

Original Paper

Numerical investigation of the mechanisms of fluid pressure drop induced by rod centralizer in progressing cavity pump wellbore annulus

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ABSTRACT

To elucidate the pressure drop characteristics and underlying mechanisms induced by a rod centralizer in a progressing cavity pump (PCP) wellbore annulus, a CFD-based multiphase flow numerical model of the wellbore annulus with a rod centralizer was developed. The centralizer's flow-induced rotation was simulated by Six-DOF solver, and pressure drop was computed. Entropy production theory and the Liutex criterion were applied to characterize energy dissipation and vortex distributions. Results indicate that, within the operating range, inlet velocity is the dominant factor governing pressure drop, with an independent contribution of 97.37%. More than 60% of the total pressure loss occurs in the centralizer annulus region. Entropy production components were quantified. The time-averaged component accounts for more than 50% of the total; with increasing inlet velocity, its fraction decreases, whereas the turbulent component fraction increases and the wall component fraction changes only marginally. Vortices were found to cluster in high entropy production regions, indicating that local vortex accumulation triggered by abrupt geometric transitions and flow-induced rotation of the centralizer is a primary cause of increased pressure loss. These findings advance the understanding of pressure drop mechanisms and flow field characteristics in PCP wellbores and provide insights for pressure drop prediction and control.

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1. Introduction

Progressing cavity pumps (PCPs) are widely used for artificial lift in oilfields owing to their low cost, high efficiency, ease of installation, and broad applicability. PCP lifting has become the second most widely used artificial-lift method after beam pumping. In PCP systems, a surface motor drives the downhole pump by transmitting torque through the sucker rod, enabling the pump to lift produced fluids to the surface. To mitigate rod-tubing wear, rod centralizers are commonly installed on the sucker rod. However, centralizers introduce additional local pressure losses, which

increases markedly with well depth and the number of centralizers. The resulting rise in wellbore pressure drop increases pump load and can lead to pump selection mismatch, increased leakage, reduced efficiency, and higher energy consumption, thereby degrading the overall lifting performance of PCP wells.

Centralizers are widely used in rod-operated production systems, including beam pumping units and surface-driven progressing cavity pumps. Early research primarily focused on structural design and strength analysis (Rivas et al., 1990; Peckins et al., 2001). As centralizers became more widely deployed, the associated pressure loss attracted increasing attention. Yao and Robello (2008) performed numerical simulations of pressure drop induced by a helical rod centralizer. Their results showed that centralizer-induced pressure drop is non-negligible. Singh and Samuel (2009) examined the effects of rod rotation and eccentricity on the pressure drop across a centralizer. Their results indicated that eccentricity reduces the pressure drop. Under

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Nomenclature			
C_{HPAM}	HPAM mass concentration, mg/L	$\bar{S}_{\text{WA}}$	Area average of wall entropy production, W/(m ² ·K)
f_{ep}	Fraction of entropy production, %	ΔS	Total entropy production, W/K
f_{V6}	Fraction of total entropy production from region V6, %	ΔS_{D}	Time-averaged entropy production, W/K
ΔM	Torque fluctuation amplitude of the centralizer, N·m	ΔS_{T}	Turbulent entropy production, W/K
M_{c}	Torque of the centralizer, N·m	ΔS_{W}	Wall entropy production, W/K
M_{max}	Maximum torque of the centralizer, N·m	α_{o}	Oil phase volume fraction, %
Δn_{c}	Speed fluctuation amplitude of the centralizer, r/min	α_{w}	Water phase volume fraction, %
n_{c}	Rotational speed of the centralizer, r/min	β	Empirical constant of turbulent entropy production rate
n_{rod}	Rotational speed of the sucker rod, r/min	$\bar{\tau}_{\text{a}}$	Area averaged of wall shear stress, Pa
n_{s}	Steady rotational speed of the centralizer, r/min	Ω_{R}	Vortex enstrophy, s ⁻²
U_{in}	Inlet velocity, m/s	Ω_{S}	Shear enstrophy, s ⁻²
S_{D}	Time-averaged entropy production rate, W/(m ³ ·K)	$\bar{\Omega}_{\text{RV}}$	Volume average of vortex enstrophy, s ⁻² ·m ⁻³
S_{T}	Turbulent entropy production rate, W/(m ³ ·K)	$\bar{\Omega}_{\text{SV}}$	Volume average of Shear enstrophy, s ⁻² ·m ⁻³
S_{W}	Wall entropy production rate, W/(m ² ·K)	CAR	Centralizer annulus region
$\bar{S}_{\text{V}}$	Volume average of total entropy production, W/(m ³ ·K)	CDR	Centralizer downstream region
$\bar{S}_{\text{DV}}$	Volume average of time-averaged entropy production, W/(m ³ ·K)	CIR	Centralizer inlet region
$\bar{S}_{\text{TV}}$	Volume average of turbulent entropy production, W/(m ³ ·K)	COR	Centralizer outlet region
		CUR	Centralizer upstream region
		IC	Independent contribution, %
		PCP	Progressing cavity pump

concentric conditions, rotation further decreases the pressure drop, whereas under eccentric conditions the pressure drop increases initially and then decreases as rotational speed rises. However, existing studies largely focus on single phase fluids, whereas produced fluids in PCP wells typically involve oil-water two-phase flow. Moreover, local geometric transitions of the centralizer and flow-induced rotational effects can markedly influence pressure drop (Kumar and Sharma, 2025), warranting further investigation.

Conventional pressure-drop based approaches can quantify overall wellbore pressure losses, but they cannot pinpoint where the largest losses occur. Entropy production characterizes irreversible mechanical energy loss. Entropy production contours from numerical simulations can therefore identify where high energy losses occur and which dissipation mechanisms dominate. Kock and Herwig (2004, 2005) systematically studied entropy production theory and decomposed entropy production into contributions associated with the time-averaged velocity field, velocity fluctuations, and wall effects. In recent years, entropy production theory has been increasingly applied to quantify energy loss characteristics in hydraulic machinery. Using Reynolds-averaged (RANS) modeling and entropy production theory, Zhou (2023) developed a quantitative framework for energy loss analysis in a variable cross-section annulus. The spatial distribution of entropy production rate was obtained, and the effects of inlet velocity, contraction-expansion ratio, and the inclination angle of the diameter-transition section on entropy production were analyzed. Song et al. (2025a) combined CFD with entropy production theory to quantify energy losses in Archimedes Spiral Hydrokinetic Turbines under axial and yawed inflow, revealing that wake entropy production is primarily driven by tip and hub vortices and increases substantially with blade angle. Li et al. (2026) investigated flow features in a hydrogen circulation pump and reported that viscous dissipation contributes more than 70% of total entropy production, with major sources located in inter-blade clearances, near rotor edges, and within axial gaps. In addition, Ren et al. (2023, 2025b)

incorporated transported loss into the conventional entropy production method, which further improved the accuracy of energy loss calculation in micropumps.

The mechanisms by which complex vortical flows affect fluid energy dissipation have long been a key research focus. In hydraulic machinery and related fields, vortex identification criteria are often used to relate vortices to energy loss and to interpret loss mechanisms. Xu et al. (2025) examined energy loss and vortex distributions in an axial flow turbine under upstream wave excitation. They reported that the streamwise evolution of vortical structures is consistent with the trend of energy loss. Song et al. (2025b) investigated how vortex motion affects hydraulic losses in an axial flow turbine and proposed a linkage between vortex intensity and turbulence-related losses. Their results showed that vortex-induced turbulence propagates through the unit, leading to substantial additional hydraulic losses. Using a mixed flow turbine as a case study, Xu et al. (2022) combined the Liutex criterion with entropy production theory to assess the impact of upstream-turbulence-induced vortices on hydraulic losses. They identified the primary loss regions and emphasized that suppressing vortex formation is critical for loss reduction. In summary, integrating entropy production theory with vorticity-field analysis provides a useful framework for investigating pressure drop in PCP wellbores equipped with centralizers and for clarifying the underlying pressure loss mechanisms.

PCP rod centralizers commonly adopt a helical geometry and have an axial degree of rotational freedom, enabling flow-induced rotation under hydrodynamic loading. Meanwhile, produced fluids are typically oil-water two-phase flows, and polymer addition to the aqueous phase often introduces shear-thinning rheology. These complexities make analytical evaluation of wellbore pressure drop challenging. Accordingly, a three-dimensional CFD multiphase flow model of the PCP wellbore annulus with a centralizer was developed to characterize pressure drop behavior, and sensitivity analysis was conducted to identify the dominant controlling factors. Entropy production analysis was then used to quantify the spatial distribution and types of pressure losses.

Vorticity-field analysis was further integrated to elucidate the mechanisms responsible for pressure loss formation.

2. Theory

2.1. Governing equations

The fluid domain considered comprises oil-water two-phase flow and is modeled using the Mixture multiphase model. The flow is assumed to be isothermal. In the Mixture model, phases are treated as interpenetrating continua, and the governing equations include mixture continuity and momentum, together with an algebraic relation for the relative velocity.

The continuity equation for the mixture is:

$$\frac{\partial}{\partial t}(\rho_m) + \nabla \cdot (\rho_m \mathbf{v}_m) = 0 \quad (1)$$

where $\mathbf{v}_m$ is the mass-averaged velocity:

$$\mathbf{v}_m = \frac{\sum_{i=1}^a \alpha_i \rho_i \mathbf{v}_i}{\rho_m} \quad (2)$$

and ρ_m is the mixture density:

$$\rho_m = \sum_{i=1}^a \alpha_i \rho_i \quad (3)$$

and α_i is the volume fraction of phase i .

The momentum equation for the mixture is:

$$\begin{aligned} \frac{\partial}{\partial t}(\rho_m \mathbf{v}_m) + \nabla \cdot (\rho_m \mathbf{v}_m \mathbf{v}_m) = & -\nabla p + \nabla \cdot [\mu_m (\nabla \mathbf{v}_m + \nabla \mathbf{v}_m^T)] \\ & + \rho_m \mathbf{g} + \mathbf{F} - \nabla \cdot \left(\sum_{i=1}^a \alpha_i \rho_i \mathbf{v}_{dr,i} \mathbf{v}_{dr,i} \right) \end{aligned} \quad (4)$$

where a is the number of phases, $\mathbf{F}$ is the body force, and μ_m is the viscosity of the mixture:

$$\mu_m = \sum_{i=1}^a \alpha_i \mu_i \quad (5)$$

and $\mathbf{v}_{dr,i}$ is the drift velocity for secondary phase i :

$$\mathbf{v}_{dr,i} = \mathbf{v}_i - \mathbf{v}_m \quad (6)$$

For the high water cut conditions considered in this study, the oil volume fraction is at most 10%, with oil present as the dispersed phase and water as the continuous phase. The centralizer promotes local oil-water mixing. In addition, the differences between oil and water in density, viscosity, and related physical properties are relatively modest. Collectively, these factors lead to a small drift velocity between the phases.

2.2. Six-DOF solver

The model accounts for flow-induced rotation of the centralizer. A six degree of freedom (Six-DOF) solver is employed to compute the torque acting on the centralizer and to update the rotational motion of its center of mass. The angular acceleration vector $\dot{\omega}_B$ governing centralizer rotation is:

$$\dot{\omega}_B = L^{-1} \left(\sum \mathbf{M}_B - \omega_B \times L \omega_B \right) \quad (7)$$

where L is the moment of inertia, $\mathbf{M}_B$ is the torque vector, and ω_B is the angular velocity vector. After the angular acceleration is computed from Eq. (7), the angular velocity is obtained by numerical integration. The rigid body orientation is then updated using the angular velocity within the sliding mesh framework.

