

Article

The Influence of the Geometric Parameters of an Impeller on the Transport Capability of Long Flexible Fiber in a Non-Clogging Pump

Rongsheng Liu ¹, Qiang Zhang ², Suguo Zhuang ³ and Kai Wang ^{4,*} 

¹ School of Intelligent Engineering, Henan Institute of Technology, Xinxiang 453003, China; rslu_tech@hait.edu.cn

² Suzhou Xidian Intelligent Technology Co., Ltd., Suzhou 215163, China; qiang.zhang01@foxmail.com

³ School of Mechanical Engineering, Northwestern Polytechnical University, Xi'an 710072, China; zhuangsuguo@mail.nwpu.edu.cn

⁴ Research Center of Fluid Machinery Engineering and Technology, Jiangsu University, Zhenjiang 202013, China

* Correspondence: wangkai@ujs.edu.cn

Abstract: The influence of a different blade number, blade wrapping angle and blade outlet angle on flexible fiber passing performance is analyzed numerically with CFD-DEM coupling. The results demonstrate that a non-clogging pump with two blades exhibits superior passing performance compared to the non-clogging pump with three blades. Specifically, when the fiber length L is 150 mm, the passing performance of the pump with different wrapping angles is $270^\circ > 240^\circ > 300^\circ$, from highest to lowest, and the transport time T_0 is 0.27 s, 0.34 s, 0.46 s, respectively. When the length L is 200 mm, the passing performance is $240^\circ > 270^\circ \approx 300^\circ$, and the transport time T_0 is 0.48 s, 0.55 s, and 0.55 s, respectively. When the fiber length L is 250 mm, the passing performance is $240^\circ \approx 270^\circ > 300^\circ$. When the fiber length L is 150 mm, the passing performance of the pump with different outlet angles is $15^\circ > 25^\circ > 20^\circ$, and the transport time T_0 is 0.17 s, 0.27 s, and 0.34 s, respectively. When the fiber length L is 200 mm, the passing performance is $25^\circ > 15^\circ \approx 20^\circ$ and the transport time T_0 is 0.26 s, 0.50 s, and 0.48 s, respectively. When the fiber length L is 250 mm, the passing performance is $25^\circ > 15^\circ > 20^\circ$, and the transport time T_0 is 0.31 s, 0.54 s and 0.96 s, respectively.

Keywords: geometric parameters; non-clogging pump; CFD-DEM coupling; transport capability; long flexible fiber



Citation: Liu, R.; Zhang, Q.; Zhuang, S.; Wang, K. The Influence of the Geometric Parameters of an Impeller on the Transport Capability of Long Flexible Fiber in a Non-Clogging Pump. *Processes* **2024**, *12*, 1779. <https://doi.org/10.3390/pr12081779>

Academic Editor: Václav Uruba

Received: 14 July 2024

Revised: 13 August 2024

Accepted: 21 August 2024

Published: 22 August 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

In the transport of solid–liquid two-phase flow by non-clogging pumps, a distinctive flow type is encountered: solid–liquid two-phase flow containing long flexible fibers. During the operation of non-clogging pumps, these long flexible fibers are prone to clogging and entanglement, leading to pump blockage, reduced efficiency, and, in severe cases, entangled pump shafts and burned-out motors. Addressing this issue necessitates urgent research on the performance of non-clogging pumps in the presence of long flexible fibers. However, current studies on solid–liquid two-phase flow in non-clogging pumps predominantly focus on the transport of rigid small particle solid–liquid two-phase flow and fine fiber suspensions. Significant technical bottlenecks and challenges persist in managing media containing long flexible fibers. Therefore, investigating solid–liquid two-phase flow in non-clogging pumps with long flexible fibers is critical for enhancing pump performance and achieving more efficient medium transport.

Research on solid–liquid two-phase flow within pumps encompasses theoretical studies, experimental measurements, and numerical simulations. Theoretical research primarily focuses on the laws of motion of solid particles within the pump. In 1942, Fairbank [1] analyzed the laws of motion and force states of solid particles with a centrifugal

pump and proposed an expression for the theoretical head of the pump when conveying solid–liquid two-phase flow. Experimental research addresses not only the motion laws of particles but also the influence of the solid phase on the external characteristics of the pump and the wear of particles on the pump's flow components. In 1994, Walker et al. [2] investigated the effect of flow rate and particle size on the wear of slurry pumps through experiments. The results indicated minimal particle wear on the pump at 0.8 times the rated flow rate. Coarse particles caused more severe impeller wear, whereas fine particles led to more significant wear of the volute throat. Charoenngam [3] utilized PIV experiments to investigate the velocity and kinetic energy fluctuations of particles at the baffle position of a centrifugal pump. The study revealed that increasing the impeller speed from 750 rpm to 1000 rpm led to a 2–5-fold increase in particle kinetic energy fluctuations. Salim et al. [4] analyzed the effects of particle size and concentration on slurry pump performance, revealing that the pump head decreased most significantly when the particle size was 4 mm and the concentration was 5%, while efficiency was lowest when the particle size was 20 mm and the concentration was 5%. Tarodiya et al. [5] investigated the influence of particle size and concentration on slurry pump performance, demonstrating that both pump head and efficiency diminished as particle concentration and size increased. Tan et al. [6] utilized high-speed photography to study the movement rules of large-diameter spherical particles in solid–liquid two-phase flow pumps, their ability to pass through the pump, and the collision laws between particles and the tongue. The results demonstrated that for particle volume fractions of 1%, 3%, and 5%, the collision probability between particles and the tongue was 0.5%, 0.69%, and 0.9%, respectively. For particle diameters of 6 mm, 8 mm, and 10 mm, the collision probability in the tongue region was 0.69%, 0.63%, and 0.55%, respectively. Wang et al. [7] analyzed the performance of a double-suction centrifugal pump under sandy water flow conditions. The results showed that due to the presence of sediment, the pump head and shaft power were lower than those under pure water conditions and decreased with increasing sediment concentration and particle size. Zhang et al. [8] studied the effect of different particle concentrations on the performance of a centrifugal pump and found that compared to pure water conditions, the high-efficiency zone of the centrifugal pump shifted towards a lower flow rate when transporting solid particles.

In the realm of numerical simulation research, Pagalthivarthi [9,10] utilized Fluent to simulate impeller wear during the transport of solid–liquid two-phase flow in a centrifugal pump, discovering that the impeller experienced greater wear than the volute. In 2012, Datta [11] investigated the variation of shear stress and solid concentration on the wall of a deep-sea mining pump, using parameters based on a dual-fluid model. The analysis revealed that the maximum values of shear stress and solid concentration occurred near the eighth section of the volute, with both values increasing as particle concentration and size increased. Shi [12] studied the flow field characteristics of two-phase flow in a low-specific-speed centrifugal pump and proposed a new iterative convergence method to solve the two-phase flow problem. The experimental results showed that the improved method was very effective for the convergence of numerical simulations. With the continuous development of numerical simulation technology, the CFD-DEM coupling method emerged, which combines CFD solutions with DEM solutions for particle phase motion. This method is superior to traditional two-phase flow calculation methods. Chaumeil et al. [13] employed CFD-DEM to simulate Brownian particles, successfully capturing the sedimentation of particles within a pipeline and validating the coupled simulation's accuracy through experimental comparison. Similarly, Azimian et al. [14] utilized the CFD-DEM coupling method to calculate particle erosion in pipeline flow, confirming the high reliability of the coupled simulation with experimental data.

Yamamoto et al. [15] introduced a flexible fiber model capable of simulating the stretching, bending, and twisting deformations of fibers in fluid by adjusting the connecting distance, bending angle, and torsion angle between adjacent spheres. Building on this foundation, various flexible fiber models, including the spherical chain fiber model,

ellipsoidal chain fiber model, and cylindrical rod chain fiber model, have been proposed by numerous researchers [16–18]. Liu and Wang et al. [19] developed a numerical simulation method for solid–liquid two-phase flow involving long fibers in non-clogging pumps, analyzing the impact of different densities, lengths, and diameters of single fibers on the transport capability of a double-blade non-clogging pump. Geng et al. [20] employed a slender chain structure for numerical simulation to examine the distribution characteristics of slender flexible particles in a fluidized bed. Kang [21] utilized a Fluent–EDEM bidirectional coupling method to simulate the flow process of flexible fiber suspensions in a pump, investigating the internal flow field and the motion characteristics of the fibers.

In conclusion, it can be observed that current research on solid–liquid two-phase flow mainly focuses on the interactions between particles and liquid. However, there is a lack of research on the motion of solid–liquid two-phase flow containing flexible fibers, especially in the context of long-fiber solid–liquid two-phase flow in non-clogging pumps. Therefore, this paper proposes a CFD–DEM coupling method to study the passage performance of flexible long fibers in non-clogging pumps. Additionally, different designs of non-clogging pumps with varying numbers of blades, blade wrap angles, and outlet angles are explored to investigate the influence of blade parameters on the passage capability of flexible long fibers.

2. Simulation Model and Research Plan

2.1. Calculation Model

The design parameters for the non-clogging pump [19] are specified as follows: a flow rate (Q_d) of 25.86 m³/h, a head (H_d) of 3.45 m, and a rotational speed (n) of 750 r/min. The primary structural parameters of the impeller and volute of the non-clogging pump are detailed in Table 1.

Table 1. Principal structural parameters of the double-blade pump [19].

Structural Parameters	Value	Unit
Inlet diameter of impeller D_1	90	mm
Outlet diameter of impeller D_2	200	mm
Inlet shaft diameter of impeller d_h	40	mm
Blade number of impeller z	2	
Blade wrapping angle of impeller φ	240	°
Blade outlet angle β_2	20	°
Outlet width b_2	50	mm
Volute casing base circle diameter D_3	212	mm
Volute casing inlet width b_3	77	mm

The simulation model of the double-blade non-clogging pump comprises an open impeller, a volute, a suction chamber, an inlet extension section, and an outlet extension section, as depicted in Figure 1.

A tetrahedral mesh is utilized to discretize the computational domain of the non-clogging pump, with refined grids applied to the blades and interface regions. Five different grid partitioning schemes with varying grid densities are employed, ensuring that the grid quality in each section exceeds 0.3. The pump head for each grid scheme under rated operating conditions is calculated using FLUENT 2020 R2 software to perform a grid independence analysis. The results of this analysis are summarized in Figure 2.

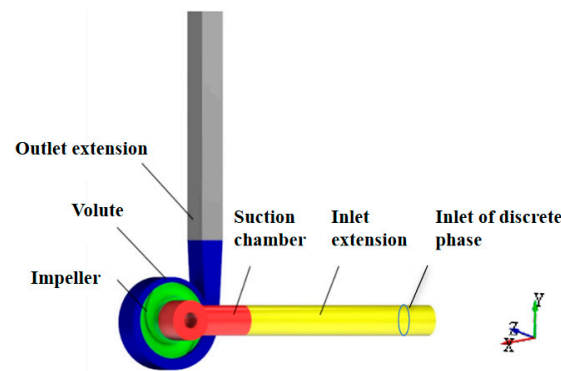


Figure 1. Calculation model of the double-blade pump [19].

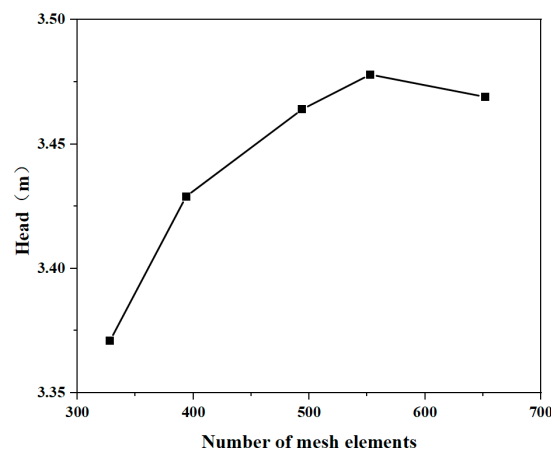


Figure 2. Mesh independence analysis.

