure Oil and Gas Pipelines; Energy Dissipation Efficiency.

1. Introduction

In the production of oil and gas fields, hydraulic fracturing and other extraction methods result in the return of the extraction fluid at high pressure, which not only shortens the service life of the equipment, but also poses a threat to the safety of production, so it is necessary to carry out energy dissipation and pressure reduction of the fluid in the pipeline. Currently, the oil field often uses the nozzle for pressure reduction, which has the disadvantages of rapid wear, low productivity and high maintenance costs. Hedge-type energy dissipation device is to consume pressure energy head and velocity energy head by mutual impact between fluids and convert them into internal energy and thermal energy to achieve the purpose of energy dissipation and pressure reduction[1].At present, the hedge type energy dissipation device is often used in water conservancy dams, energy dissipation sluice and other semi-closed and semi-open environment, on the use of hedge energy dissipation in the fully enclosed pipeline mode of research is relatively small. Therefore, the study of hedonic energy dissipation devices in pipelines is expected to be a completely new area of application for hedonic energy dissipation[2].

Previously, scholars have studied the energy dissipation of fully enclosed pipelines. Zhang Xuelan et al[3]. investigated the flow field characteristics such as velocity, pressure, streamline distribution and energy dissipation efficiency of the rotary ladder energy dissipation device under the conditions of different ladder plate spacing by using CFD software. The results show that The total energy dissipation efficiency increases gradually as the flow rate and the distance between the conductor plates increase. He Ning et al[4]. used the standard model to numerically simulate and analyse the flow field of an orifice plate with different aperture ratios. It was found that the smaller the aperture ratio, the higher the flow rate, the higher the energy dissipation coefficient and the better the energy dissipation effect. Wang Ningning et al.[5] simulated the unidirectional fluid-solid coupling of a spherical hedonic energy dissipator using Fluent software. The results show: In the range of 20~50MPa, the energy dissipation efficiency of the 10mm hedge type energy dissipator is less affected by the total inlet pressure, and the energy dissipation efficiency is basically stabilised at 70%;The outlet velocity of a hedge energy dissipator does not increase abruptly relative to the inlet velocity, emphasising the advantage of a hedge energy dissipator that does not generate high flow velocities while dissipating energy. Zhang Renjie [6]improved the spherical hedonic dissipative structure by changing the spherical shape of the hedonic zone to a square shape to investigate the flow field distribution and erosion characteristics. The results show: As the flow rate and the diameter of the solid particles in the fluid increase, the erosion rate of the square counterpoise energy dissipator is higher than that of the spherical counterpoise energy dissipator. The Tesla valve was first proposed by Nikola Tesla, compared with needle valves, there is no movement between components, which provides a longer service life. According to the working principle of the Tesla valve, the design of energy dissipation device for pipeline energy dissipation, Tesla energy dissipation device, its working principle is to change the structure of the flow path itself, so that the fluid flowing through the valve at the beginning of the end of the diversion, so that the fluid is diverted into two streams of different directions, different flow rates, different velocities, and with a certain angle of the fluid. At the confluence end of the fluid and fluid, fluid and pipe wall intense fluid shear, so that the formation of strong shear within the fluid, the emergence of part of the vortex flow, and triggered by violent impact, resulting in turbulence phenomenon, the formation of hedonic self-consumption in the pipeline, so as to achieve the purpose of eliminating the energy to reduce the pressure[7].Previously, many scholars have studied the performance of Tesla valves. Zhou Runzhong et al.[8] numerically simulated the performance of the Tesla valve using COMSOL software to study the effect of relevant parameters on the unidirectional flowability of the valve. The results show: Tesla valves are suitable for low viscosity, high density fluids. Feng Luwen et al.[9] modelled and simulated the Tesla valve with COMSOL and obtained the results of its forward and backward pressure drop while varying the characteristic length and characteristic angle for multiple simulations to optimise the unidirectional conductivity of the Tesla valve. Wen Ya et al.[10] mechanistically determined the feasibility of large-scale Tesla valves applied to aqueduct corridors mechanistically by performing seepage simulations of large-scale single-stage and multi-stage Tesla valves with Re numbers ranging 0.001 to 1000.