2.3. Entropy production theory

Entropy production theory has been widely used to analyze energy loss across a broad range of engineering applications. When heat transfer is neglected, a portion of the mechanical energy in the wellbore flow is irreversibly dissipated as internal energy, leading to increased entropy production in the flow field. In RANS simulations of fluid energy loss, entropy production is decomposed into time-averaged entropy production rate induced by the time-averaged velocity field and turbulent entropy production rate induced by velocity fluctuations. The time-averaged entropy production rate is:

$$\begin{aligned} S_D = & \frac{2\mu_{\text{eff}}}{T} \left[\left(\frac{\partial \bar{u}}{\partial x} \right)^2 + \left(\frac{\partial \bar{v}}{\partial y} \right)^2 + \left(\frac{\partial \bar{w}}{\partial z} \right)^2 \right] \\ & + \frac{\mu_{\text{eff}}}{T} \left[\left(\frac{\partial \bar{u}}{\partial y} + \frac{\partial \bar{v}}{\partial x} \right)^2 + \left(\frac{\partial \bar{u}}{\partial z} + \frac{\partial \bar{w}}{\partial x} \right)^2 + \left(\frac{\partial \bar{v}}{\partial z} + \frac{\partial \bar{w}}{\partial y} \right)^2 \right] \end{aligned} \quad (8)$$

where $\bar{u}$, $\bar{v}$, and $\bar{w}$ denote the time-averaged velocity components in the X, Y, and Z directions of a three-dimensional Cartesian coordinate system, m/s, respectively; T is the temperature, K; and $\mu_{\text{eff}} = \mu + \mu_t$, where μ_{eff} , μ , and μ_t are the effective, dynamic, and turbulent viscosities, Pa·s, respectively.

RANS formulations do not directly resolve instantaneous velocity fluctuations. Following Kock and Herwig (2005), the fluctuating contribution to entropy production is attributed to turbulence and can be related to the turbulence kinetic energy and specific dissipation rate in the SST $k - \omega$ model. An approximate expression for the turbulent entropy production rate is therefore obtained as:

$$S_T = \beta \frac{\rho k \omega}{T} \quad (9)$$

where $\beta = 0.09$, k is the turbulent kinetic energy, $\text{m}^2 \cdot \text{s}^{-2}$, and ω is the specific dissipation rate, s^{-1} .

Following Kock and Herwig (2004), wall effects contribute to entropy production and should not be neglected. The wall entropy production rate is calculated using the approach proposed by Hou et al. (2016):

$$S_W = \frac{\tau \cdot \mathbf{v}}{T} \quad (10)$$

where τ is the wall shear stress, Pa, and $\mathbf{v}$ is the mean velocity of the near-wall grid cell, m/s.

Entropy production is obtained by integrating the entropy production rate over the relevant domain, using a volume integral for the flow field and an area integral for wall surfaces. The time-averaged, turbulent, and wall components are evaluated using Eqs. (11)–(13), respectively. The total entropy production is defined as their sum, as given in Eq. (14).

$$\Delta S_D = \int_V S_D dV \quad (11)$$

$$\Delta S_T = \int_V S_T dV \quad (12)$$

$$\Delta S_W = \int_S S_W dS \quad (13)$$

$$\Delta S = \Delta S_D + \Delta S_T + \Delta S_W \quad (14)$$

2.4. Vortex identification criterion

The Liutex vortex identification criterion (Liu et al., 2018) is employed to accurately extract the rigid body rotation component of the flow. Its mathematical expression is given as follows:

$$\omega_R = (\omega \cdot \mathbf{r}) - \sqrt{(\omega \cdot \mathbf{r})^2 - 4\lambda_{ci}^2} \quad (15)$$

$$\omega_R = \omega_R \cdot \mathbf{r} \quad (16)$$

where ω denotes the vorticity vector, $\mathbf{r}$ denotes the Liutex direction vector, and the term involving λ_{ci} corresponds to the imaginary part of the complex eigenvalue of the velocity gradient tensor. On this basis, the shear component of vorticity ω_S can be separated (Wu et al., 2025). The corresponding expression is given as follows:

$$\omega_S = \omega - \omega_R \quad (17)$$

Because vorticity is not directly equivalent to energy loss, the energy characteristics related to vorticity are represented by enstrophy. The enstrophy is calculated as follows:

$$\Omega = \frac{\omega \cdot \omega}{2} \quad (18)$$

Similarly, the enstrophy associated with vortex ω_R and shear component ω_S are calculated as follows:

$$\Omega_R = \frac{\omega_R \cdot \omega_R}{2} \quad (19)$$

$$\Omega_S = \frac{\omega_S \cdot \omega_S}{2} \quad (20)$$

3. Simulation setup and validation

3.1. Geometric model

Helical centralizers are commonly used in PCP wells, and a representative centralizer is shown in Fig. 1. The solid domain of the model consists of the tubing, sucker rod, and centralizer, with geometric dimensions summarized in Table 1. A three-dimensional solid model was first constructed and simplified where appropriate, as illustrated in Fig. 2. The fluid domain was then extracted from the solid model. The X–Z plane was defined as the horizontal reference plane, with the Y axis oriented vertically. The oil–water mixture flows through the annular passage, with the primary flow direction aligned with the positive Y axis.

3.2. Model motion description

Because centralizer installation substantially reduces rod–tubing eccentricity, the sucker rod, centralizer, and tubing are simplified as a concentric configuration, representing an idealized condition in which eccentricity effects are significantly reduced. Two types of motion are considered in the model, as illustrated in



Fig. 1. PCP rod centralizer.

Table 1
Geometric parameters of the model.

Geometric parameter	Dimension
Tubing inner diameter	76 mm
Sucker-rod diameter	28 mm
Tubing/sucker-rod length	1000 mm
Centralizer outer diameter	62 mm
Centralizer inner diameter	32 mm
Centralizer length	130 mm
Helical rib thickness	7.5 mm
Helical rib width	15 mm
Helix pitch	520 mm

Fig. 2. First, sucker rod rotation is imposed via moving wall with a prescribed rotational speed. Second, flow-induced rotation of the centralizer is captured using a Six-DOF solver; the governing formulation is provided in Section 2.2. The centralizer is made of nylon and has a mass of 0.3665 kg as calculated from its geometry. Only the axial rotational degree of freedom is retained, with the rotation axis aligned with the Y axis and the rotation center located at (0, 500, 0). The moment of inertia is $6.4 \times 10^{-4} \text{ kg} \cdot \text{m}^2$. With these parameters and the hydrodynamic loads acting on the centralizer, the Six-DOF solver updates the centralizer's rotational motion. To capture the coupling between centralizer rotation and the flow field, a sliding mesh approach is adopted. The mesh in the rotating region moves synchronously with the centralizer.

3.3. Numerical simulation setup

The SST $k - \omega$ turbulence model was adopted to simulate the complex flow in the wellbore annulus with a rod centralizer. This model combines the $k - \varepsilon$ and $k - \omega$ models through blending functions, using the $k - \omega$ model near the wall and the $k - \varepsilon$ model in the far field. For the complex flow near the centralizer, including high near-wall shear, local separation and recirculation induced by

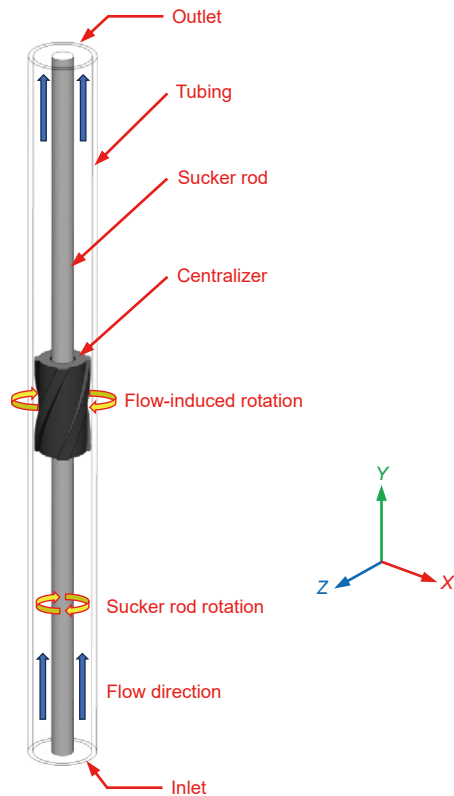


Fig. 2. Three-dimensional model of the solid domain.

geometric transitions, the SST $k-\omega$ model provides a suitable balance between computational accuracy and cost (Ren et al., 2025a).

The produced fluid is modeled as an oil-water two-phase flow using the Mixture multiphase model with a pressure-based solver. Gravity is included, with an acceleration of 9.81 m/s^2 applied in the negative Y direction. To improve accuracy and convergence, second-order upwind discretization is used for the momentum equation and the turbulence transport equations. Pressure is discretized using the Body Force Weighted scheme, and velocity-pressure coupling is handled using the Coupled algorithm. A time step of 0.01 s is adopted to ensure numerical stability and reliability.

The flow is assumed to be isothermal, and the fluid properties are specified at room temperature, 20°C (Li et al., 2019). The oil phase has a density of 860 kg/m^3 and a viscosity of $0.02 \text{ Pa}\cdot\text{s}$. The aqueous phase is an HPAM solution with a density of 998.2 kg/m^3 . Its viscosity follows a shear-thinning power-law rheology, which is described by:

$$\tau = K\dot{\gamma}^n \quad (21)$$

where τ is the shear stress, Pa; K is the consistency index; $\dot{\gamma}$ is the shear rate, s^{-1} ; and n is the power-law exponent. Different HPAM mass concentrations (C_{HPAM}) yield different values of the consistency index K and power-law exponent n . Rheometer measurements were fitted to the power-law model to determine the rheological parameters for each concentration, as summarized in Table 2.

Boundary conditions are specified as follows. A velocity-inlet condition is applied, with inlet velocity (U_{in}), oil volume fraction (α_o), turbulence intensity, and hydraulic diameter prescribed for each case. A pressure-outlet condition is imposed at the outlet

Table 2

Rheological parameters of HPAM aqueous solutions at different mass concentrations.

C_{HPAM} , mg/L	K	n
400	0.00334	0.90476
800	0.00581	0.84405
1200	0.00849	0.80839
1600	0.01112	0.79318

with a gauge pressure of 0 Pa . A no-slip condition is applied on all wall boundaries. Prior to the simulations, the flow field is standard-initialized and at $t = 0$, set $\alpha_o = 0$ and $\alpha_w = 1$.

3.4. Meshing and grid-independence validation

The three-dimensional fluid domain was meshed and divided into a rotating region and a stationary region. The rotating region corresponds to the annular region around the centralizer, which features complex geometry; therefore, an unstructured tetrahedral mesh was employed in this region. A structured hexahedral mesh was used in the stationary region. Data exchange between the two regions was enabled via interfaces. Boundary-layer refinement was applied to the inner and outer annulus walls and on the centralizer surfaces. The near-wall mesh satisfied the SST $k-\omega$ turbulence model requirement, with $y^+ < 1$. The mesh was generated using a multi-zone meshing strategy, as shown in Fig. 3.