As shown in Figure 2, when the grid numbers are 4.94 million and 5.52 million, the calculated head values are 3.464 m and 3.478 m, respectively, with a relative deviation of 0.40% between these two schemes. To conserve computational resources and improve efficiency, Scheme 3 is chosen for the numerical simulation. This scheme consists of 4.93 million grids, with a maximum impeller grid size of 3 mm. The maximum grid size for the volute, suction chamber, and inlet and outlet extension sections is 4 mm. Additionally, the grids for the blades, volute tongue, and interfaces are refined.

2.2. Calculation Setting

In our previous research, we developed a numerical simulation method for solid–liquid two-phase flow with long fibers in non-clogging pumps using a CFD-DEM coupling model, which was validated as detailed in Reference [19].

The liquid phase calculations are performed in FLUENT during the pre-processing stage. The reference pressure is set to standard atmospheric pressure (101,325 Pa), and gravitational acceleration is defined as 9.81 m/s^2 in the direction opposite to the pump outlet. The inlet boundary condition is specified as a mass flow rate inlet, with values adjusted according to actual operating conditions. The outlet boundary condition is set as a free outflow, while the wall boundary condition employs the standard wall function. The time step is configured to correspond to one step per 6° of impeller rotation, resulting in a Δt of 0.00133 s. Each step undergoes 20 iterations with a convergence criterion of 10^{-3} . The coupled solver is used, with gradients and pressure discretized using the least squares cell-based method and the PRESTO! scheme, respectively. Momentum is discretized using the bounded central differencing scheme, while the turbulence kinetic energy, turbulence dissipation rate, and the energy equation are all discretized using the second-order upwind scheme. All relaxation factors are set to their default values.

The water domain of the double-blade non-clogging pump is divided into wall surfaces and imported into Rocky. The wall material is defined as steel, with a density of 7850 kg/m^3 and a Young's modulus of $1 \times 10^{11} \text{ N/m}^2$. The impeller wall rotation speed is set at 750 r/min. A discrete-phase material inlet is established at the inlet extension of the pump, with the mass flow rate at the discrete-phase inlet adjusted to ensure the transport of a single fiber within the pump. Flexible fiber model schemes with varying lengths, diameters, and densities are developed, as detailed in Table 2.

Table 2. Research schemes of double-blade.

Scheme	Blade Number of Impeller z	Blade Wrapping Angle of Impeller $\varphi/^\circ$	Blade Outlet Angle $\beta_2/^\circ$
1	2	240	20
	3	240	20
2	2	240	20
	2	270	20
	2	300	20
3	2	240	15
	2	240	20
	2	240	25

Utilizing flexible fiber schemes of varying lengths for numerical simulation, hay grass fiber was selected as the fiber material, with a density of 732 kg/m^3 and a Young's modulus of $1 \times 10^7 \text{ N/m}^2$. The calculation time step for the discrete phase is set at a $n\Delta t$ of 0.00665 s, where n is 5, matching the total duration of the fluid phase calculation. To ensure fiber outflow, the total duration is set to the time required for the impeller to complete ten rotations, denoted as T , which is 0.8 s. Fiber models of different lengths are shown in Figure 3.

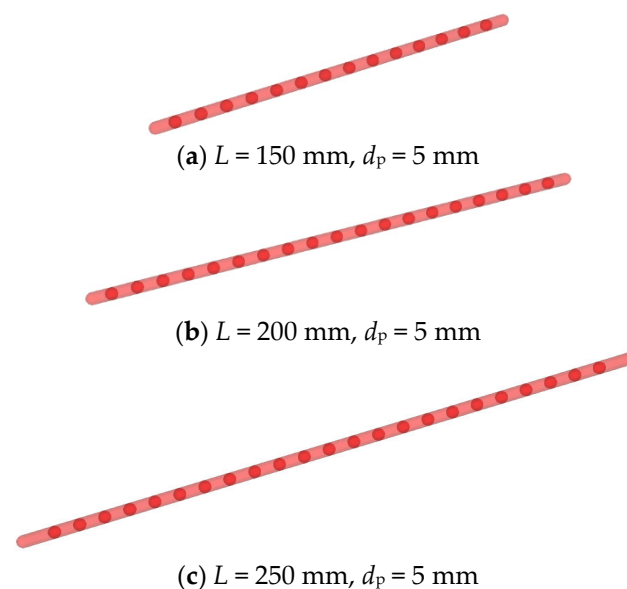


Figure 3. Fiber models with different lengths and diameters [19].

3. Results and Analysis

3.1. Influence of Blade Number of Impeller on Long Flexible Fiber Passage Performance

(1) Fiber length L of 150 mm

Figure 4 illustrates the flow characteristics of a 150 mm long flexible fiber transported in non-clogging pumps with varying blade counts at the rated flow rate. With a blade count

of 2, the 150 mm flexible fiber does not aggregate within the double-blade non-clogging pump. Upon entry, the fiber moves from the outer edge of one blade towards the suction surface of the adjacent blade, exiting the impeller along the suction surface and entering the volute at a t of 0.4655 s. After initially passing through the diffuser section of the volute, the fiber impacts the tongue, leading to the continued rotation of the fiber within the volute.

When the blade count is 3, the flow behavior of the 150 mm long flexible fiber is similar to that observed in non-clogging pumps with two blades. In both configurations, the fiber transitions from the outer side of one blade to the suction surface of another blade and then progresses towards the trailing edge. However, in the pump with three blades, the narrower flow passage increases the likelihood of fiber interaction with the blades upon detachment from the inlet edge, thereby reducing its detachment velocity. At a t of 0.4655 s, the fiber remains centrally positioned between the blades. As the flexible fiber moves through the volute, it does not encounter the tongue. Consequently, the fiber exits the outlet extension section more rapidly in the non-clogging pump with three blades compared to the pump with two blades.

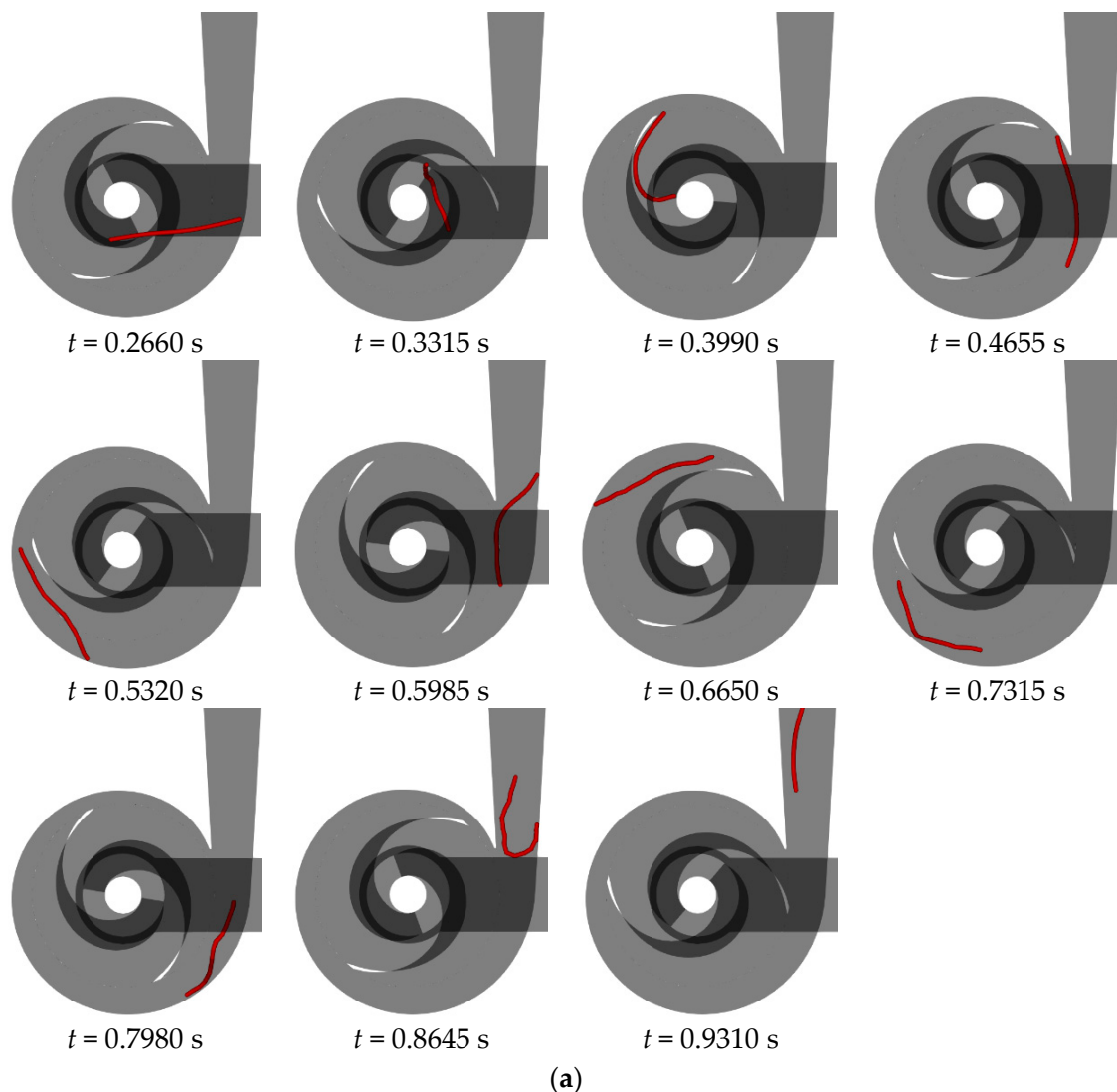


Figure 4. Cont.

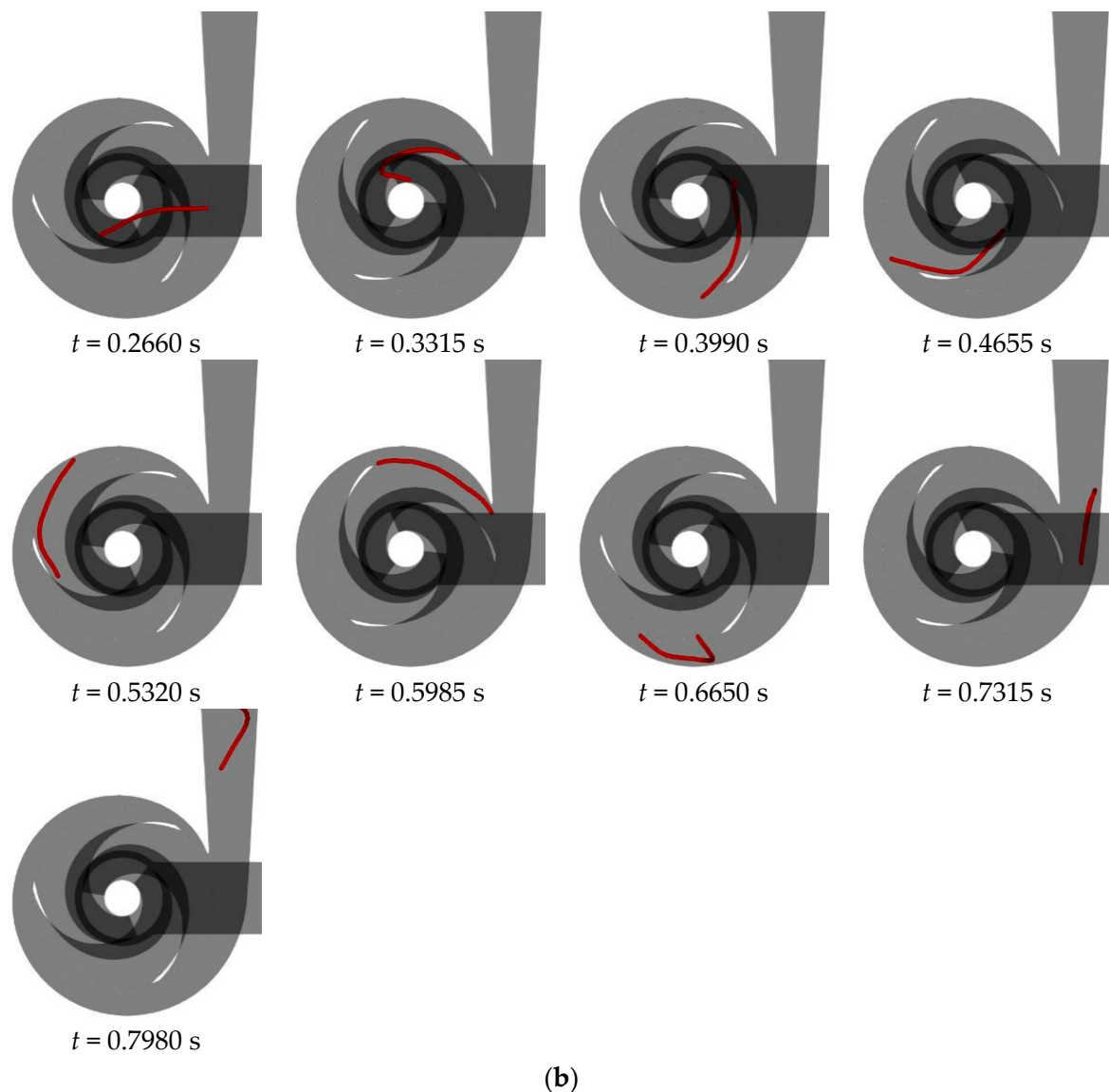


Figure 4. The flow behavior of the 150 mm long flexible fiber in the non-clogging pump with different numbers of impeller blades. (a) $z = 2$ [19], (b) $z = 3$.