In this paper, we mainly use Fluent software in ANSYS to simulate the energy dissipation efficiency of Tesla energy dissipation device, and study the effects of inlet pressure, fluid components and different cascade numbers on the dissipation efficiency of Tesla energy dissipation device, so as to provide reference for improving the economic efficiency and safety of oil and gas production and transportation.

2. Computational Model

Compared with the RNG k-ε Turbulence Model and Realizable k-ε Turbulence Model, the Standard k-ε Model is widely used to analyse industrial equipment with complex flow structures with high adaptability and accuracy.Song et al. [11]compared different turbulence models and found that with different turbulence models, the standard k-ε model has very little effect on the simulation results. Therefore, in this paper, the standard$k$-εturbulence model is chosen for the numerical simulation of the Tesla energy dissipation device. Its turbulent kinetic energy k and dissipation rate ε can be expressed by the following equations:

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u_i)}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\left\{\left(\mu + \frac{\mu_i}{\partial x_j}\right)\right\}\right] + G_k + G_b - \rho\varepsilon - Y_M + S_k \tag{1}$$

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u_i)}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\left\{\mu + \frac{\mu_i}{\sigma_\varepsilon}\right\}\frac{\partial k}{\partial x_i}\right] + G_{1\varepsilon}\frac{\varepsilon}{k}(G_k + C_{2\varepsilon}G_B) - C_{3\varepsilon}\rho\frac{\varepsilon^2}{k} + S_\varepsilon \tag{2}$$

$$\varepsilon = \frac{u}{\rho}\left(\frac{\partial u_i'}{\partial x_k}\right)\left(\frac{\partial u_i'}{\partial x_j}\right) \tag{3}$$

$$G_k = \mu_t\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\frac{\partial u_i}{\partial x_j} \tag{4}$$

$$G_b = \beta g_i \frac{u_t}{\rho r_t}\frac{\partial T}{\partial x_j} \tag{5}$$

$$Y_M = 2\rho\varepsilon M_t^2 \tag{6}$$

Where: $G_k$represents Turbulent kinetic energy due to average velocity gradient;G_b represents Turbulent kinetic energy due to buoyancy; Y_M represents Turbulent kinetic energy from fluid dissipation rate in compressible turbulence; μ_t represents turbulent viscosity; $C_{1\varepsilon}$, $C_{2\varepsilon}$, $C_{3\varepsilon}$represents empirical constant, $G_{1\varepsilon}$=1.44, $C_{2\varepsilon}$=1.92, $C_{3\varepsilon}$=0.09; S_k and S_ε represents the source terms of k and ε respectively; σ_ε and σ_k represents Planck's number corresponding to the dissipation rate equation and the turbulent kinetic energy equation, dimensionless number. Since the fluid studied in this paper is an incompressible fluid, G_b=0,Y_M=0.

Selection of standard wall functions for the near-wall region, pressure-velocity coupling using the fast converging SIMPLEC algorithm, The discretisation of momentum, turbulent kinetic energy and turbulent dissipation rate are all in second-order windward format, and the cycling surface is in relative no-slip boundary conditions with stationary walls.

3. Physical Modeling

3.1. Geometric Modeling and Meshing

The Tesla energy dissipation device consists of an inlet section, an outlet section, and an inclined pipe section, and the model schematic is shown in Figure 1. The parameters of the Tesla energy dissipation device are set according to the actual situation, where the length of the valve inlet section is 210mm, the length of the valve outlet section is 210mm, the length of the valve inclined pipe section is 45mm, the angle between the inclined pipe section and the straight pipe section is 40°, the radius of the inner curve is 45mm, and the depth of the pipe and the width of the pipe are both 25mm.