Because pressure drop is the primary response variable of interest, it was selected as the metric for the grid-independence validation. As shown in Fig. 4, increasing the grid number from 0.77 million to 1.04 million led to a pronounced increase in the simulated pressure drop. Further increasing the grid number from 1.04 million to 2.12 million changed the simulated pressure drop by only 1.75%, whereas the computational time increased by a factor of three. Therefore, the grid number of 1.04 million was considered sufficiently grid-independent for pressure-drop simulation, and further refinement would substantially increase the computational cost.

3.5. Experimental data validation

To validate the numerical approach, a numerical model was developed based on the experimental setup reported by Shu et al. (2006). The apparatus consists of a concentric annular pipe with an outer pipe inner diameter of 50 mm and an inner pipe outer diameter of 25 mm . The total annulus length is 2.5 m . A helical

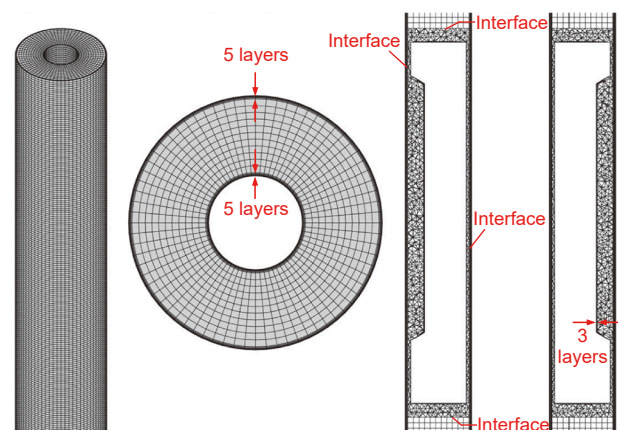


Fig. 3. Grid of the numerical model.

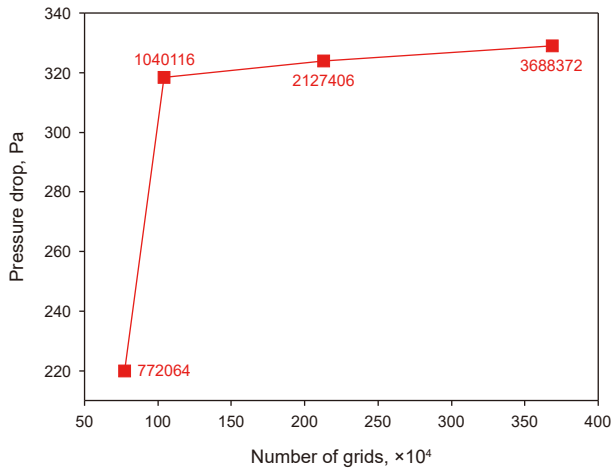


Fig. 4. Grid-independence validation.

centralizer was installed at a location 20 hydraulic diameters downstream of the inlet, and the pressure drop was measured using sensors. The validation model in the present study was established strictly according to the experimental parameters and employed the same concentric and stationary configuration as the experiment. The simulated results are compared with the experimental data in Table 3.

Across four operating conditions, pressure losses for pure water and power-law fluids flowing through an annulus centralizer at different flow rates were simulated and showed good agreement with experimental measurements. The maximum relative error was 8%, indicating that the model can predict pressure drop in the centralizer annulus with acceptable accuracy.

4. Results and discussion

4.1. Pressure drop characteristics and sensitivity analysis

The key factors considered to affect pressure drop include inlet velocity (U_{in}), oil volume fraction (α_o), sucker rod rotational speed (n_{rod}), and HPAM mass concentration (C_{HPAM}). The investigated ranges of these parameters were selected based on field operating conditions of PCP wells in a representative oilfield and are listed in Table 4.

Transient simulations were performed in this study. After 6 s of simulation, the flow field reaches a quasi-steady stage, during which the rotational speed and hydrodynamic force of the centralizer become stable. The pressure drop shows no sustained increasing or decreasing trend, but only small fluctuations, with a relative fluctuation amplitude of approximately 1.2%. Therefore, the flow field after 6 s is considered to have reached a statistically steady state, and all subsequent analyses are based on time-averaged results obtained during this stable stage.

Table 3
Comparison of experimental and simulated results.

Case ID	Rheological parameters		Flow rate, L/s	Pressure loss, Pa		Relative error, %
	n	K		Measured value	Simulated value	
1	1	0.001	0.478	130	123.71	4.84
2	0.7705	0.0035	0.508	510	489.12	4.09
3	0.7705	0.0035	1	890	961.26	8.00
4	0.7705	0.0035	1.5	1510	1629.08	7.89

Table 4
Parameters and ranges for pressure-drop analysis.

Parameters	Ranges
U_{in} , m/s	0.2, 0.3, 0.4, 0.5, 0.6
α_o , %	0, 2.5, 5, 7.5, 10
n_{rod} , r/min	30, 40, 50, 60, 70
C_{HPAM} , mg/L	0, 400, 800, 1200, 1600

Fig. 5 presents the dependence of pressure drop on U_{in} , α_o , n_{rod} , and C_{HPAM} , respectively. Pressure drop increases approximately quadratically with U_{in} and C_{HPAM} , whereas it increases approximately linearly with α_o and n_{rod} .

To identify the dominant factors governing pressure drop, a sensitivity analysis was performed by combining an orthogonal experimental design with analysis of variance (ANOVA) over preset ranges of four factors: U_{in} , α_o , n_{rod} , and C_{HPAM} . 25 mixed-level strictly orthogonal cases were simulated using CFD, and the resulting pressure drops are summarized in Table 5. A main-effects-only general linear model was then fitted, with pressure drop as the response and the four factors treated as categorical predictors. Type III ANOVA was used to assess the independent effect of each factor. To quantify relative importance, the Type III sums of squares for the four factors were normalized to yield an independent contribution (IC) for each factor, enabling identification and ranking of the dominant contributors. The sensitivity analysis results are summarized in Table 6.

Sensitivity analysis indicates that, within the investigated ranges, pressure drop is most sensitive to U_{in} . The independent contribution of U_{in} is approximately 97.37%, making it the dominant factor of pressure drop. α_o is a secondary factor with an independent contribution of about 1.51%. C_{HPAM} and n_{rod} have much smaller contributions of approximately 0.86% and 0.26%, respectively. Given that inlet velocity is the dominant factor, its influence on pressure drop is examined in detail in the following sections.

4.2. Flow-induced rotational behavior of the centralizer

Fig. 6 shows the torque acting on the centralizer. Owing to its helical geometry, hydrodynamic forces generate a driving torque that induces rotation. The temporal evolution of torque is similar across inlet velocities: immediately after start-up, the torque increases rapidly to a peak value, then decreases gradually, and finally approaches a steady state with a near-zero net torque. Torque fluctuations are observed during the transient stage, which are attributed to changes in local mixture properties as the oil-water flow enters the centralizer region and modifies the hydrodynamic loading. As shown in Fig. 7, increasing U_{in} increases the peak torque while reducing the relative fluctuation amplitude, and it shortens the time required to reach the steady state.

Fig. 8 shows the rotational speed of the centralizer. The temporal evolution is similar at different inlet velocities: the speed

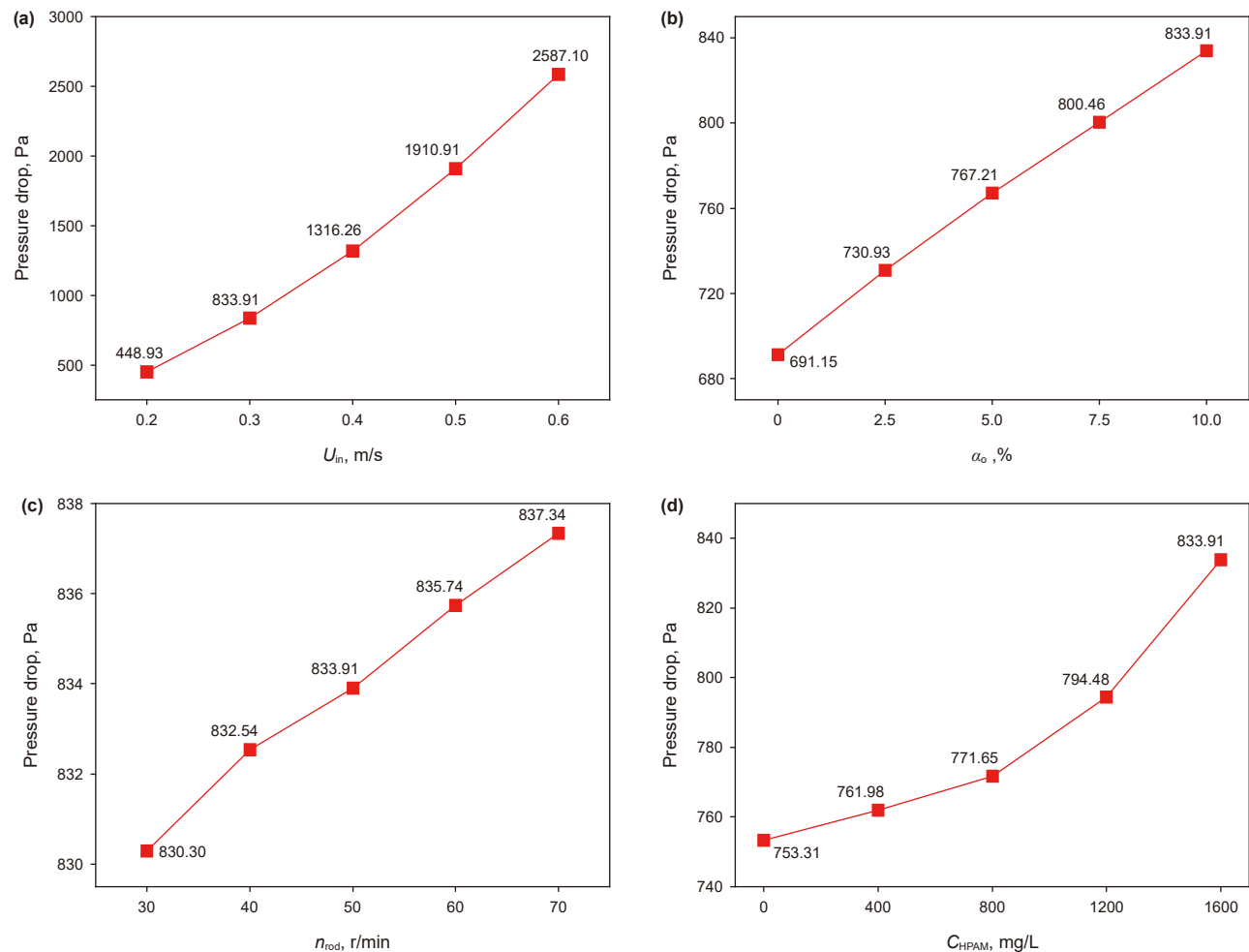


Fig. 5. Effects of different parameters on pressure drop: (a) U_{in} ; (b) α_o ; (c) n_{rod} ; (d) C_{HPAM} .

Table 5
Orthogonal experimental design (full table is provided in [Appendix A](#)).