Figure 5 displays the mean coordinates of the 150 mm long flexible fiber at the rated flow rate in non-clogging pumps with varying blade numbers. The figure shows that the fiber's entry time into the impeller is similar for pumps with two and three blades. In the non-clogging pump with two blades, the first half of the fiber enters the volute diffusion section at a t of 0.58 s after two rotations. However, due to collisions between the fiber's middle section and the tongue, the fiber remains in the volute and completes an additional rotation. At a t of 0.83 s, the fiber re-enters the volute diffusion section. During this rotation, the fiber's interaction with the volute wall causes fluctuations in the maximum y-axis positive coordinate value. In the non-clogging pump with three blades, the fiber initially enters the volute diffusion section at a t of 0.72 s after four rotations, without colliding with the tongue, and proceeds smoothly into the outlet extension section.

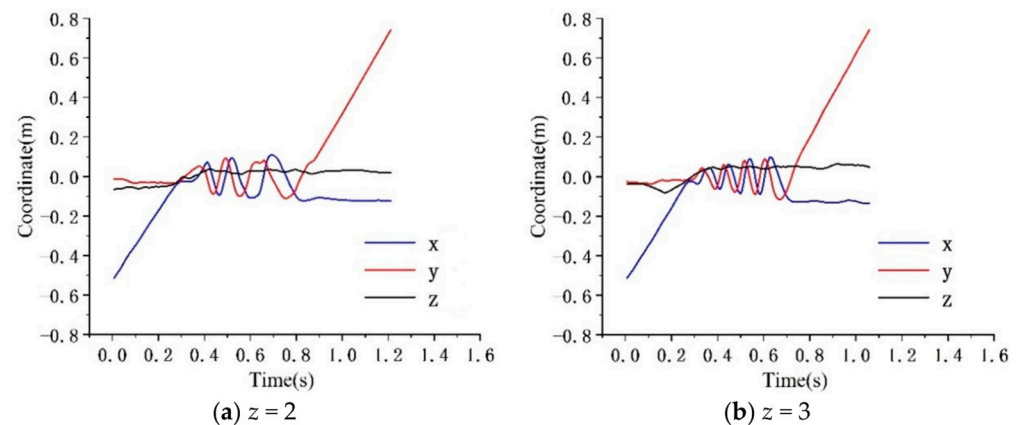


Figure 5. The average coordinates of the 150 mm long flexible fiber in the non-clogging pump.

Figure 6 depicts the transit time of a 150 mm flexible fiber in non-clogging pumps with varying blade quantities. From the figure, although the flexible fiber with a length of 150 mm has a longer T_1 in the non-clogging pump with a blade number z of 2, T_0 is shorter and the number of rotation cycles N is smaller with a blade number z of 2. So, it is believed that when conveying flexible fiber with a length of 150 mm, the non-clogging pump with a blade number z of 2 has a better passing performance.

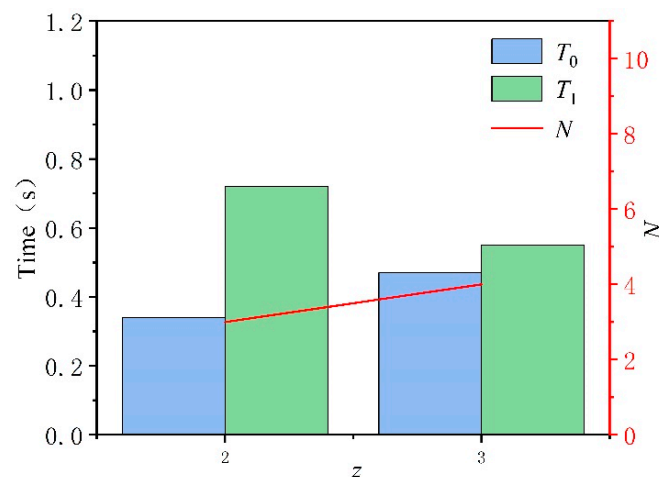


Figure 6. The transit time of the 150 mm flexible fiber.

(2) Fiber length L of 200 mm

Figure 7 illustrates the flow behavior of a 200 mm long flexible fiber in non-clogging pumps with varying blade counts under rated flow conditions. In the pump with two blades ($z = 2$), the fiber initially collides with the suction surface of a blade near the inlet upon entering the impeller, causing aggregation in the fiber's first half. As the liquid phase progresses, this aggregation gradually extends from the outer edge towards the trailing end of the blade, eventually exiting the impeller. Within the volute, the fiber encounters the tongue, resulting in bending and continued flow through one cycle before exiting the volute. In the pump with 3 blades ($z = 3$), the flow characteristics of the flexible fiber are more complex. The narrower flow passage in the three-blade non-clogging pump causes the fiber to obstruct the suction surface of the blade in its initial half upon impeller entry. This leads to the fiber bending between the blade's inlet edge and the pump shaft and then sliding towards the blade's mid-point along the suction surface. The central flow passage of the blade gradually widens, allowing the fiber to extend and enlarge before entering the volute's diffuser section after sufficient rotation.

Figure 8 illustrates the mean coordinates of the flow characteristics of a 200 mm long flexible fiber under rated operating conditions in non-clogging pumps with varying blade numbers. According to the flow state analysis in the figure, in non-clogging pumps with two blades ($z = 2$), the flexible fiber impacts the tongue at $t = 0.58$ s after three rotations and enters the volute's diffusion section at $t = 0.72$ s after another rotation. In non-clogging pumps with three blades ($z = 3$), upon entering the impeller, the flexible fiber undergoes extended rotation due to the narrow flow passage. The fiber rotates within the non-clogging pump for nine cycles before entering the volute's diffusion section at $t = 1.12$ s.

Figure 9 depicts the transit time of a 200 mm long flexible fiber in non-clogging pumps with varying blade numbers. According to the figure, the 200 mm flexible fiber exhibits shorter T_0 and T_1 durations and a smaller number of rotation cycles N in the non-clogging pump with two blades. Thus, it can be concluded that for conveying 200 mm flexible fibers, the non-clogging pump with two blades demonstrates superior performance.

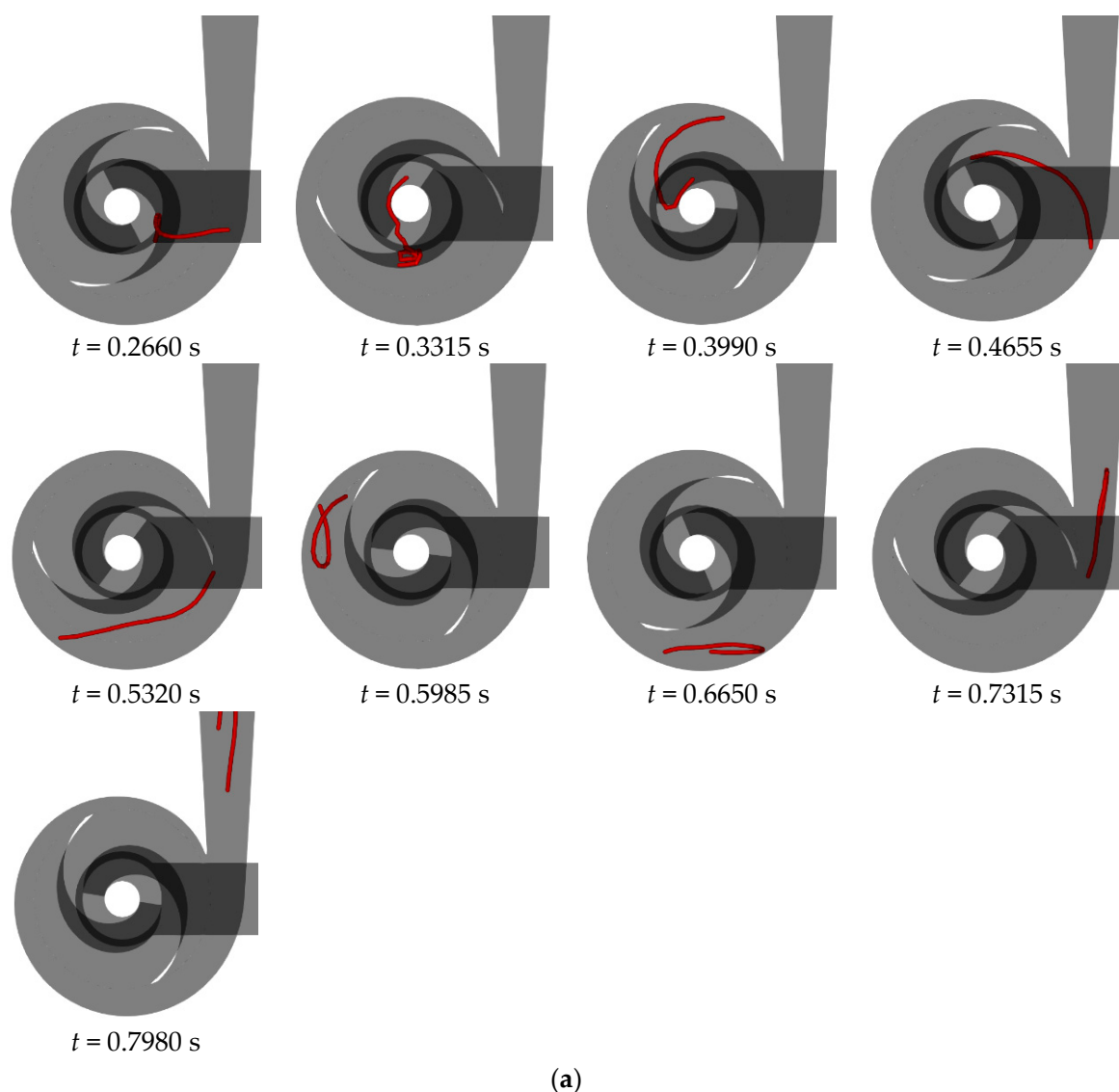


Figure 7. Cont.