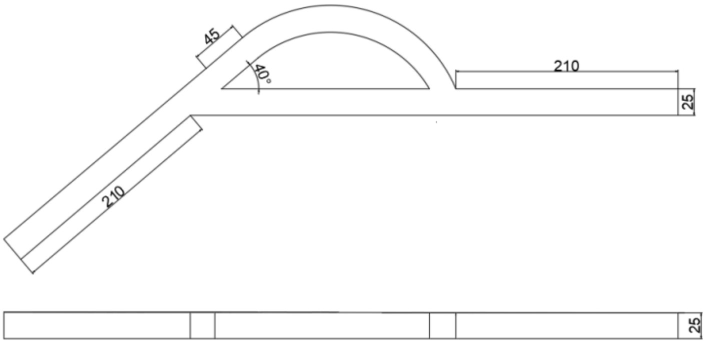

Fig 1. Physical model of Tesla's energy dissipation device

The meshing software in Fluent was used to mesh the model using a multi-area meshing method. This method allows the model to be divided into small cubic meshes, which is very suitable for the model in this paper. To ensure the accuracy of the calculation of the complex flow field inside the pipeline, the energy dissipation device is locally encrypted and the processed mesh is shown in Figure 2:

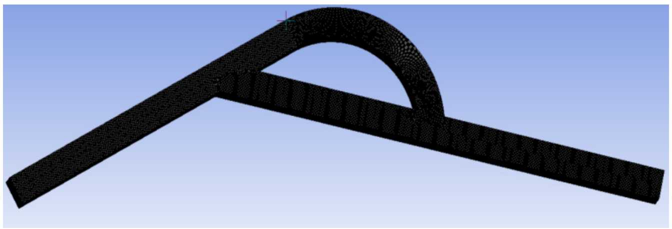

Fig 2. Grid diagram of Tesla's energy dissipation device

3.2. Grid-independent Verification

In order to improve the simulation accuracy and to reduce the computational cost, the processed model is checked for mesh independence. As shown in Figure 3, the number of meshes in 2100000, the differential pressure tends to flatten out, the pressure drop is basically unchanged, the impact on the calculation results of the model is relatively small and negligible, so the number of meshes of 2100000 is selected for calculation.

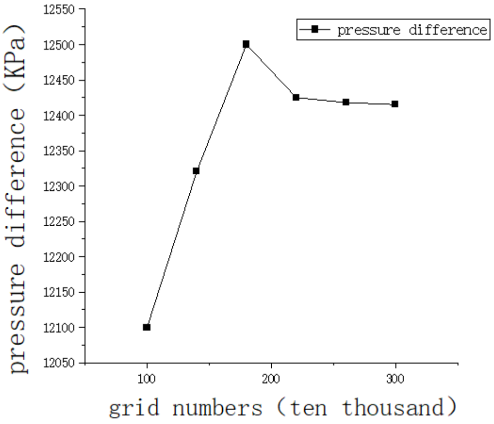

Fig 3. Differential pressure with different number of grids

3.3. Boundary Conditions

High pressure oilfield site recovery fluids have high pressures, generally in the range of 8 to 25MPa. Combined with the actual oilfield work, 10MPa is used as the inlet pressure value for the numerical simulation in this paper. The wall function between the pipe and the wall is set to the system default of a no-slip wall.

3.4. Feasibility Verification

In order to verify the accuracy of the numerical model constructed in this paper, its calculation results are compared with the experimental data of Zhou Runzhong[8]. Validation is carried out by comparing the *Di* values of the unidirectional conduction performance parameters of the Tesla energy dissipation device at different fluid densities. After simulation, it is found that the average error between the experimental data and the simulated values in this paper is 8.7% (within 10%), which is within the acceptable range of error and verifies the feasibility of the model, as shown in Fig. 4:

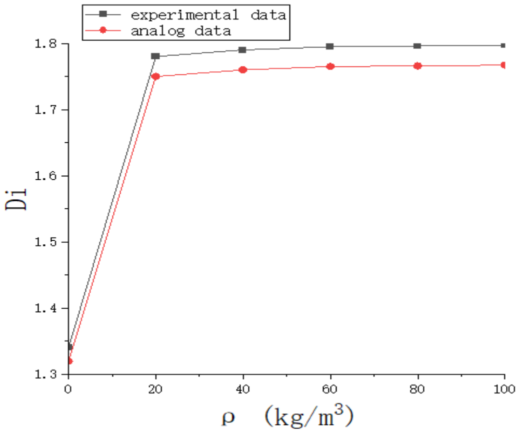

Fig 4. Comparison of experimental data and simulation data

4. Results and Discussion

4.1. Calculation Method of Energy Dissipation Efficiency of Tesla Energy Dissipation Device

The energy dissipation efficiency can be calculated using the following formula:

$$\eta = \frac{P_{in} - P_{out}}{P_{in}} \times 100\% \tag{7}$$

Where:P_{in} represents Pipe inlet pressure, Pa; P_{out} represents Pipe outlet pressure, Pa.