Case ID	U_{in} , m/s	α_o , %	n_{rod} , r/min	C_{HPAM} , mg/L	Pressure drop, Pa
1	0.2	0.0	30	0	275.19
2	0.2	2.5	40	400	339.62
3	0.2	5.0	50	800	376.89
...	...	...	...	...	...
23	0.6	5.0	40	0	1778.52
24	0.6	7.5	50	400	2435.16
25	0.6	10.0	60	800	2539.79

Table 6
ANOVA results.

Parameter	Type III SS	IC, %
U_{in}	11771733.60	97.37
α_o	182633.70	1.51
C_{HPAM}	103665.01	0.86
n_{rod}	31427.36	0.26

increases from zero and eventually reaches a steady value. During the transient stage, the speed exhibits fluctuations that correspond to the torque oscillations. As shown in Fig. 9, increasing U_{in} leads to a higher steady rotational speed and a smaller fluctuation amplitude.

These results indicate that U_{in} strongly affects the hydrodynamic loading and rotational state of the centralizer. Higher inlet velocity intensifies the centralizer-induced disturbance to the flow field and consequently increases its impact on pressure drop.

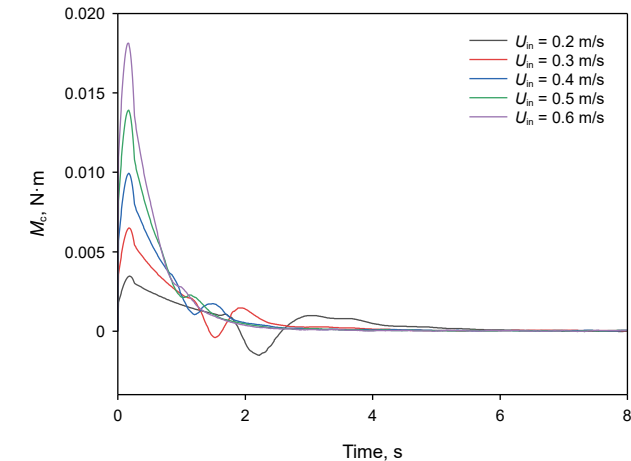
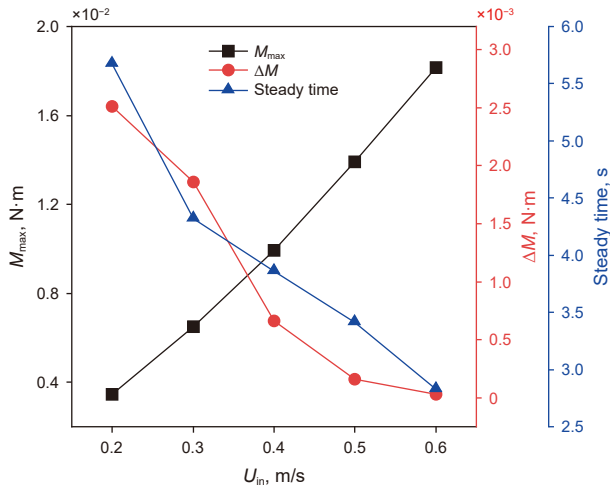
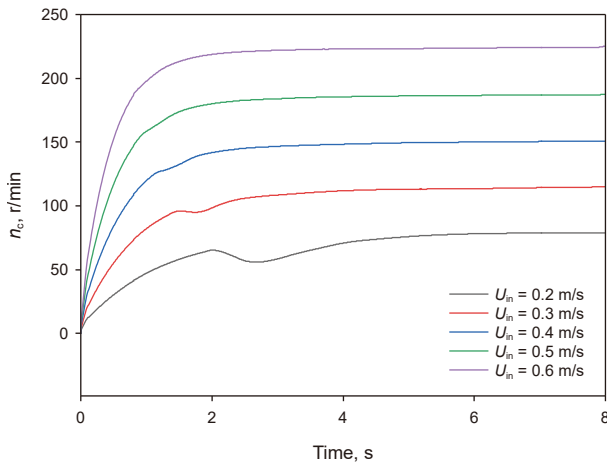
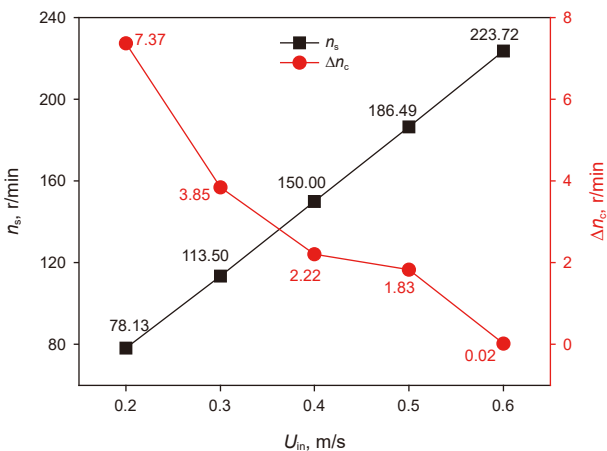


Fig. 6. Centralizer torque at different U_{in} .

Fig. 7. Centralizer torque fluctuations at different U_{in} .Fig. 8. Centralizer rotational speed at different U_{in} .Fig. 9. Centralizer rotational speed fluctuations at different U_{in} .

4.3. Spatial distribution of entropy production rate

For clarity in describing spatial variations, the fluid domain was divided into 11 streamwise regions (V1–V11), as shown in Fig. 10.

Regions V1–V5 correspond to the centralizer upstream region (CUR), V6 represents the centralizer annulus region (CAR), and V7–V11 correspond to the centralizer downstream region (CDR). In addition, V5 and V7 are designated as the centralizer inlet region (CIR) and the centralizer outlet region (COR), respectively.

4.3.1. Time-averaged entropy production rate (S_D)

Fig. 11 presents cross-sectional contours of the time-averaged entropy production rate at different U_{in} . Because its magnitude varies substantially among cases, the contours are displayed on a logarithmic scale to better reveal spatial patterns. As U_{in} increases from 0.2 to 0.6 m/s, the volume-averaged time-averaged entropy production rate rises from 0.21 to 2.45 W/(m³·K). High-value regions are mainly concentrated in the near-wall boundary layers and CAR. As shown in Fig. 12, values in the boundary layers are far higher than those in the non-boundary layers region. The streamwise distribution in Fig. 13 shows that CAR has the highest time-averaged entropy production rate among the three regions.

4.3.2. Turbulent entropy production rate (S_T)

Fig. 14 presents cross-sectional contours of the turbulent entropy production rate at different U_{in} . As U_{in} increases from 0.2 to 0.6 m/s, the volume-averaged turbulent entropy production rate rises from 0.05 to 1.43 W/(m³·K). The turbulent entropy production rate exhibits pronounced streamwise non-uniformity, with high-value regions concentrated in CAR and CDR. As shown in Fig. 15, the CUR exhibits the lowest turbulent entropy production rate. At inlet velocities of 0.2–0.3 m/s, the CDR contributes more than the CAR, whereas at 0.4–0.6 m/s the CAR becomes the dominant region.

4.3.3. Wall entropy production rate (S_W)

The wall entropy production rate is evaluated on three surfaces: centralizer surface, outer annulus wall, and sucker rod wall.

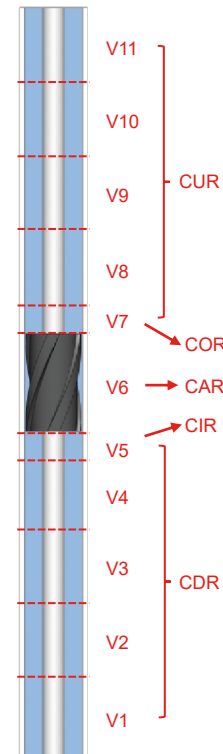


Fig. 10. Subregion division of the fluid domain.

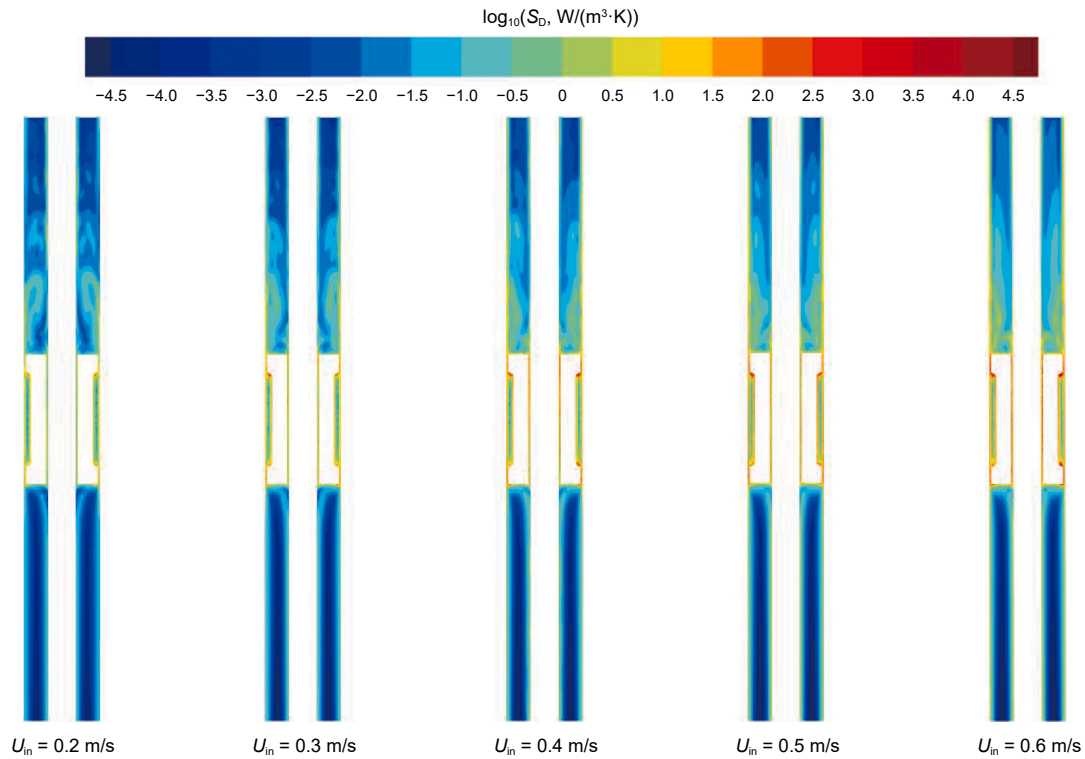


Fig. 11. Cross-sectional contours of the time-averaged entropy production rate at different U_{in} .

Fig. 16 illustrates the distribution of wall entropy production rate on the centralizer surface at different U_{in} . The distribution is relatively uniform, except for a localized high-value region near the lower end of the centralizer. As U_{in} increases from 0.2 to 0.6 m/s, the area-averaged wall entropy production rate on the centralizer rises from 0.00296 to 0.03543 W/(m²·K).

Figs. 17 and 18 show the wall entropy production rate distributions on the outer annulus wall and sucker rod wall, respectively, for different U_{in} . Because these walls are cylindrical, the surfaces are unwrapped into planar rectangles to better visualize spatial variations. As U_{in} increases from 0.2 to 0.6 m/s, the area-averaged wall entropy production rate

increases from 0.000158 to 0.0031 W/(m²·K) on the outer wall and from 0.000296 to 0.00229 W/(m²·K) on the sucker rod wall. As indicated by Figs. 19 and 20, both surfaces exhibit pronounced streamwise non-uniformity. High wall entropy production rate is concentrated in CAR and is substantially higher than that in CUR and CDR.