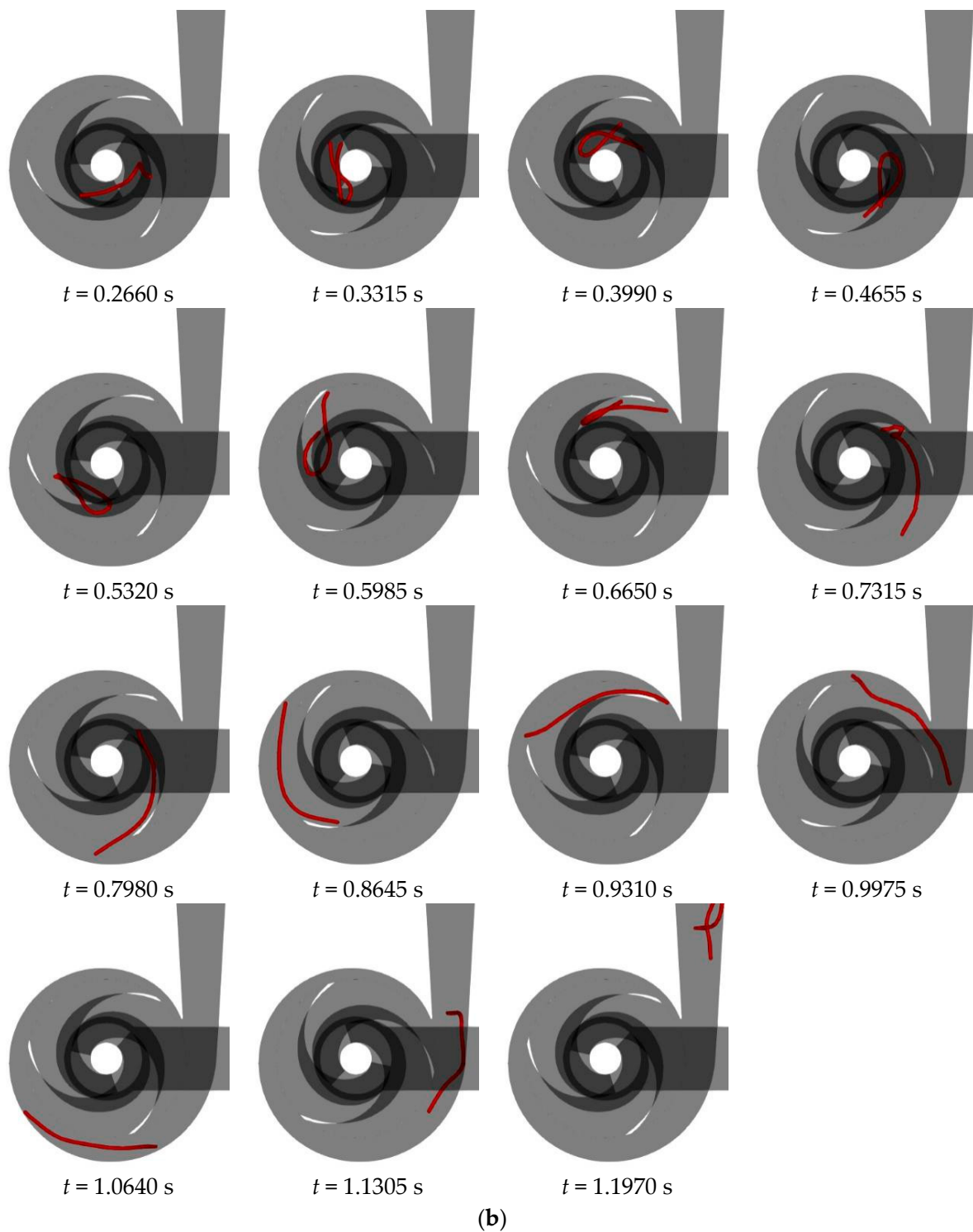


Figure 7. The flow behavior of the 200 mm long flexible fiber in the non-clogging pump with different numbers of impeller blades. (a) $z = 2$ [19], (b) $z = 3$.

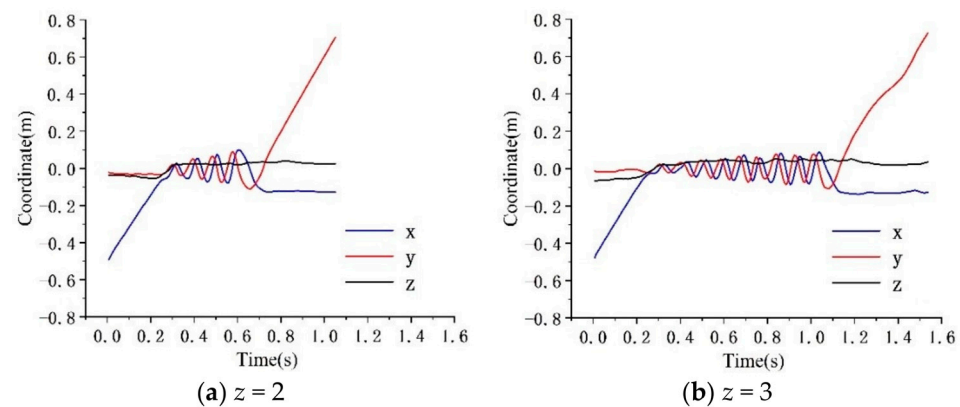


Figure 8. Average coordinates of the 200 mm long flexible fiber in the non-clogging pump.

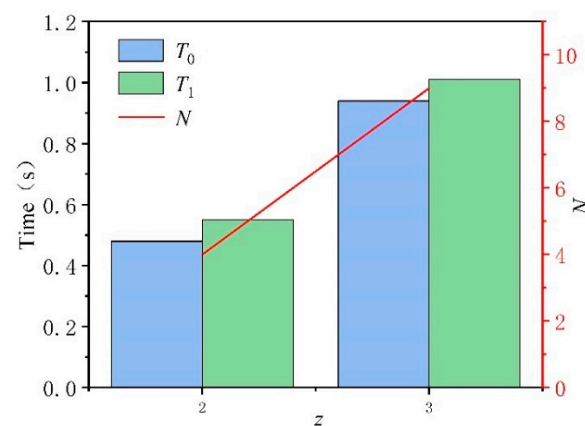


Figure 9. The transit time of the 200 mm flexible fiber.

(3) Fiber length L of 250 mm

Figure 10 illustrates the flow characteristics of a 250 mm long flexible fiber in non-clogging pumps with varying blade counts at the rated flow rates. The figure shows that in a non-clogging pump with two blades ($z = 2$), after the flexible fiber enters the impeller, the first half moves towards the outer side of the blade, while the second half wraps around the pump shaft, impeding further movement towards the outer side. Consequently, both ends of the fiber repeatedly collide with the blade wall, resulting in bending or aggregation, which keeps the fiber at the center of the impeller. Over time, the fiber gradually shifts to one side. At a t of 0.7980 s, the first half of the fiber returns to the outer side of the blade, and the second half is drawn towards the blade's exterior, forming a circular shape influenced by eddy currents, which progressively extends and unfolds. The fiber exits after rotating within the volute.

In a non-clogging pump with three blades ($z = 3$), the flexible fiber immediately wraps around the pump shaft upon entering the impeller. During the subsequent second, the fiber's relative position remains constant, continuously wound around the pump shaft at the inlet edge of the blades and unable to disengage. Therefore, it can be concluded that the 250 mm long flexible fiber cannot pass smoothly through the non-clogging pump with three blades.

Figure 11 depicts the mean coordinates of the flow characteristics of a 250 mm long flexible fiber under rated operating conditions in non-clogging pumps with varying blade numbers. According to the figure, in the non-clogging pump with two blades ($z = 2$), the flexible fiber enters the volute's diffusion section after nine cycles of rotation. During the initial six cycles, the fiber wraps around the pump shaft and remains at the impeller's center, resulting in minimal change in the average peak coordinate. Periodic weakening due to blade collisions occurs during the third and fourth cycles, resulting in indistinct

peaks and valleys. By the seventh cycle, the fiber gradually detaches from the impeller's center, leading to a gradual increase in the average extreme coordinate value. Finally, at $t = 1.15$ s, the fiber enters the volute's diffusion section.

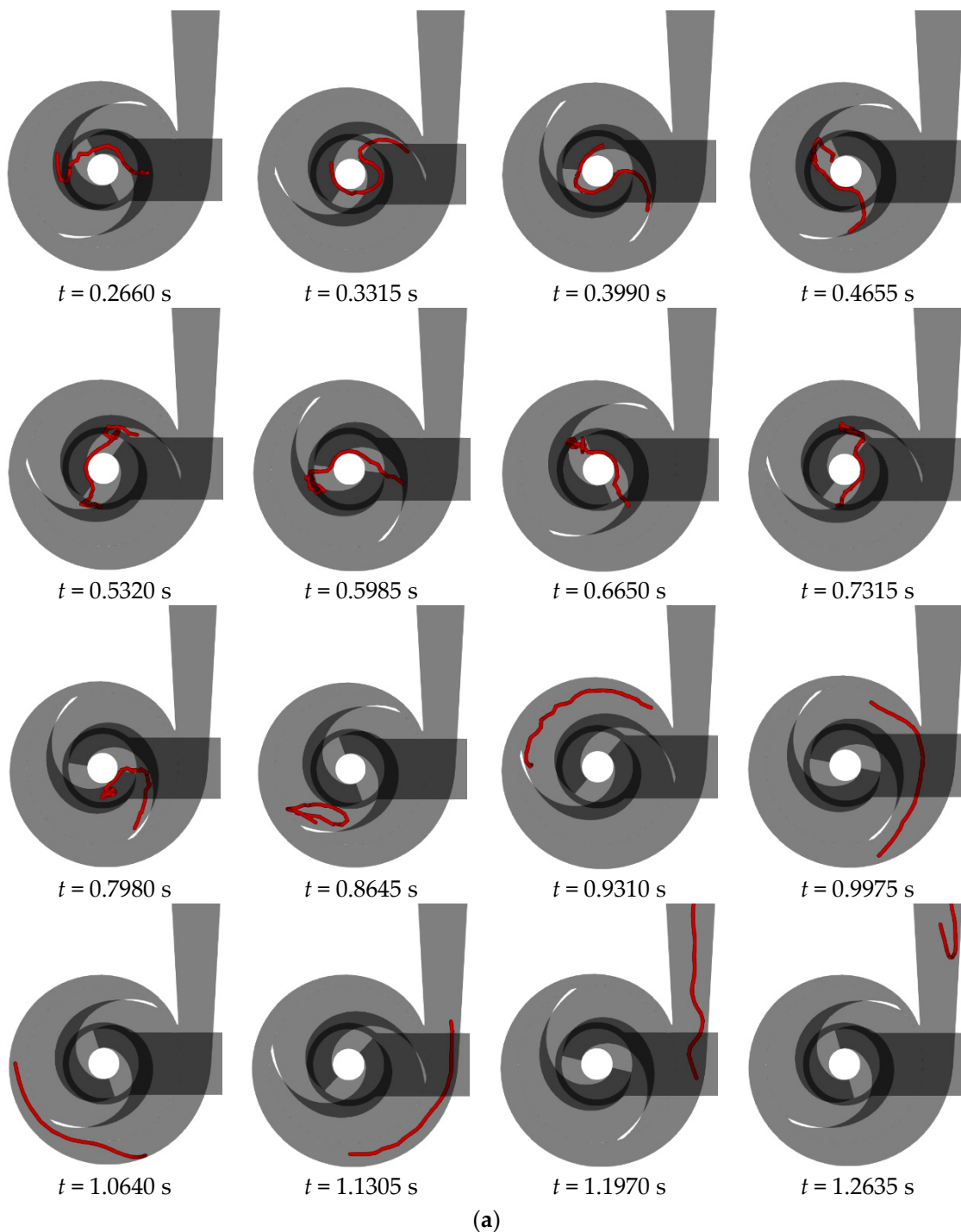


Figure 10. Cont.