The total pressure value of the Tesla energy dissipation device consists of a static pressure value and a dynamic pressure value, which is the pressure converted from the velocity when the fluid in the energy dissipation device is secured, and is expressed as follows:

$$P_d = \frac{1}{2}\rho V^2 \tag{8}$$

So the power dissipation efficiency equation can be changed to:

$$\eta = \frac{\left(P_{is} + \frac{1}{2}\rho V_{in}^2\right) - \left(P_{os} + \frac{1}{2}\rho V_{out}^2\right)}{\left(P_{is} + \frac{1}{2}\rho V_{in}^2\right)} \times 100\% \tag{9}$$

Where: V_{in},V_{out} represents Velocity values at the inlet and outlet of the energy dissipation device, m/s; P_{is},P_{os} represents Pressure at the inlet and outlet of the energy dissipation device, Pa.

4.2. Effect of Different Inlet Pressures on the Energy Dissipation Efficiency of Tesla Energy Dissipation Device

The energy dissipation efficiency of the Tesla energy dissipation device with inlet pressures of 8MPa, 11MPa, 14MPa, 17MPa, 20MPa and 23MPa was analysed according to the actual working conditions in the field. The pressure distribution of the Tesla energy dissipation device at different inlet pressures is shown in Fig. 5:

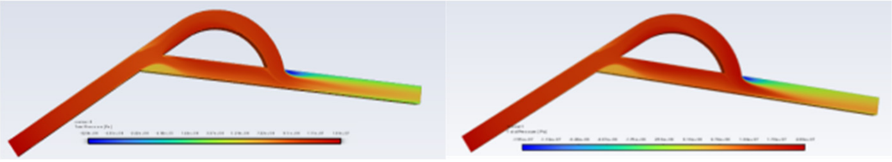

Fig.(a) Inlet pressure of 8MPa Fig.(b) Inlet pressure of 11MPa

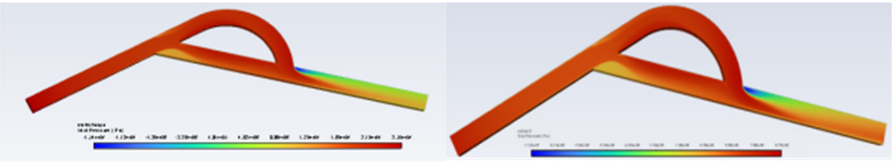

Fig. (c) Inlet pressure of 14MPa Fig.(d) Inlet pressure of 17MPa

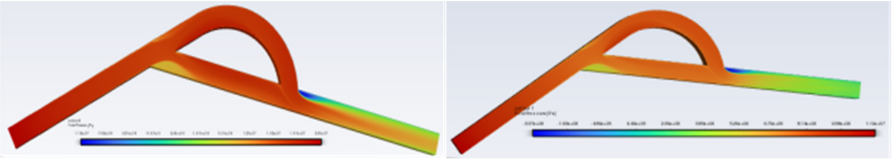

Fig.(e) Inlet pressure of 20MPa Fig.(f) Inlet pressure of 23MPa

Fig 5. Pressure distribution of Tesla energy dissipation device at different inlet pressures

From Fig. 5, it can be seen that the pressure cloud distribution in the Tesla energy dissipation device is similar at different inlet pressures, and the area of the low-pressure region of the fluid in the straight pipe section of the Tesla energy dissipation device tends to increase gradually with the increase of the inlet pressure. The energy dissipation efficiency of the Tesla energy dissipation device at different inlet pressures is shown in Table 1:

Table 1. Analysis of energy dissipation efficiency of Tesla energy dissipation device under different inlet pressures

inlet pressure (MPa)	8	11	14	17	20	23
pressure difference(MPa)	4.11	5.77	7.68	9.54	11.68	13.98
energy dissipation efficiency(%)	51.3	5 2.5	54.9	56.1	58.4	60.8

As can be seen from Table 1, the energy dissipation efficiency of the Tesla energy dissipation device shows a gradual increase with the increase of the inlet pressure in the range of 8~25MPa. At the same time the higher the inlet pressure, the higher the inlet pressure, the larger the pressure drop difference of the Tesla energy dissipation device and the higher the pressure drop efficiency.

4.3. Effect of Different Fluid Components on the Energy Dissipation Efficiency of Tesla Energy Dissipation Devices

In order to obtain the effect of different fluid components on the energy dissipation efficiency of the Tesla energy dissipation device, this paper selects three different fluid media, namely oil, water and oil-water mixed medium, for comparative investigation. The inlet pressure is set to 23MPa, and other parameters are kept unchanged. In the simulation of oil-water mixed media, the model selection of multiphase flow model in the VOF model, the fluid in the pipe is set as oil and water two-phase, respectively, select the oil content of 90%, 70% and 50% of three different oil-water ratio for simulation and analysis. The VOF model was introduced by Hirt [12]in 1987 as a surface tracking method based on a fixed Eulerian grid. The model is based on two or more fluids that cannot be mixed by solving separate sets of momentum equations and tracking the volume fraction of each fluid over the entire region[13]. The VOF method is suitable for calculating the flow of fluids such as oil and water which cannot be mixed with each other, and is therefore applicable to this work. The obtained pressure distribution clouds obtained for the three different fluids are shown in Fig. 6:

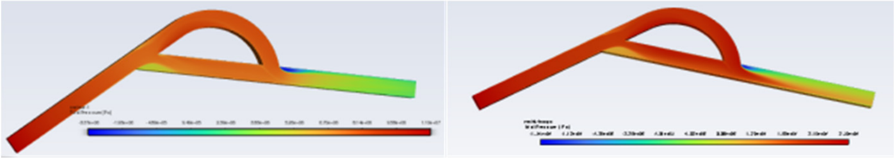

Fig. (a) Oil Fig. (b) water

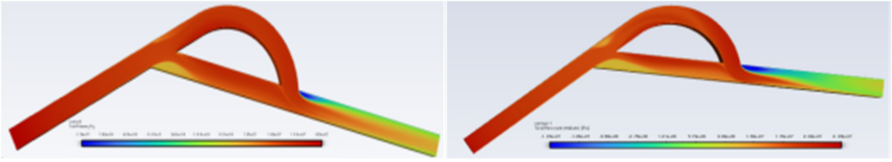

Fig. (c) Oil 50% Fig. (d) Oil 70%

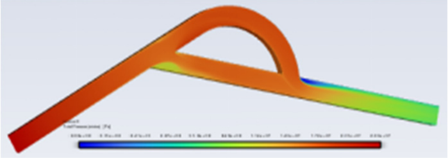

Fig. (e) Oi1 90%

Fig 6. Pressure distribution cloud of three different fluid media

From Fig. 6, it can be seen that the three different fluid media all produce different degrees of pressure drop, the pressure cloud of water is the darkest in colour and has the worst pressure reduction effect; the pressure cloud of oil is the lightest and has the best pressure reduction effect. Comparing Fig. (c), Fig. (d) and Fig. (e), it can be seen that the greater the proportion of oil, the better the pressure reduction effect. The energy dissipation efficiency of the Tesla energy dissipation device in different fluid media is shown in Table 2:

Table 2. Analysis of energy dissipation efficiency of Tesla energy dissipation device under different fluid

fluids	Water	Oil 50%	Oil 70%	Oil 90%	Oil
pressure difference (MPa)	13.98	14.56	15.14	16.01	16.97
energy dissipation efficiency(%)	60.8	63.3	65.8	69.6	73.8

As can be seen from Table 2, the energy dissipation efficiency of the Tesla energy dissipation device is greatest in oil, followed by oil-water mixed media, and finally water. And in the oil-water mixed medium, the higher the ratio of oil, the more obvious the energy dissipation effect.