Overall, the entropy production rate distributions indicate that energy dissipation is highly non-uniform in the streamwise direction and is mainly concentrated in CAR and its adjacent transition regions. The flow-field mechanisms responsible for these localized high entropy production regions are further analyzed in Section 4.5.

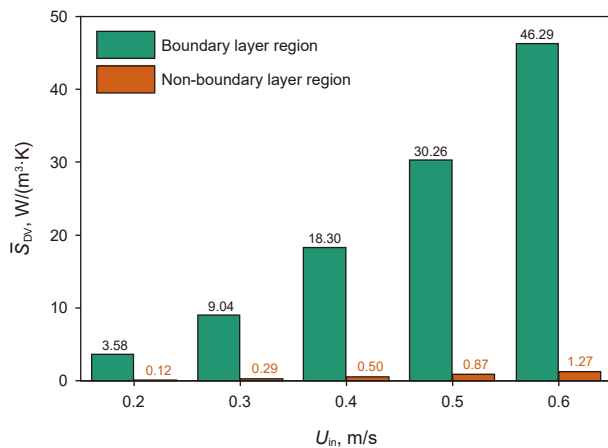


Fig. 12. Time-averaged entropy production rate in boundary-layer and non-boundary layer region.

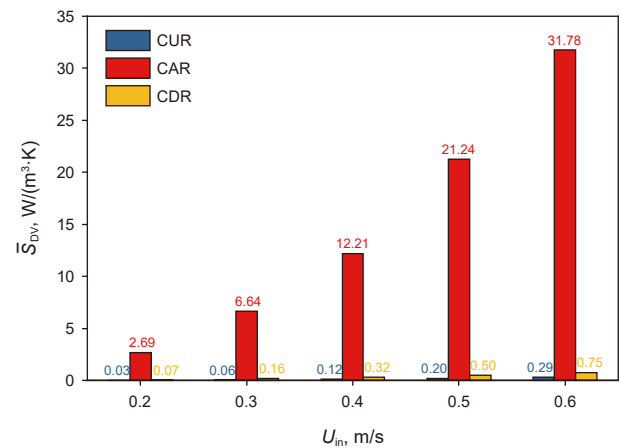


Fig. 13. Streamwise distribution of the time-averaged entropy production rate in different regions.

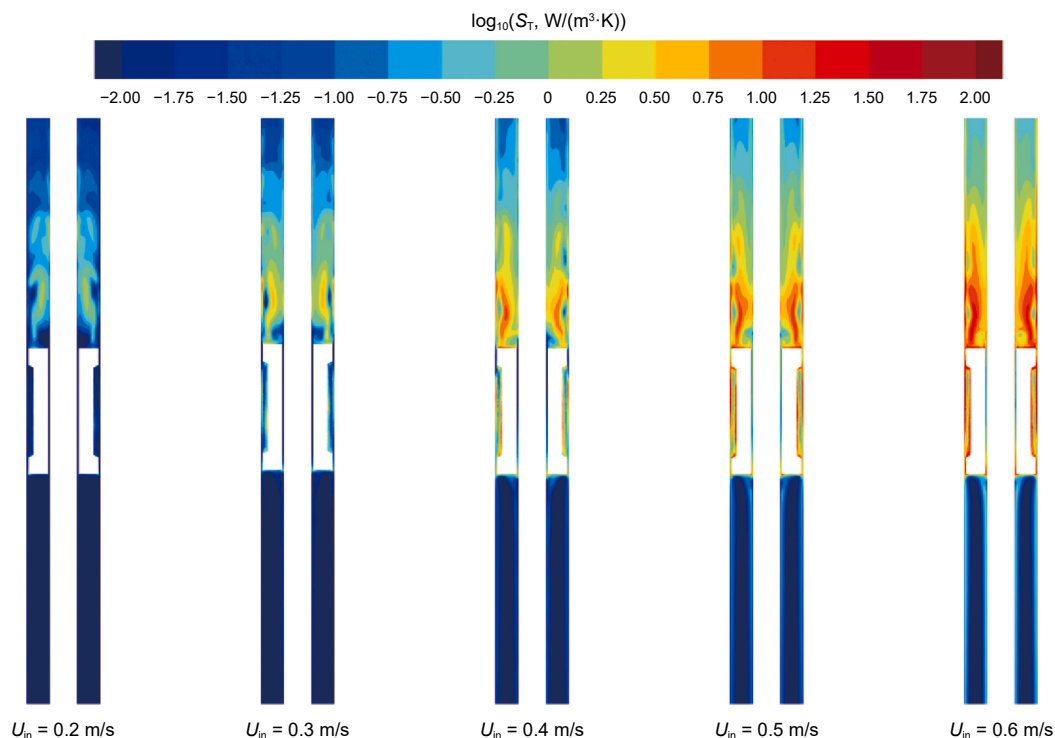


Fig. 14. Cross-sectional contours of the turbulent entropy production rate at different U_{in} .

4.4. Quantitative analysis of entropy production

To quantify the streamwise distribution of total entropy production while removing the bias introduced by unequal region volumes, the volume-averaged total entropy production was evaluated for regions V1–V11. Fig. 21 shows that total entropy production is relatively low in CUR (V1–V5) but increases sharply in CAR (V6). In CDR (V7–V11), the level remains higher than that in CUR and gradually decreases with increasing distance from the centralizer. Fig. 22 reports the fraction of total entropy production occurring in CAR (V6) at different inlet velocities. In all cases, more than 60% of total entropy production originates from V6, indicating that the centralizer annulus region is the dominant energy loss region.

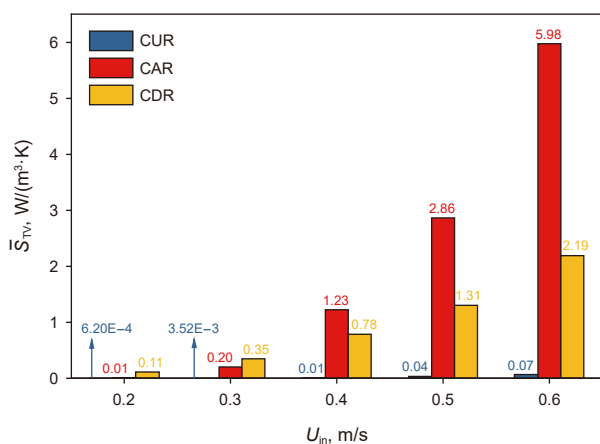


Fig. 15. Streamwise distribution of the turbulent entropy production rate in different regions.

Fig. 23 illustrates the effect of U_{in} on time-averaged, turbulent, wall, and total entropy production. All components increase with increasing U_{in} . In terms of relative amplification from 0.2 to 0.6 m/s, time-averaged entropy production increases by a factor of 10.52, turbulent entropy production by 25.11, and wall entropy production by 11.82. Therefore, U_{in} has the strongest effect on turbulent entropy production, followed by wall entropy production and then time-averaged entropy production.

Fig. 24 presents the fraction of each entropy production component at different U_{in} . Within the investigated U_{in} range, time-averaged entropy production dominates, accounting for more than 50% in all cases. This dominance arises because the velocities considered are relatively low, resulting in weak turbulence and limited wall-friction dissipation; consequently, viscous dissipation associated with the time-averaged velocity field is the primary source of energy loss. As U_{in} increases, the fraction of time-averaged entropy production decreases, whereas the turbulent fraction increases. This trend reflects the rise in turbulence intensity with U_{in} , which amplifies turbulence-related dissipation. Although time-averaged entropy production also increases with inlet velocity, its relative contribution to the total energy loss diminishes. The wall contribution varies only weakly across the investigated U_{in} range.

Overall, the quantitative results show that energy loss is mainly concentrated in CAR and that time-averaged entropy production is the primary contributor to total entropy production. These findings provide the basis for the flow-field mechanism analysis in Section 4.5.

4.5. Flow-field analysis

Building on the entropy production analysis, the flow-field characteristics are examined to elucidate the mechanisms

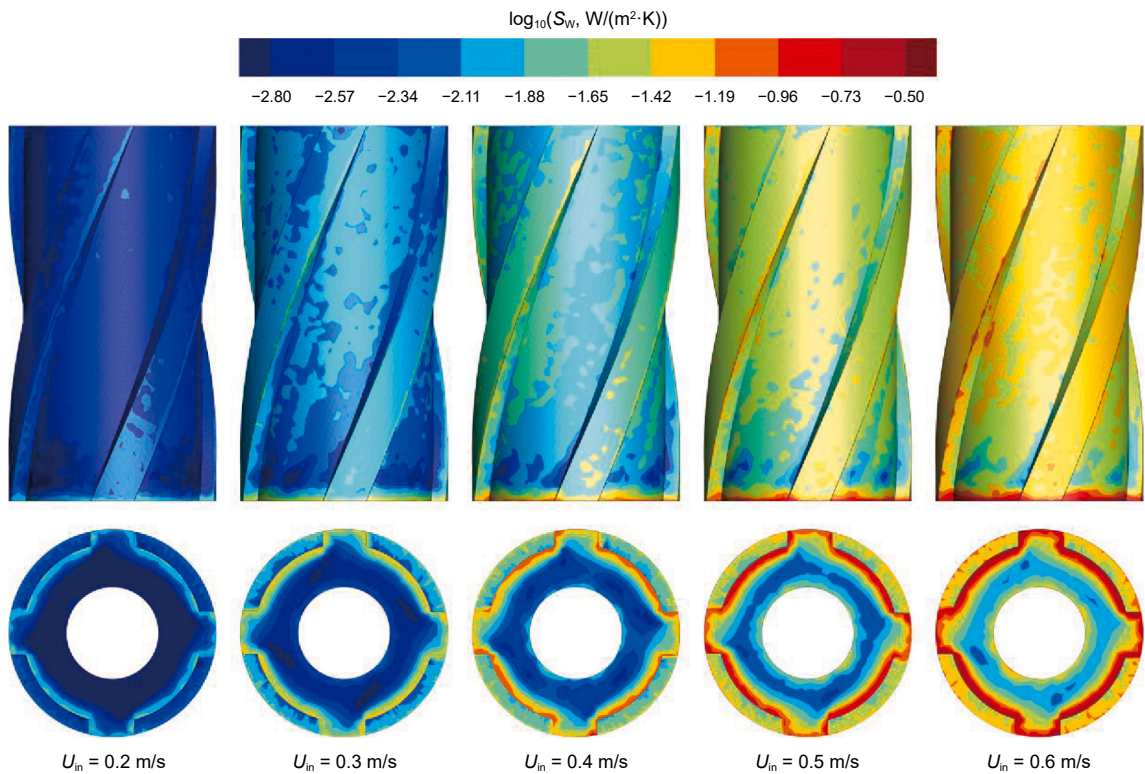


Fig. 16. Contours of the wall entropy production rate on the centralizer surface at different U_{in} .