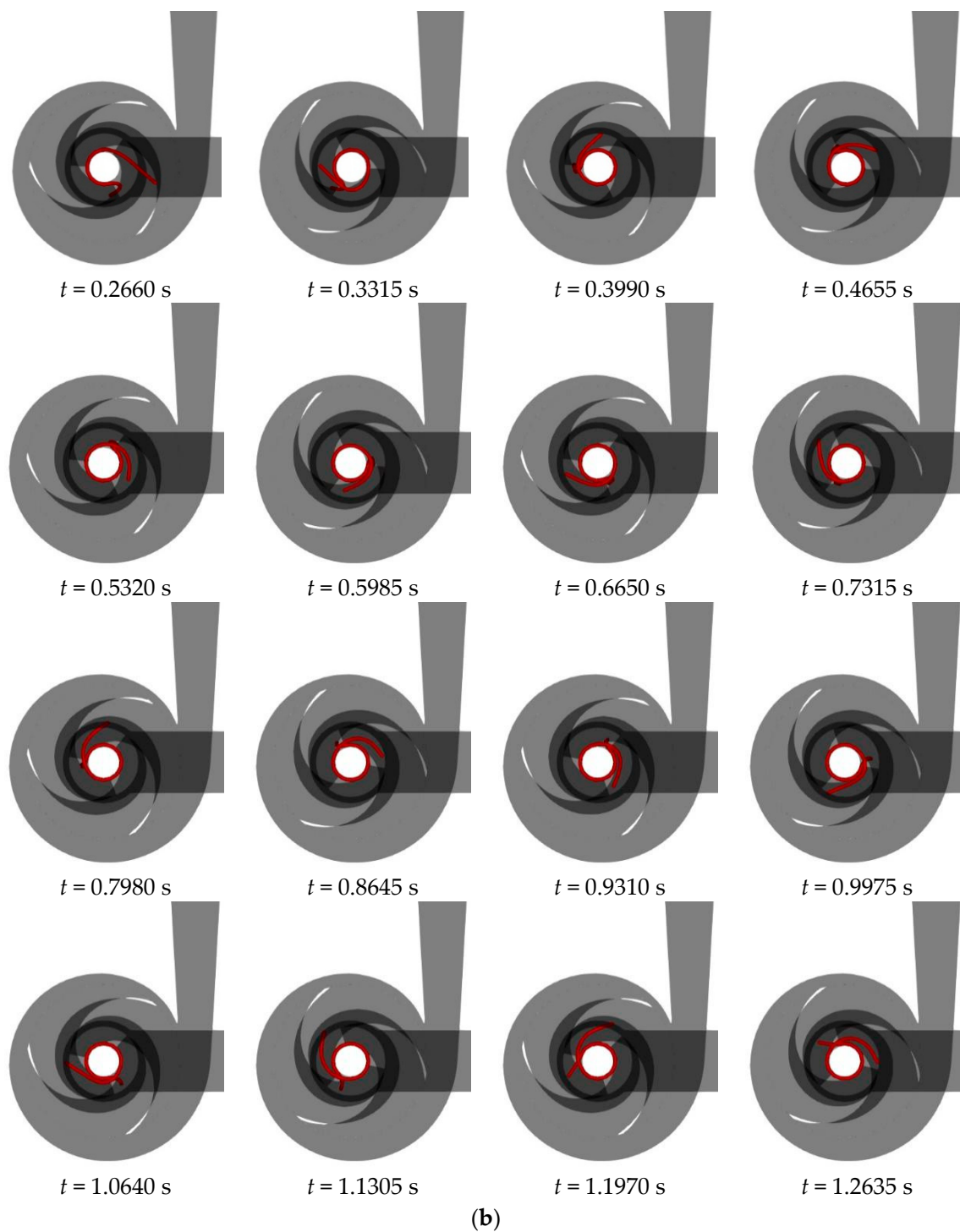


Figure 10. The flow behavior of the 250 mm long flexible fiber in the non-clogging pump with different numbers of impeller blades. (a) $z = 2$ [19], (b) $z = 3$.

In the non-clogging pump with three blades ($z = 3$), upon entering the impeller, the fiber wraps around the pump shaft and maintains a consistent relative position thereafter. Consequently, starting from $t = 0.27$ s, the average coordinates of the flexible fiber exhibit periodic changes resembling a sinusoidal curve.

A 250 mm long flexible fiber cannot pass through a non-clogging pump with three blades, so when conveying a length of 250 mm flexible fiber, the non-clogging pump with two blades has better performance.

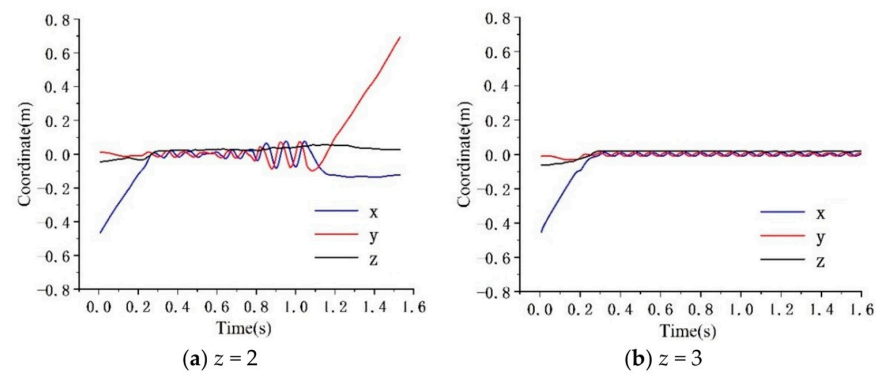


Figure 11. The average coordinates of the 250 mm long flexible fiber in the non-clogging pump.

3.2. Influence of Blade Wrapping Angle of Impeller on Long Flexible Fiber Passage Performance

(1) Fiber length L of 150 mm

Figure 12 illustrates the behavior of a 150 mm long flexible fiber at the rated flow rate in a double-blade non-clogging pump with varying blade wrap angles. The figure shows that under rated flow conditions, the 150 mm fiber does not aggregate in the double-blade non-clogging pump. With a blade wrap angle of 140° , the fiber enters the pump and transitions from the outer side of one blade to the suction surface of the adjacent blade. At a t of 0.4655 s, the fiber exits the impeller along the suction surface of the blade and enters the volute. Within the volute, the fiber encounters the tongue during its initial passage, which causes it to continue flowing in the volute for an additional cycle before exiting.

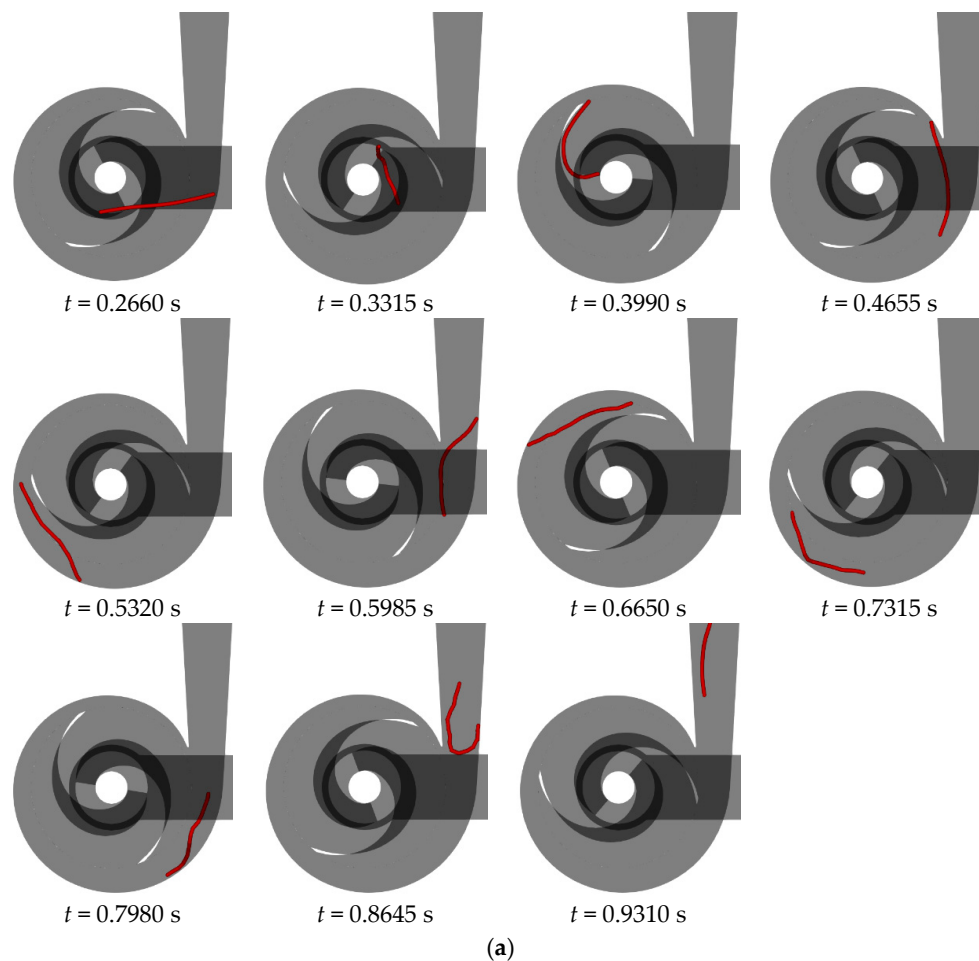


Figure 12. Cont.

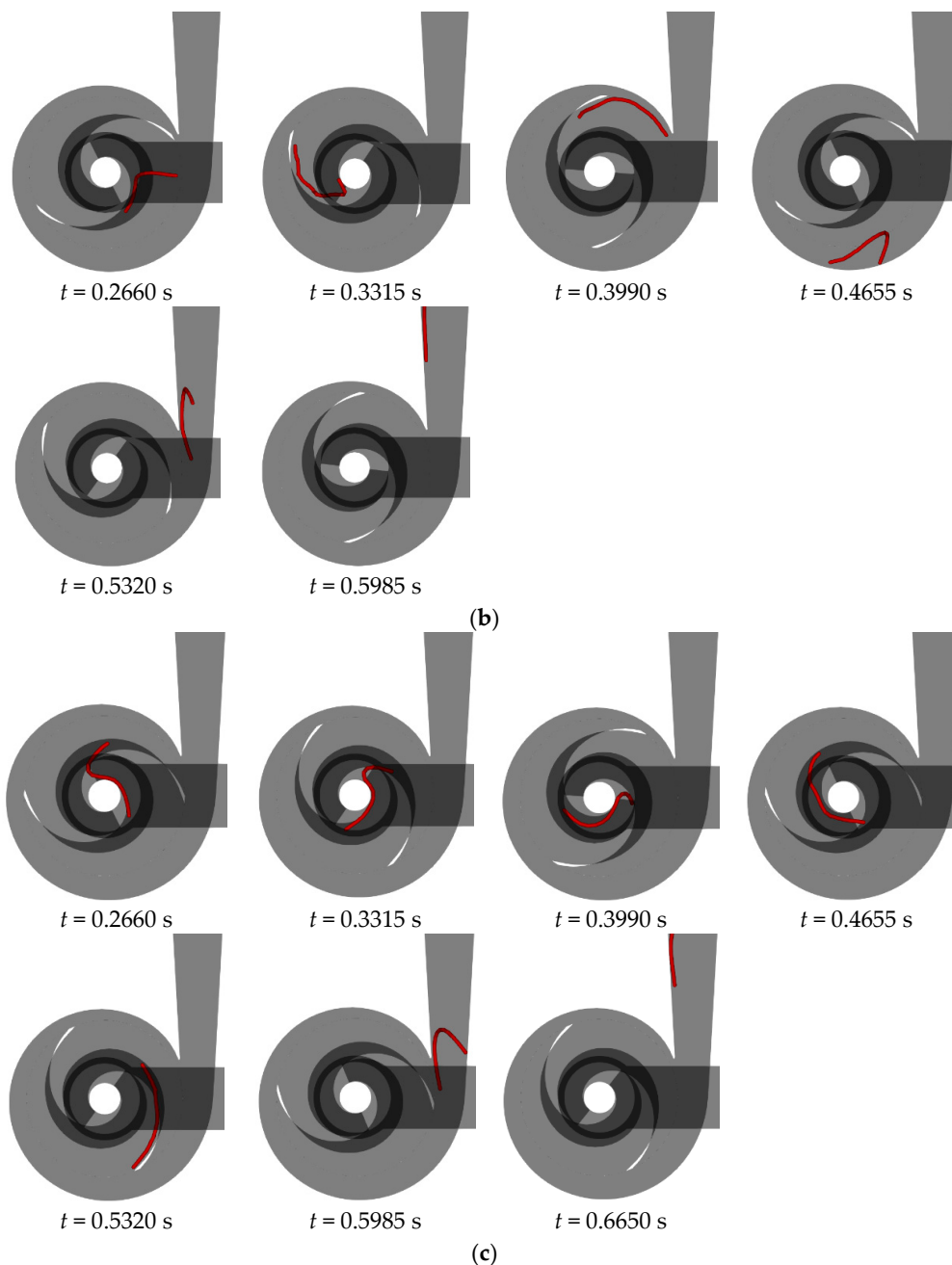


Figure 12. The flow behavior of the 150 mm long flexible fiber in the non-clogging pump with different wrap angles. (a) $\varphi = 240^\circ$ [19], (b) $\varphi = 270^\circ$, (c) $\varphi = 300^\circ$.