4.4. Effect of Different Number of Series Stages on the Energy Dissipation Efficiency of Tesla Energy Dissipation Device

In order to obtain the effect of different numbers of series stages on the energy dissipation efficiency of the Tesla energy dissipation device, simulations of the Tesla energy dissipation device with the number of stages 2, 3, 4, and 5 respectively are carried out in this paper, respectively. The setup method of the numerical simulation is the same as that used in the previous simulation. The inlet pressure is set to 23 MPa and other parameters are kept constant. The pressure clouds obtained for the four Tesla energy dissipation devices with different numbers of series stages are shown in Fig. 7:

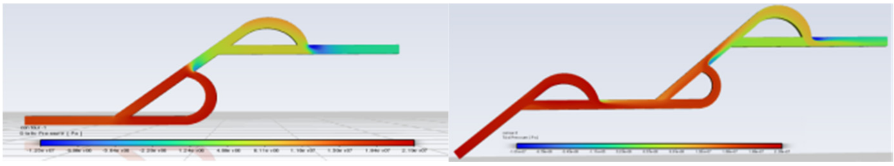

Fig. (a) Level 2 Fig. (b) Level 3

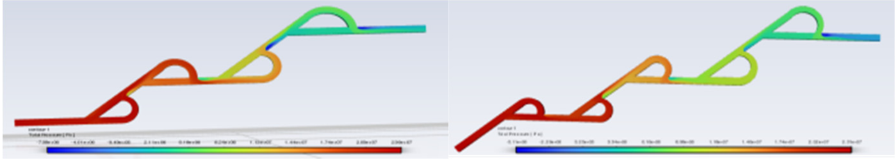

Fig. (c) Level 4 Fig.(d) Level 5

Fig 7. Pressure clouds of Tesla energy dissipation devices with four different numbers of series stages

As can be seen from Figure 7, the pressure distribution of each stage of the Tesla energy dissipation device is relatively similar, will produce a certain pressure drop, and are in the second half of the elbow outlet and the straight pipe section of the intersection of the formation of a larger jet hedge effect, where a blue low-pressure region as shown in the figure, this is due to the generation of the jet hedge so that the region produces a reflux, and the region's area with the increase in the number of series connection of the number of stages is a gradual The area of this region tends to decrease with the increase of the number of cascade stages. Each stage of the series Tesla energy dissipation device produces a pressure drop, and although the pressure drop produces a certain amount of recovery, the pressure value is smaller than the pressure value before energy dissipation. Meanwhile, it can be seen from Fig. 7 that the pressure drop of the same level of Tesla energy dissipation device is gradually decreasing with the increase of the number of series stages, and it is found that in different series Tesla energy dissipation devices, the pressure difference generated by each level of valves is gradually decreasing with the increase of the number of stages of the valves, and the minimum pressure is found in the last level of valves at the meeting point of the elbow outlet and the straight section of the pipeline, and the minimum pressure shows a gradually decreasing tendency with the increase of the number of stages of the Tesla energy dissipation device series. And with the increase of the number of Tesla energy dissipation device series, the minimum pressure shows a gradually decreasing trend. The energy dissipation efficiency of Tesla energy dissipation device in different stages is shown in Table 3:

Table 3. Analysis of energy dissipation efficiency of different tandem Tesla energy dissipation devices

series stage	2	3	4	5
pressure difference (Mpa)	16.72	18.13	18.63	18.70
energy dissipation efficiency (%)	72.7	78.8	81.0	81.3

As can be seen from Table 3, the energy dissipation efficiency is significantly improved when the number of series connection stages is 2 and 3, but the energy dissipation efficiency only increases by 2.2% when the number of stages is 4, and the energy dissipation efficiency only increases by 0.3% when the number of stages is 5, which indicates that the enhancement amplitude of the dissipation efficiency of the series Tesla dissipation device gradually decreases with the increase of the number of series connection stages of the energy dissipation device.