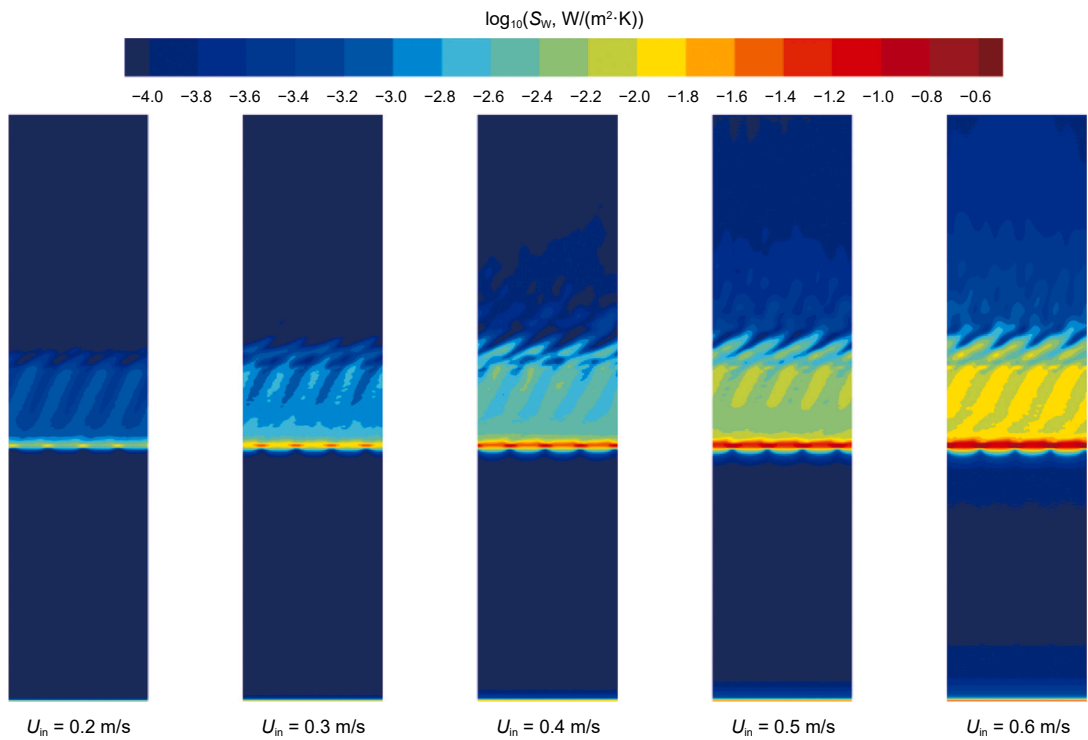


Fig. 17. Contours of the wall entropy production rate on the outer annulus wall at different U_{in} .

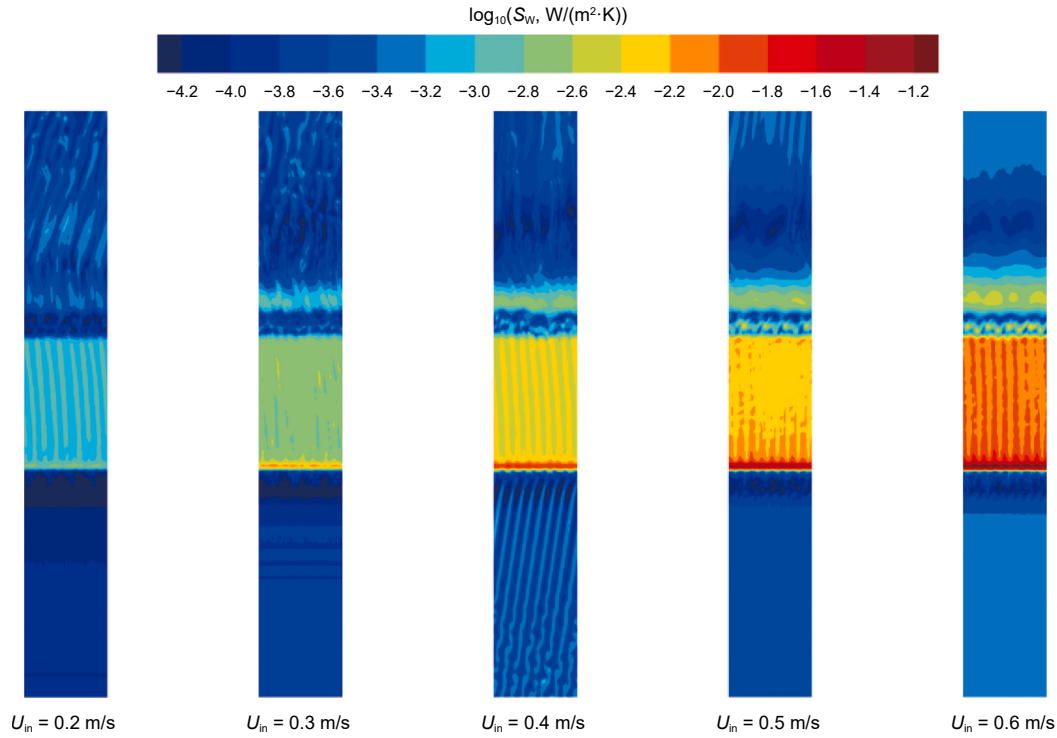


Fig. 18. Contours of the wall entropy production rate on the sucker rod wall at different U_{in} .

responsible for localized pressure loss. The case with $U_{in} = 0.6$ m/s is used as a representative example.

4.5.1. Shear component of vorticity

Time-averaged entropy production reflects irreversible dissipation associated with molecular viscosity. The time-averaged entropy production rate exhibits high values primarily within near-wall boundary layers and CAR. In these regions, velocity gradients are large, resulting in high shear (Liao et al., 2025). To quantify the relationship between time-averaged entropy production and shear intensity, the shear component of vorticity was separated following Section 2.4. The volume-averaged time-averaged entropy production ($\bar{S}_{DV}$) and the volume-averaged shear

enstrophy ($\bar{\Omega}_{SV}$) were then computed for each of the 11 subregions.

Fig. 25 shows the streamwise distributions (V1–V11) of the $\bar{S}_{DV}$ and $\bar{\Omega}_{SV}$. The two profiles exhibit highly consistent trends across the regions, indicating a strong association between viscous dissipation and shear. Both quantities remain low in V1–V5, increase sharply in V6, and then decrease gradually in V7–V11. Their maxima both appear in CAR, which is consistent with the result in Fig. 13 that CAR is the dominant viscous loss region.

Fig. 26 shows the cross-sectional distributions of total enstrophy, shear enstrophy, and vortex enstrophy. Shear enstrophy is mainly concentrated in the near-wall boundary layer region,

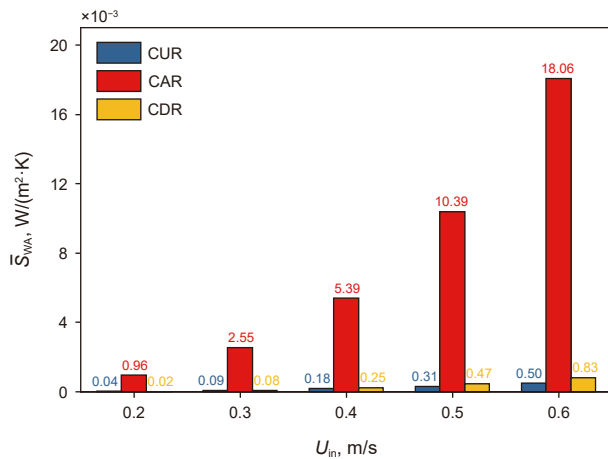


Fig. 19. Streamwise distribution of the wall entropy production rate on the outer annulus wall in different regions.

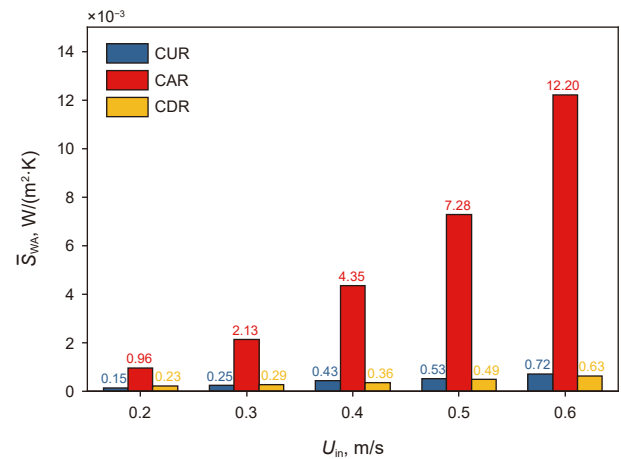


Fig. 20. Streamwise distribution of the wall entropy production rate on the sucker rod wall in different regions.

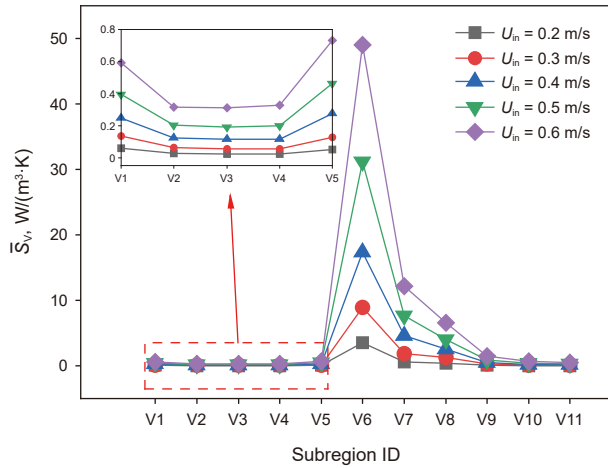


Fig. 21. Streamwise distribution of volume-averaged total entropy production.

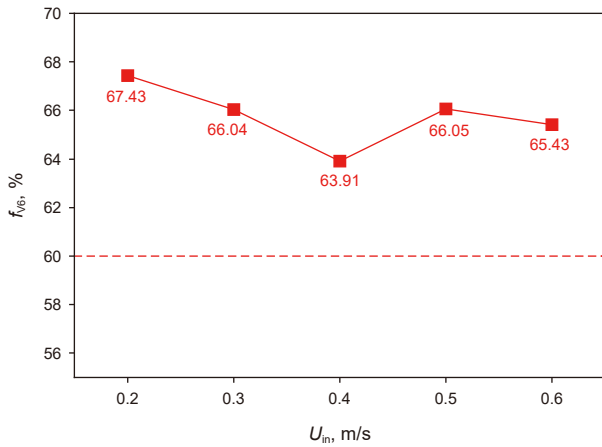


Fig. 22. Fraction of total entropy production from region V6 at different U_{in} .

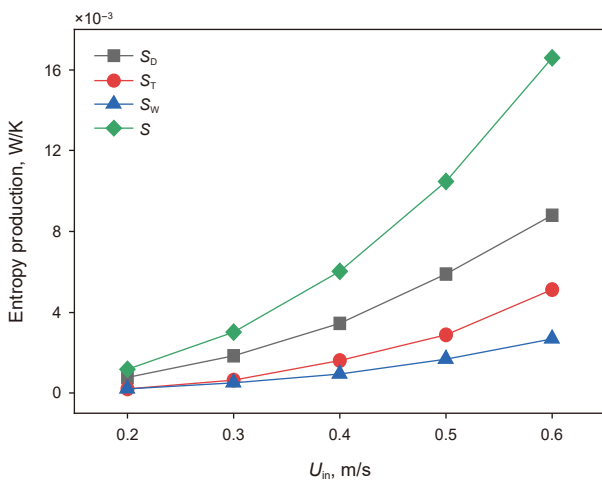


Fig. 23. Entropy production components at different U_{in} .