When the blade wrapping angle is 270° , the flow characteristics of the fiber resemble those at a 240° wrapping angle. However, owing to increased blade curvature, the fiber experiences significant bending along the blade's suction surface during flow. Compared to the 240° angle, at 270° the fiber's outflow velocity from the impeller increases. By $t = 0.3990$ s, more than half of the fiber has already entered the volute. Within the volute, the fiber collides and bends against the wall. Due to its early entry into the volute for centrifugal motion, the fiber smoothly exits the impeller without colliding with the tongue when reaching its position.

When the blade wrap angle is 300° , the flow characteristics of the fiber markedly differ from those observed at 240° and 270° angles. As the fiber bends at the blade's inlet edge, the pronounced blade curvature prevents it from moving towards the outer side, instead directing it outward along the blade's suction surface from the inner side. This results in a

significant increase in the time required for the fiber to exit the impeller. At a t of 0.5320 s, the fiber remains entirely within the impeller. However, upon exiting the impeller, the fiber collides with the baffle, causing additional bending and accelerating its detachment from the impeller, thereby allowing it to directly enter the outlet section of the volute.

Figure 13 presents the mean coordinates of a 150 mm long flexible fiber flowing in a double-blade non-clogging pump at various blade wrap angles under rated flow conditions. The figure shows that in the double-blade non-clogging pump with a 240° wrap angle, the fiber enters the volute's diffusion section after three rotations. The extreme coordinates of the third cycle are similar to those of the second cycle. Flow dynamics analysis reveals that the fiber's continued rotation into the third cycle is due to its collision with the tongue, which extends its rotation within the volute for an additional cycle. As a result, the rotational radius in the third cycle remains comparable to that of the second cycle. The flexible fiber enters the impeller at a t of 0.29 s, collides with the tongue at a t of 0.60 s, and enters the volute's diffusion section at a t of 0.83 s.

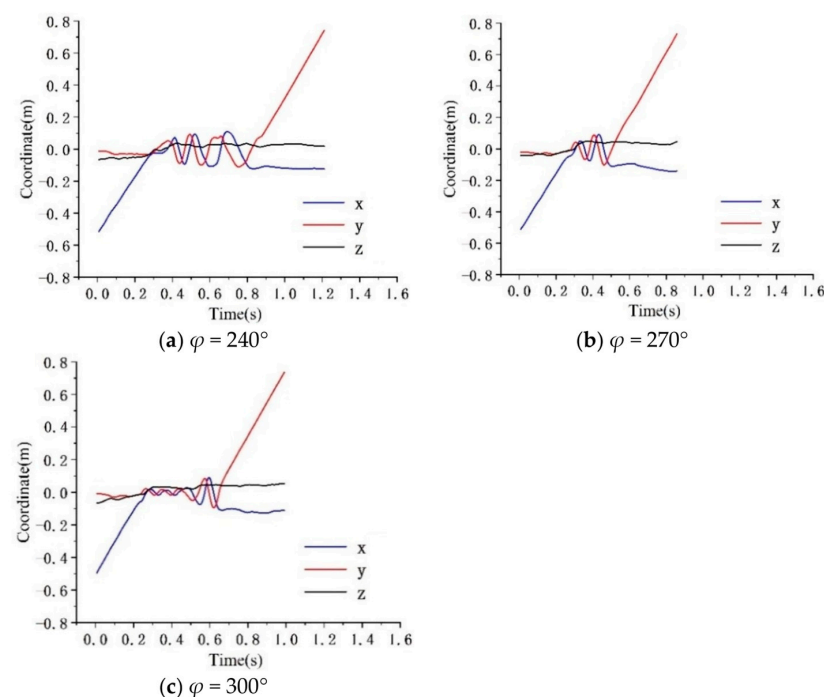


Figure 13. The average coordinates of the 150 mm long flexible fiber in the non-clogging pump.

In a double-blade non-clogging pump with a 270° wrap angle, the flexible fiber completes two rotations before entering the volute's diffusion section. It enters the impeller at a t of 0.27 s and reaches the volute's diffusion section at a t of 0.50 s without colliding with the baffle. In a double-blade non-clogging pump with a 300° wrap angle, the flexible fiber enters the impeller at a t of 0.24 s. During the first three rotations, the fiber remains at the center of the impeller, leading to relatively minor fluctuations in the coordinate curve. The fiber exits the central position of the impeller at a t of 0.51 s and enters the volute's diffusion section after one rotation at a t of 0.66 s.

Figure 14 depicts the transit time of a 150 mm long flexible fiber in non-clogging pumps with various blade wrapping angles. According to the figure, in the non-clogging pump with a blade wrapping angle of 240° , the 150 mm flexible fiber encounters the tongue, resulting in an extended time T_1 . Therefore, the non-clogging pumps rank in increasing order of T_1 time as follows: 270° , 300° , and 240° . Consistently, changes in T_0 and N align, with minimum values observed at 270° and maximum values at 300° . Thus, for conveying a 150 mm flexible fiber, the double-blade pump at 270° exhibits the highest passage efficiency, followed by the pump at 240° with lower efficiency, and the pump at 300° with the least efficient passage capacity.

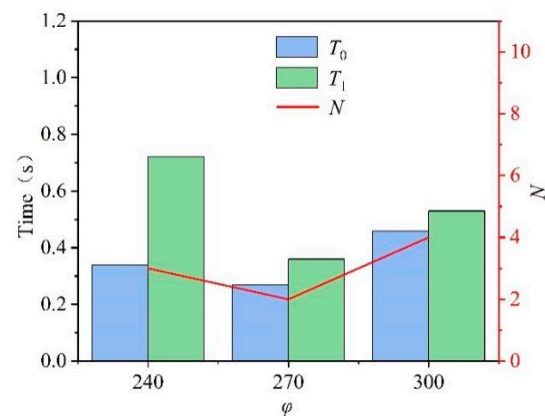


Figure 14. The transit time of the 150 mm flexible fiber.

(2) Fiber length L of 200 mm

Figure 15 illustrates the flow behavior of a 200 mm long flexible fiber at the rated flow rate in a double-blade non-clogging pump with varying blade wrapping angles. A detailed analysis of the fiber's behavior in a double-blade pump with a 240° blade wrapping angle is provided in Section 3.1. Upon entering the impeller, the fiber impacts the suction surface of the opposing blade at the inlet edge, causing aggregation of the fiber's front half. As the liquid phase progresses, this aggregation extends and shifts from the outer side of the blade toward the trailing end, eventually leading to the fiber's exit from the impeller. Within the volute, the fiber encounters the tongue, leading to bending and subsequent continued flow within the volute for an additional cycle before exiting.

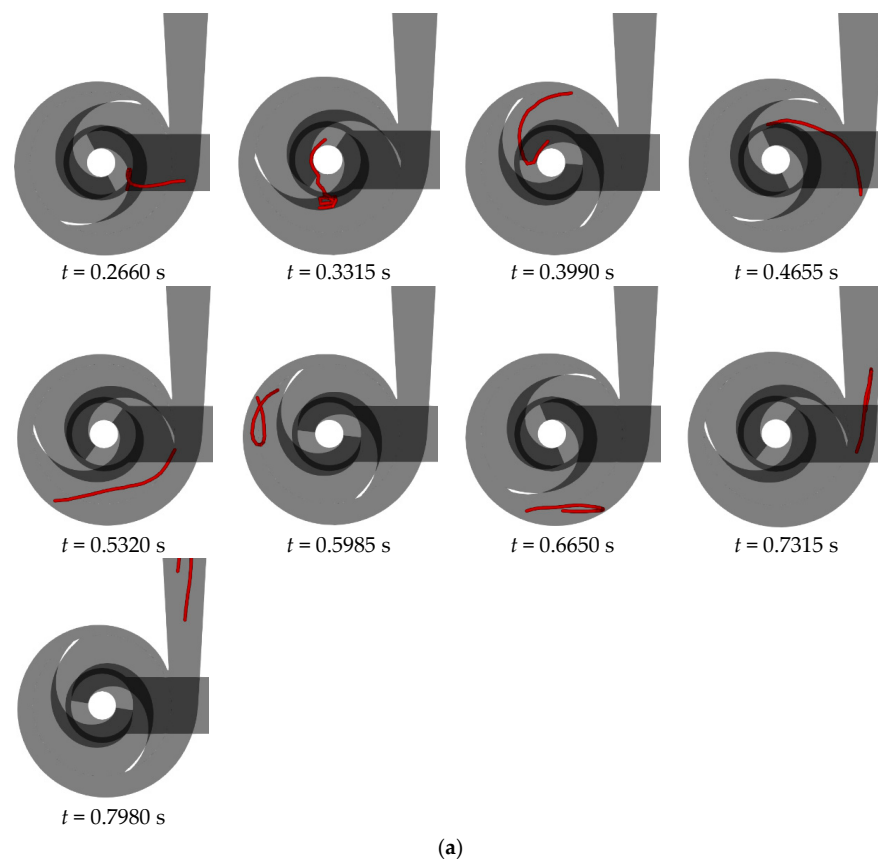


Figure 15. Cont.