Considering the requirements of the oilfield site and the economic benefits of manufacturing energy dissipation devices, it is determined after extensive consideration that the tandem Tesla valve energy dissipation device with the number of dissipation device stages of 4 is the optimal energy dissipation structure with the best economic benefits.

5. Summary

(1) In the general pressure range of high-pressure oilfield recovery fluid, by analysing the energy dissipation efficiency of Tesla energy dissipation device under different inlet pressures, it is found that with the increase of inlet pressure, the dissipation efficiency of single-stage Tesla energy dissipation device shows a gradual increase with the increase of inlet pressure, and the larger the inlet pressure is, the higher the energy dissipation efficiency is.

(2) By analysing the energy dissipation efficiency of the Tesla energy dissipation device under different fluid media, it is found that under a certain inlet pressure, the energy dissipation efficiency of the single-stage Tesla energy dissipation device for different flow media is as follows, in descending order: oil, oil-water mixed medium, water. And in the oil-water mixture, the higher the proportion of oil, the better the energy dissipation effect.

(3) Under a certain inlet pressure, the energy dissipation efficiency of Tesla energy dissipation devices with different numbers of stages gradually increases with the increase in the number of stages connected in series, and the pressure drop generated by Tesla energy dissipation devices with different numbers of stages shows a tendency of gradual decrease with the increase in the number of stages of energy dissipation devices. It is also found that the 4-stage Tesla energy dissipation device in series is the optimum energy dissipation structure with the best economic efficiency.

References

[1] Tingxue Jiang, Yun Xu,Shaoli Zhang, et al. Dynamic optimization method of nozzle size during flowback period after hydraulic fracturing. oil drilling technology.2008,Vol.23(No.13),p.45-56.

[2] Chunlei Jin, Yaoxing Ting, Hui Wen. Experimental investigation on energy dissipation effect of rotary lobe spiral flow energy dissipation device. Hydropower Energy Science.2015, Vol.31(No.37), p. 89-98.

[3] Xuelan Zhang, Yongye Li, Guoli Ma,et al. Study on the effect of ladder plate spacing on the energy dissipation efficiency of rotary ladder energy dissipation device. China Rural Water Conservancy and Hydropower.2024, Vol.27 4(No.32),p. 14-17.

[4] Ning He, Zhengxing Zhao. Numerical study of the orifice plate energy dissipation problem. Hydrodynamics Research and Progress Series A.2019, Vol.14(No.24),p. 358-363.

[5] Ningning Wang, Zhuo Chen. Energy dissipation efficiency and modal analysis of hedonic energy dissipators. Piping technology and equipment.2019, Vol.21(No.16),p. 123-129.

[6] Renjie Zhang. Study on the erosion of hedonic energy dissipation device in high pressure desander. Xi'an Petroleum University.2023.

[7] Bowen Cui, Study of a unidirectional flow characterized flexible Tesla valve micro-mixer. Tohoku Electric Power University.2023.

[8] Runzhong Zhou, Zijie Qiao, Yuxiang Zhang,et al. Simulation study of Tesla valve performance. physical experiment.2020, Vol.11(No.40),p.44-48.

[9] Luwen Feng, Zekun Cheng, et al.Optimization and Improvement Simulation of Tesla Valve. Technology & Markets.2019, Vol.25(No.26),p.57-63.

[10] Ya Wen, Rongfang Chen, et al. Feasibility study on seepage characteristics of large-scale Tesla valves and their application to aqueduct corridors. Hydrodynamics Research and Progress Series A.2020, Vol.5(No.12),p. 3-9.

[11] Xi Song et al., A CFD analysis of the dynamics of a direct-operated safety relief valve mounted on a pressure vessel. Energy Conversion & Management.2014, Vol.3(No.46),p. 12-17.

[12] Hirt C W, et al. Volume of fluid (VOF) method for the-dynamics of free boundaries. Journal of computational physics.1981, Vol.36(No.74),p.47.

[13] Xiangxiang Wei, Qihong Feng, Xianmin Zhang, et al. Study on pore-scale residual oil distribution state in water-driven reservoirs based on the VOF method. Computational physics.2021, Vol.16 (No.15), p.17-28.