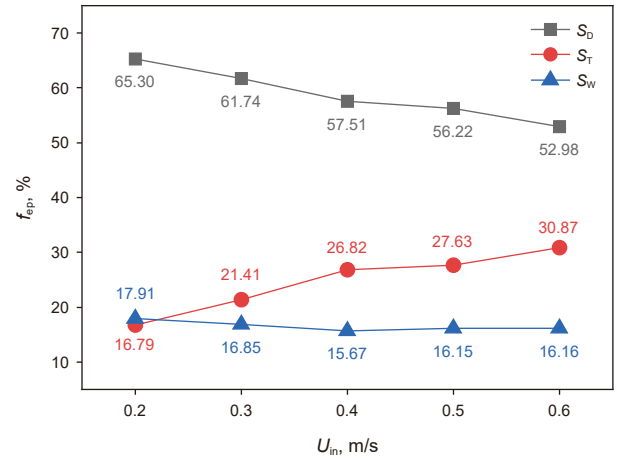


Fig. 24. Fraction of each entropy production component at different U_{in} .

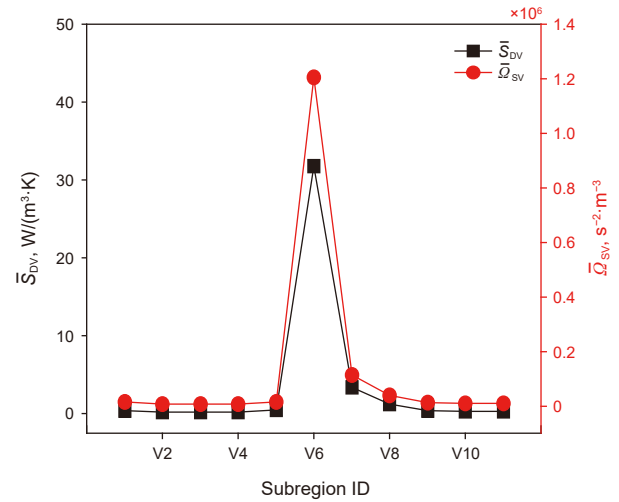


Fig. 25. Streamwise distributions of $\bar{S}_{Dv}$ and $\bar{Q}_{Sv}$.

vortices are the primary cause of high time-averaged entropy production regions.

The formation of these high-shear regions can be explained by the local geometry of the centralizer. When the flow enters the centralizer annulus region, the effective flow area is reduced by the centralizer body, forcing the fluid to accelerate through the narrow annular clearances. This produces large near-wall velocity gradients and strong shear.

In addition, Fig. 26 shows that the spatial distribution and magnitude of shear entropy are very similar to that of total entropy, whereas vortex entropy only exhibits limited high-value regions near COR. This indicates that entropy in the present flow field is mainly dominated by the shear component, while the rotational component primarily reflects local recirculation and rotational structures and contributes relatively little to the overall energy loss. This is consistent with the conclusion drawn from Fig. 24 that time-averaged entropy production dominates the total energy loss.

4.5.2. Rotational component of vorticity

The centralizer geometry and its rotation can locally induce vortices, potentially leading to elevated turbulent entropy

and CAR, which is highly consistent with the distribution of time-averaged entropy production rate shown in Fig. 11. This further confirms their correlation and indicates that shear

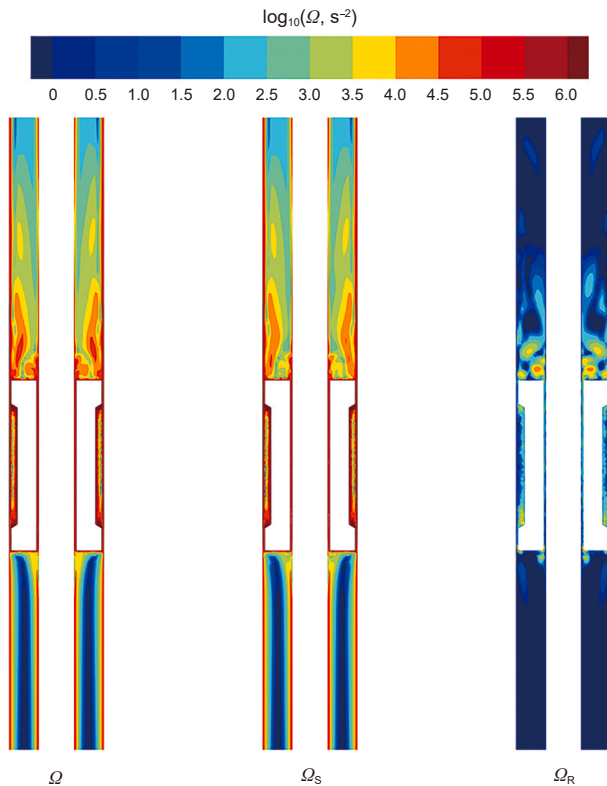


Fig. 26. Cross-sectional contours of enstrophy.

production. Therefore, the turbulent entropy production is analyzed in conjunction with vortex characteristics. Vortices were identified using the Liutex criterion.

The volume-averaged turbulent entropy production ($\bar{S}_{TV}$) and the volume-averaged vortex enstrophy ($\bar{\Omega}_{RV}$) were evaluated for each of the 11 subregions. As shown in Fig. 27, the two profiles exhibit similar streamwise trends. Both quantities increase markedly at V6 and attain their maxima at V7, indicating a strong association between vortices and turbulent dissipation.

To distinguish the contributions of vortices with different orientations, the Y axis is defined as the streamwise direction.

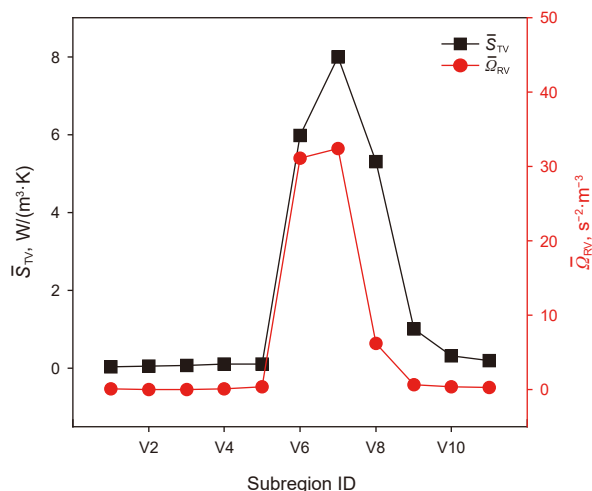


Fig. 27. Streamwise distributions of $\bar{S}_{TV}$ and $\bar{\Omega}_{RV}$.

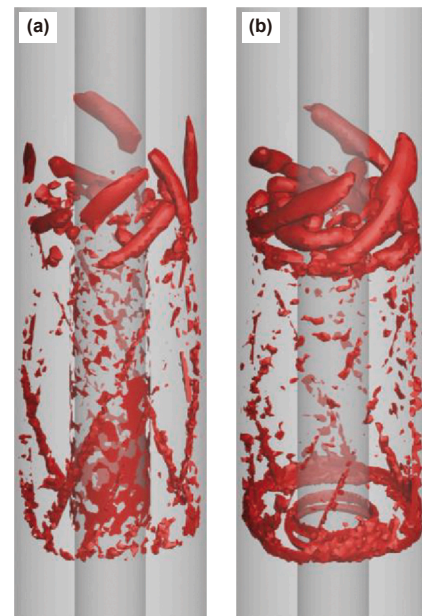


Fig. 28. Spatial distributions of streamwise and transverse vortices: (a) streamwise vortices; (b) transverse vortices.

Vortices with axes aligned with the streamwise direction are classified as streamwise vortices, whereas those with axes oriented along the circumferential tangential direction of the annulus are classified as transverse vortices. As shown in Fig. 28, streamwise vortices are mainly located near the outer edge of the centralizer and in the annular clearance region, where the combined effects of centralizer rotation and sucker rod rotation introduce tangential motion. Transverse vortices are mainly distributed near CIR and COR, where contraction-expansion transitions cause flow deflection and local recirculation.

The integrated vortex intensity is 0.0139 s^{-1} , with streamwise and transverse contributions of 0.0081 and 0.0096 s^{-1} , respectively. The two contributions are of the same order of magnitude, with the transverse component being slightly larger. This indicates that transverse vortex generation is more pronounced because two annular clearances (centralizer-sucker rod and

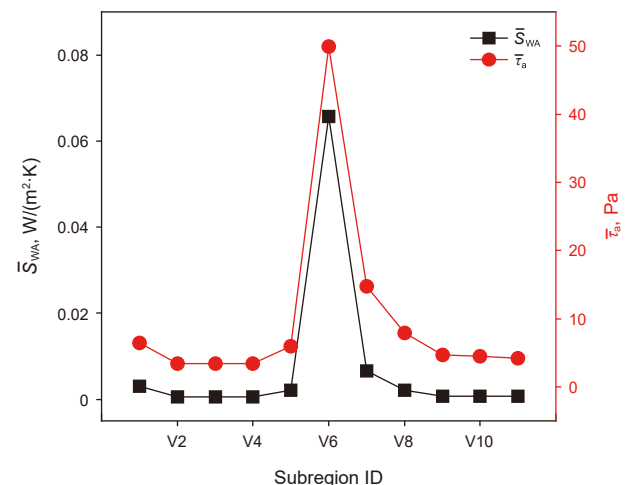


Fig. 29. Streamwise distributions of $\bar{S}_{WA}$ and $\bar{\tau}_a$.

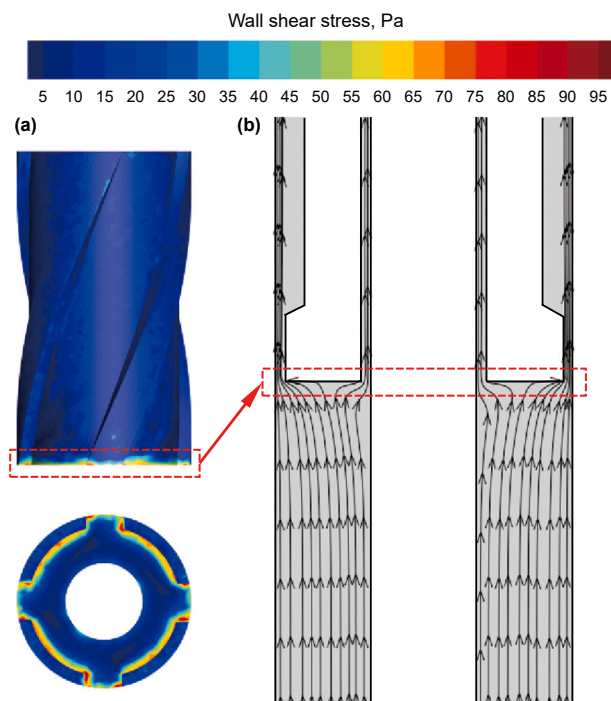


Fig. 30. Centralizer surface shear stress and cross-sectional streamlines: (a) contour of centralizer surface shear stress; (b) X–Y plane streamlines.

centralizer-outer wall) and their combined geometric transitions enhance transverse vortex generation.