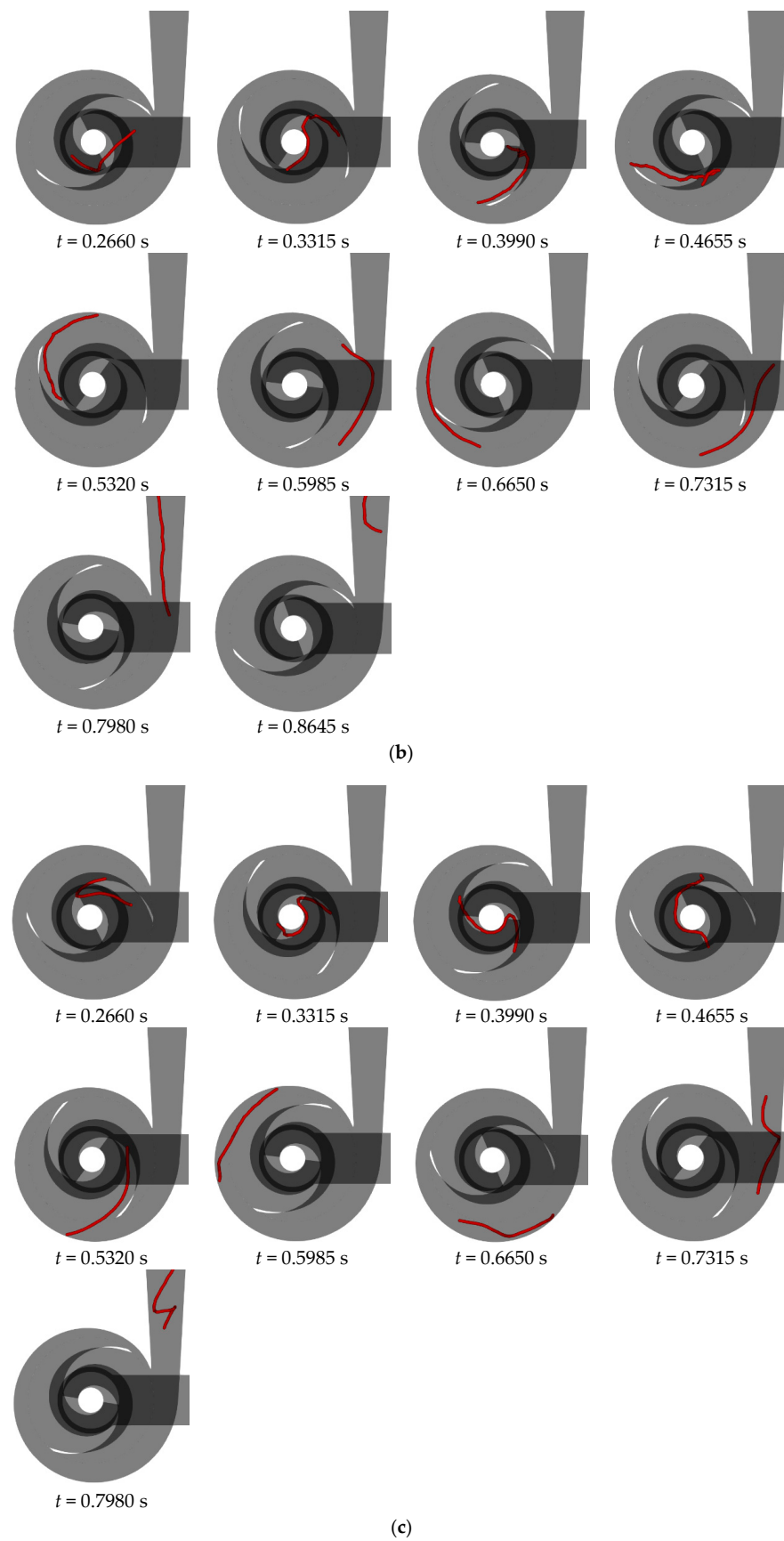


Figure 15. The flow behavior of the 200 mm long flexible fiber in the non-clogging pump with different wrap angles. (a) $\varphi = 240^\circ$ [19], (b) $\varphi = 270^\circ$, (c) $\varphi = 300^\circ$.

When the blade wrapping angle is 270° , the fiber enters the impeller along the suction surface of the blade without aggregation, progressing toward the blade's tail as the liquid phase flows. During detachment from the inlet edge on the outer side of the blade, the pronounced blade curvature causes the latter half of the fiber to bend and aggregate due to compression and collisions with the inlet edge and the suction surface of another blade. However, the fiber rapidly re-expands with the flow. This process reduces the fiber's velocity as it moves toward the blade's tail, thereby extending the duration required for the fiber to exit the impeller. Within the volute, collisions with the tongue cause the fiber to continue circulating inside the volute for an additional cycle before exiting.

When the blade wrapping angle is 300° , after the fiber enters the impeller, the initial portion of the fiber flows towards the outer side of the blade. However, due to the blade's curvature, the fiber encounters difficulties exiting smoothly from the outer side, similar to the behavior observed with a fiber length of 150 mm. At a t of 0.4655 s, the fiber repositions to the inner side of the blade and progresses along the suction surface toward the blade's tail, eventually entering the volute. Within the volute, the fiber does not interact with the tongue and exits directly. At the volute's outlet, influenced by the liquid phase flow and contact with the wall, the fiber adopts a spiral configuration.

Figure 16 presents the average coordinates of a 200 mm flexible fiber flowing through a double-blade non-clogging pump at various blade wrap angles and rated flow rates. The figure indicates that the fiber, for blade wrap angles of 240° and 270° , enters the volute diffusion section after completing four rotations. In the double-blade non-clogging pump with a 240° blade wrap angle, the fiber enters the impeller at t of 0.25 s and exhibits a consistently increasing rotation period, signifying a smooth flow. Conversely, in the pump with a 270° blade wrap angle, the fiber flows along the blade's suction surface for a certain distance, exhibiting minor fluctuations in the average x-axis coordinate before completing the first rotation.

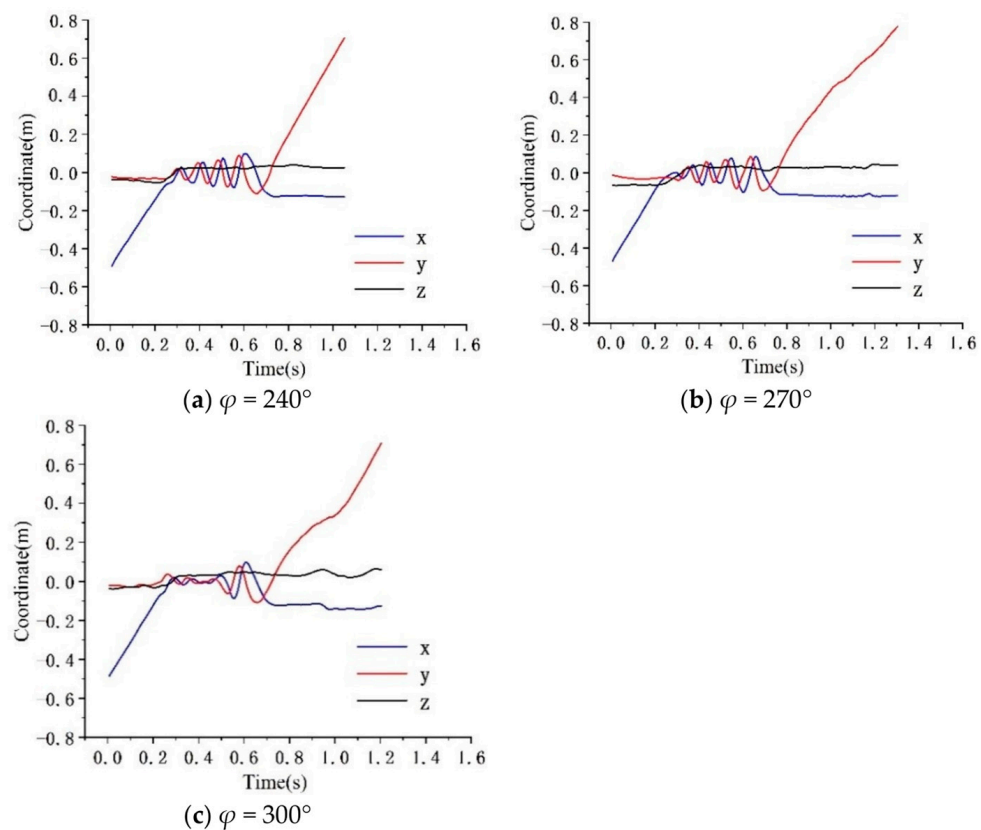


Figure 16. Average coordinates of the 200 mm long flexible fiber in the non-clogging pump.

The 200 mm flexible fiber remains centrally positioned within the impeller for an extended duration upon entering the double-blade non-clogging pump with a 300° blade wrapping angle. During this period, the fiber wraps around the pump shaft and continuously contacts the blade, leading to indistinct rotation period characteristics in the average coordinates of the fiber during the initial stages. The fiber enters the impeller at a t of 0.24 s and maintains a central position with minimal coordinate fluctuations. At a t of 0.50 s, the fiber detaches from the impeller center, progresses toward the blade's tail, and transitions into the volute's diffusion section at a t of 0.73 s.

Figure 17 depicts the transit time of a 200 mm flexible fiber through a non-clogging pump with various blade wrapping angles. The data indicate minimal variation in passage performance for the 200 mm fiber across different blade wrapping angles. Specifically, the differences between T_0 and T_1 for the double-blade non-clogging pump with 270° and 300° angles are negligible, while the difference is slightly reduced at 240° . Overall, the double-blade pump with a 240° blade wrapping angle demonstrates the optimal passage performance for the 200 mm flexible fiber, whereas the pumps with 270° and 300° angles exhibit comparable passage performance.

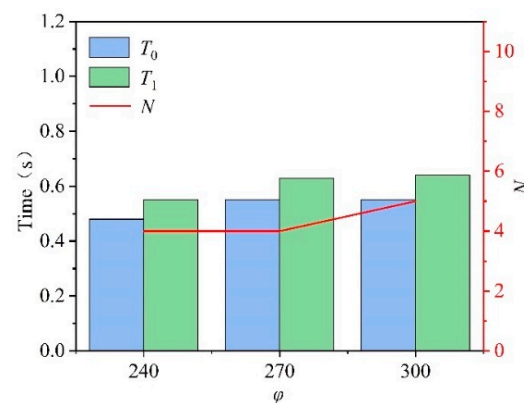


Figure 17. The transit time of a 200 mm flexible fiber.

(3) Fiber length L of 250 mm

Figure 18 depicts the flow characteristics of a 250 mm flexible fiber at the rated flow rate in a double-blade non-clogging pump with various blade wrapping angles. The figure demonstrates that the fiber's flow is markedly affected by its length. At a blade wrapping angle of 240° , upon entering the impeller, the first half of the fiber moves towards the outer side of the blade. However, the extended length of the second half prevents the fiber from exiting at the outer side, causing it to remain at the center of the impeller for a prolonged duration. During this time, the fiber's ends repeatedly collide with the blade walls, leading to bending or aggregation. The fiber subsequently expands and aligns with the liquid phase, gradually shifting to one side. At a t of 0.7980 s, the first half of the fiber returns to the outer side of the blade, pulling the second half along. Influenced by eddy currents, the fiber forms a circular shape, which progressively extends and unfolds. Following adequate centrifugal motion within the volute, the fiber exits the volute.

When the blade wrapping angle is 270° , the fiber initially moves towards the outer side of the blade upon entering the impeller, while the latter half wraps around the pump shaft due to the blade's curvature. As the liquid phase progresses, the fiber gradually shifts towards the blade's outer side. However, the entanglement of the latter half around the pump shaft impedes the fiber's detachment from the impeller's center. At a t of 0.9975 s, the fiber fully detaches from the pump shaft, and by a t of 1.0640 s, the entire fiber has entered the volute and exits smoothly.

When the blade wrapping angle is 300° , the initial flow behavior of the fiber closely resembles that observed at 270° . The first half of the fiber progresses towards the outer side of the blade, while the latter half wraps around the pump shaft. Due to the excessive curva-

ture of the blades, the fiber becomes tightly wound around the pump shaft, maintaining this configuration with minimal change from a t of 0.4655 s onwards. By a t of 1.3300 s, the fiber remains predominantly wrapped around the pump shaft, with only a small portion moving towards the outer side of the blade. Consequently, it can be inferred that a 250 mm flexible fiber experiences significant difficulty in passing smoothly through a double-blade non-clogging pump with a blade wrapping angle of 300° .