4.5.3. Wall shear stress

Wall entropy production represents irreversible energy loss associated with wall friction. To quantify its relationship with wall

shear stress, the area-averaged wall entropy production ($\bar{S}_{WA}$) and the area-averaged wall shear stress ($\bar{\tau}_a$) were computed for each of the 11 subregions.

As shown in Fig. 29, the two profiles exhibit highly consistent streamwise variations, and both reach their maxima in V6. This confirms that wall entropy production is mainly governed by local wall shear stress. The peak in CAR indicates that the centralizer intensifies wall-friction loss by narrowing the flow passage and increasing near-wall shear stress.

Fig. 30(a) shows the wall shear stress distribution on the centralizer surface. The stress is relatively uniform, except for localized high-stress regions near the lower end of the centralizer. As indicated by the cross-sectional streamlines in Fig. 30(b), the incoming flow impinges on the lower end of the centralizer when entering the CAR, resulting in elevated wall shear stress. This region coincides with high wall entropy production.

Fig. 31(a) shows the outer-wall shear stress distribution. High-shear regions are concentrated in CAR, with a distinct ring-shaped band near the centralizer inlet. Fig. 31(b) shows the corresponding streamlines on the X–Y plane. As the flow enters CAR from upstream, it is constricted by the narrow clearance between the centralizer and the outer wall. This constriction induces local acceleration and pronounced flow deflection, thereby locally increasing outer-wall shear stress. Furthermore, Fig. 31(c) shows the X–Z plane streamlines at the dashed-line location in Fig. 31(b), revealing a pronounced radial component directed toward the outer wall. This radial deflection as the flow enters the clearance strengthens outer-wall impingement and substantially increases local wall-friction loss.

Fig. 32(a) shows the wall shear stress distribution on the sucker rod wall. High shear regions are mainly concentrated in CAR and near CIR and COR. Fig. 32(b) shows the corresponding X–Y plane streamlines. Near CIR, the flow area drops sharply as the fluid enters the narrow sucker rod-centralizer clearance. The flow accelerates along the wall and develops a radial component, which

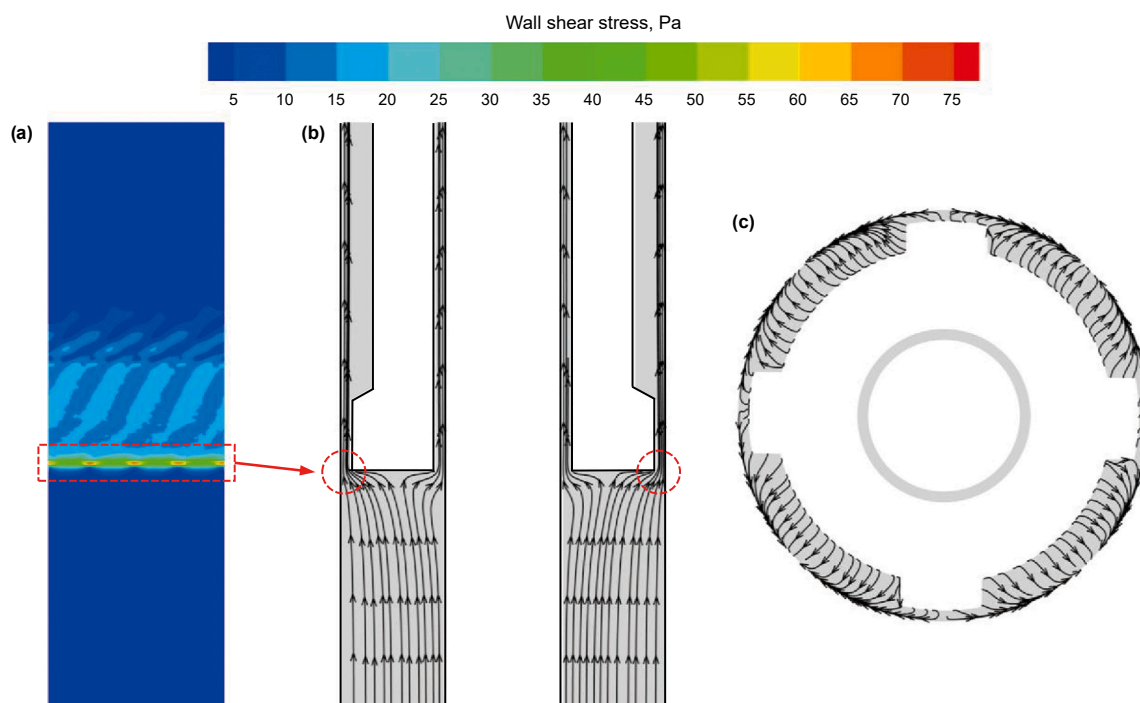


Fig. 31. Annulus outer wall shear stress and cross-sectional streamlines: (a) contour of annulus outer wall shear stress; (b) X–Y plane streamlines; (c) X–Z plane streamlines.

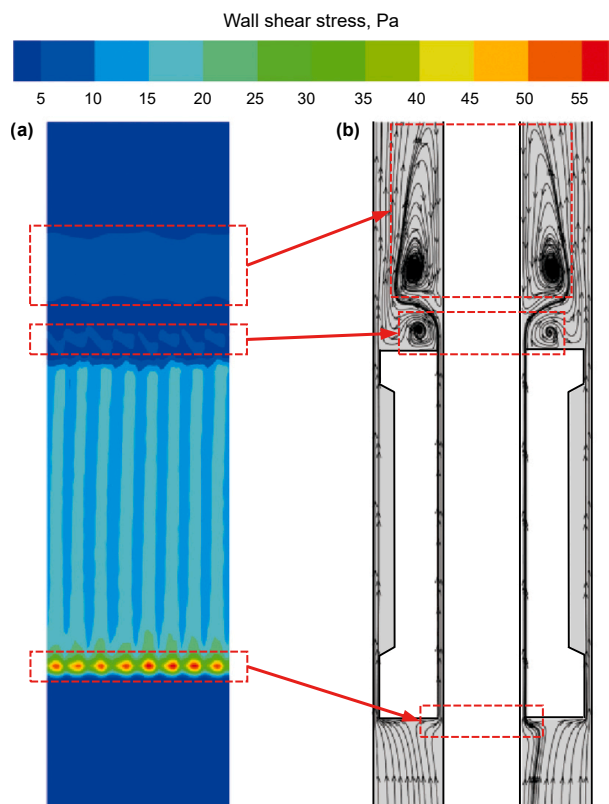


Fig. 32. Sucker rod surface shear stress and cross-sectional streamlines: (a) contour of sucker-rod surface shear stress; (b) X–Y plane streamlines.

strengthens near-wall impingement and produces a localized high wall shear stress at the inlet. After exiting the clearance into the downstream sudden-expansion section, flow separation and recirculation become pronounced. The resulting near-wall reattachment and high-shear regions lead to a banded distribution of wall shear stress on the inner rod.

5. Conclusions

A multiphase numerical model of the PCP wellbore annulus with a rod centralizer was developed to systematically investigate pressure drop and flow-field characteristics. Accounting for flow-induced rotation, oil-water two-phase flow, and power-law rheology, the pressure drop trends were quantified and the dominant factor was identified via sensitivity analysis. Entropy production analysis was then used to characterize the spatial distribution and components of energy dissipation, and vorticity-field analysis was combined to elucidate the underlying mechanisms of pressure loss. The main findings are summarized as follows.

- (1) In the PCP wellbore annulus, pressure drop increases approximately quadratically with inlet velocity and HPAM mass concentration, and approximately linearly with oil volume fraction and sucker rod rotational speed. Sensitivity analysis identifies inlet velocity as the dominant factor, with an independent contribution of 97.37%.
- (2) Flow-induced rotation of the centralizer is highly dependent on inlet velocity. Higher inlet velocity shortens the time to reach a steady rotational speed and increases the steady rotational speed. Under oil-water two-phase conditions,

both torque and rotational speed fluctuate, but the fluctuation amplitude decreases as inlet velocity increases.

- (3) Entropy production analysis shows that centralizer-induced pressure losses are highly non-uniform in space. The centralizer annulus region accounts for more than 60% of the total pressure loss. Time-averaged entropy production is the dominant component, contributing more than 50% of the total entropy production. Increasing inlet velocity amplifies all three components; however, their relative fractions evolve differently, with a decreasing time-averaged fraction, an increasing turbulent fraction, and a nearly unchanged wall fraction.
- (4) Liutex-based correlation analysis between the vorticity field and entropy production reveals strong spatial agreement, indicating that the geometric transitions and flow-induced rotation of the centralizer induce vortex clustering, which enhances energy dissipation and increases local pressure drop. Further analysis shows that shear vorticity primarily contributes to viscous loss, while rotational vorticity mainly accounts for turbulent loss.
- (5) Wall shear stress exhibits strong spatial agreement with wall entropy production, confirming that wall shear stress governs wall-friction loss. Streamline analysis indicates that local acceleration and separation-reattachment associated with contraction-expansion transitions drive the variations in wall shear stress.

This study still has certain limitations. First, the present model is mainly applicable to low gas-fraction conditions. Future work will further examine the influence of gas behavior on wellbore pressure drop characteristics. Second, the present model assumes a concentric configuration of the sucker rod, centralizer, and tubing. However, residual eccentricity can cause non-uniform local clearances, increasing velocity gradients and viscous dissipation on the narrow-gap side, while promoting asymmetric recirculation and vortex structures on the wide-gap side. Therefore, future work will further consider the influence of residual eccentricity on the energy-loss mechanism.

CRedit authorship contribution statement

De-Long Yu: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Hu-Kun Yang:** Writing – review & editing, Supervision, Resources, Project administration, Conceptualization. **Zhao-Hui Feng:** Writing – review & editing, Resources, Formal analysis. **Wei Song:** Writing – review & editing, Validation, Software. **Xia-Nan Miao:** Writing – review & editing, Formal analysis, Data curation. **Yan-Chun Li:** Writing – review & editing, Software, Funding acquisition. **Guang-Zheng Jia:** Writing – review & editing, Supervision, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. The full contents of Table 5

Table A.1
The full contents of Table 5 (orthogonal experimental design).

Case ID	U_{in} , m/s	α_o , %	n_{rod} , r/min	CHPAM, mg/L	Pressure drop, Pa
1	0.2	0.0	30	0	275.19
2	0.2	2.5	40	400	339.62
3	0.2	5.0	50	800	376.89
4	0.2	7.5	60	1200	414.72
5	0.2	10.0	70	1600	456.62
6	0.3	0.0	40	800	643.17
7	0.3	2.5	50	1200	558.79
8	0.3	5.0	60	1600	768.31
9	0.3	7.5	70	0	752.90
10	0.3	10.0	30	400	782.74
11	0.4	0.0	50	1600	1112.73
12	0.4	2.5	60	0	1043.09
13	0.4	5.0	70	400	1153.20
14	0.4	7.5	30	800	1214.16
15	0.4	10.0	40	1200	1293.45
16	0.5	0.0	60	400	1591.06
17	0.5	2.5	70	800	1660.82
18	0.5	5.0	30	1200	1731.76
19	0.5	7.5	40	1600	1834.64
20	0.5	10.0	50	0	1770.24
21	0.6	0.0	70	1200	2266.89
22	0.6	2.5	30	1600	2370.48
23	0.6	5.0	40	0	1778.52
24	0.6	7.5	50	400	2435.16
25	0.6	10.0	60	800	2539.79

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