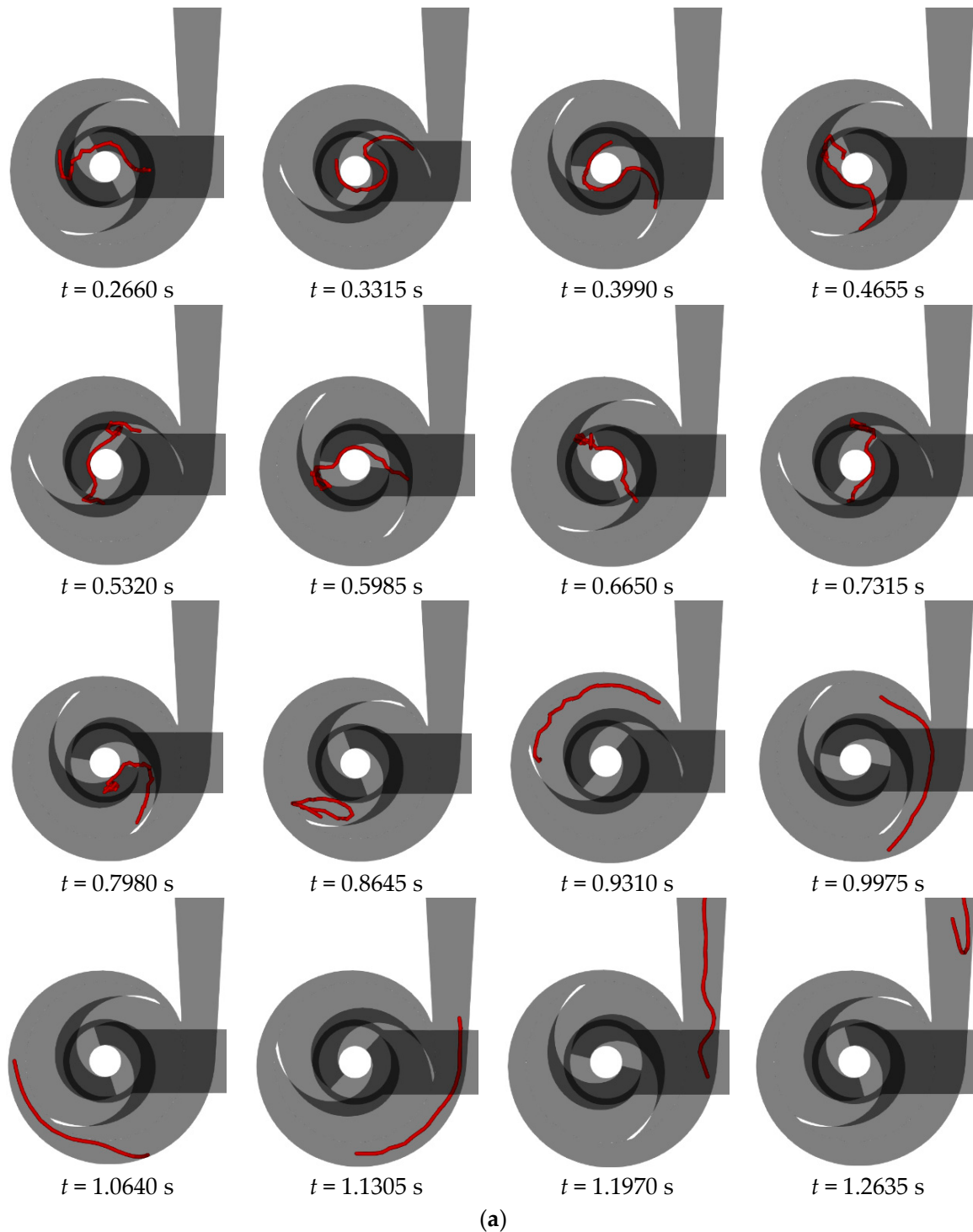


Figure 18. Cont.

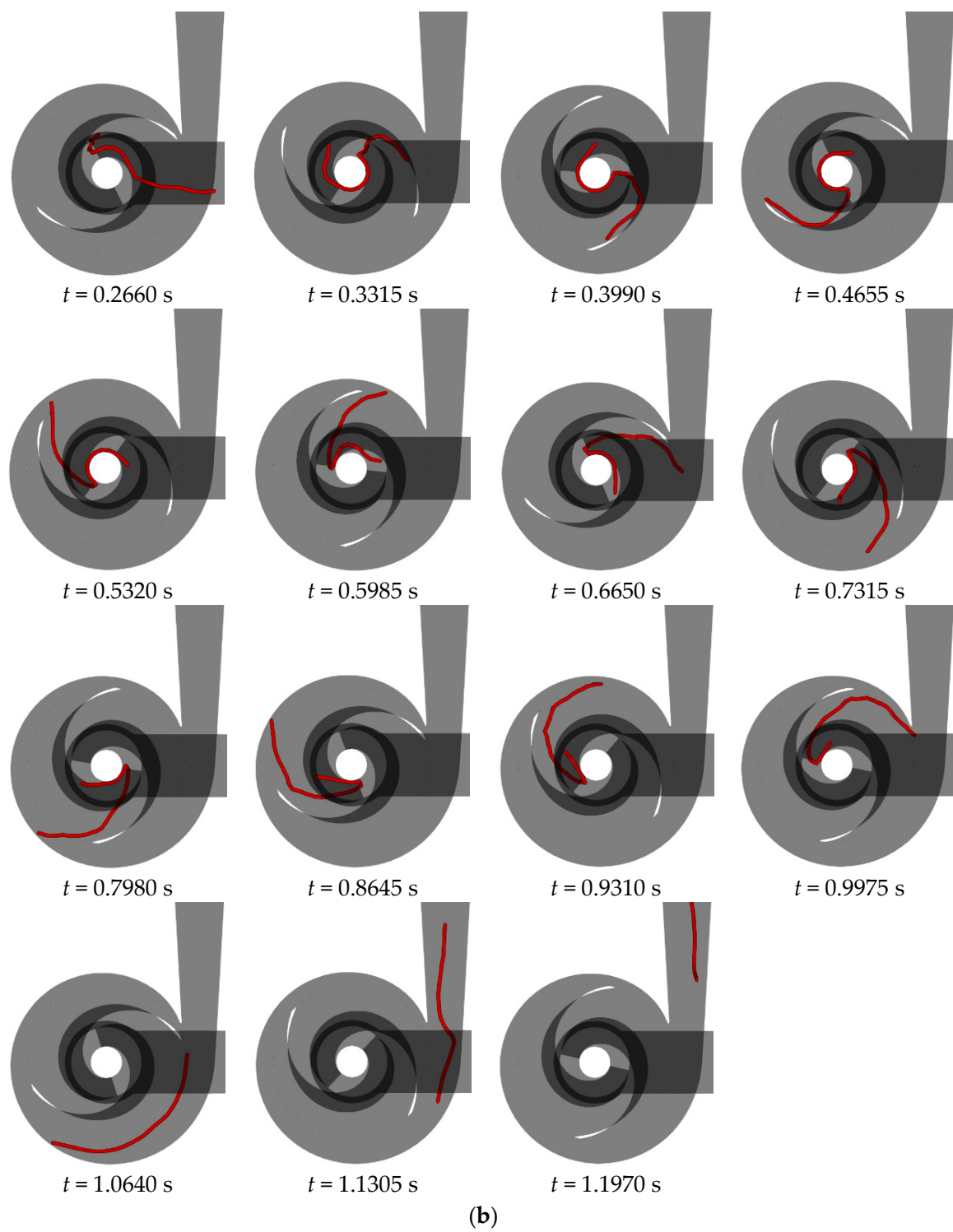


Figure 18. Cont.

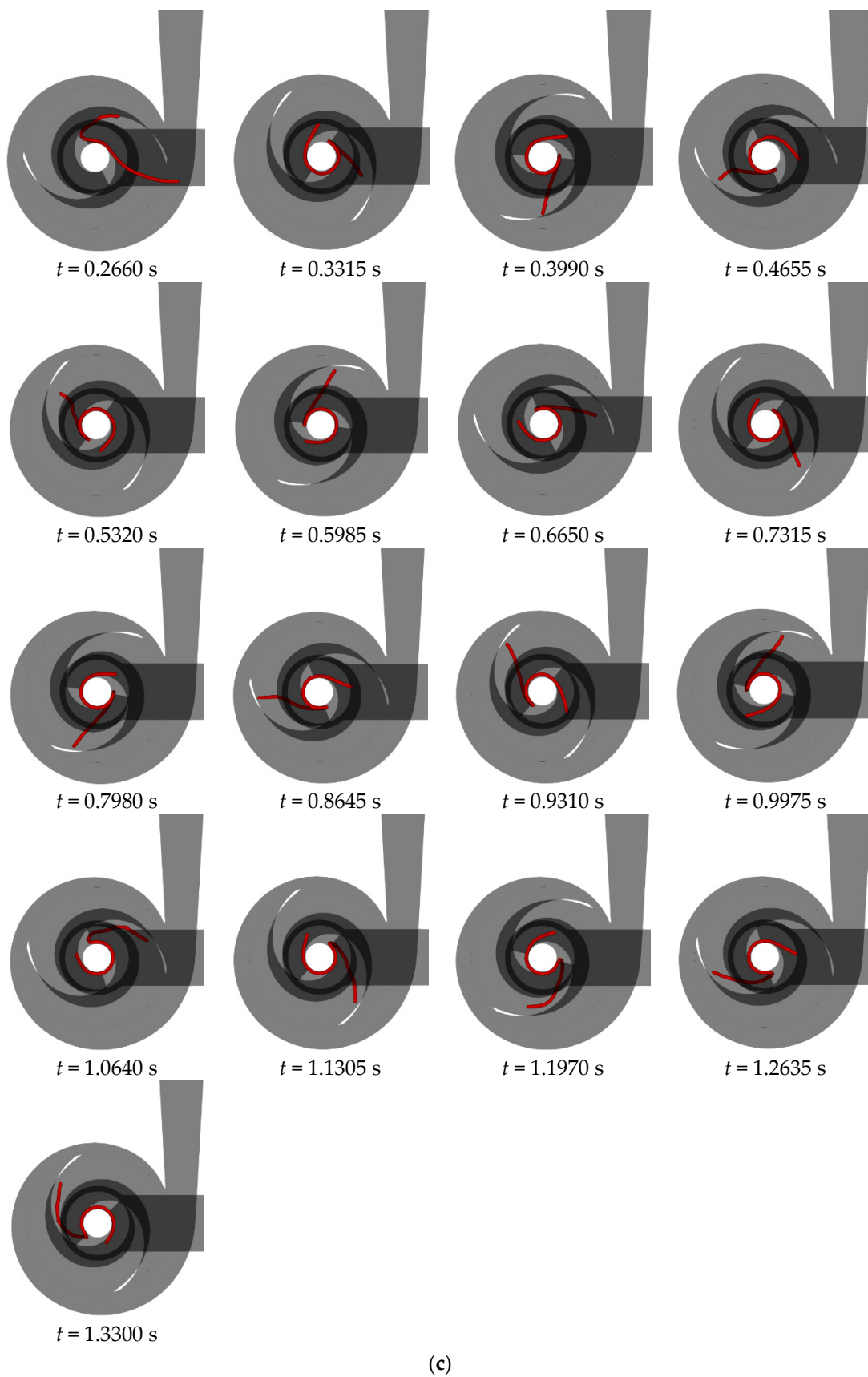


Figure 18. The flow behavior of the 250 mm long flexible fiber in the non-clogging pump with different wrap angles. (a) $\varphi = 240^\circ$ [19], (b) $\varphi = 270^\circ$, (c) $\varphi = 300^\circ$.

Figure 19 illustrates the average coordinates of 200 mm flexible fibers flowing through a double-blade non-clogging pump at various blade wrapping angles under rated flow conditions. When the fiber length is increased to 250 mm, the efficiency of fiber passage through all three double-blade non-clogging pumps significantly decreases, with a notable increase in the number of rotations the fiber completes within these pumps. In the pump with a 240° wrapping angle, the fiber enters the impeller at a t of 0.25 s. Due to its wrapping around the pump shaft, the fiber remains centered within the impeller for an extended period, showing minimal fluctuations in average coordinates from 0.25 s to 0.80 s. At a t of 0.80 s, the fiber detaches from the blade's inlet edge and moves towards the impeller's outer edge. By a t of 1.16 s, the fiber enters the diffusion section of the volute after completing 10 rotations. Similarly, in the pump with a 270° wrapping angle, the fiber completes 10 rotations and enters the volute's diffusion section at a t of 1.13 s. In contrast, in the pump with a 300° wrapping angle, the fiber enters at a t of 0.23 s and remains wrapped around the pump shaft with minimal change, exhibiting periodic fluctuations in its average coordinates.

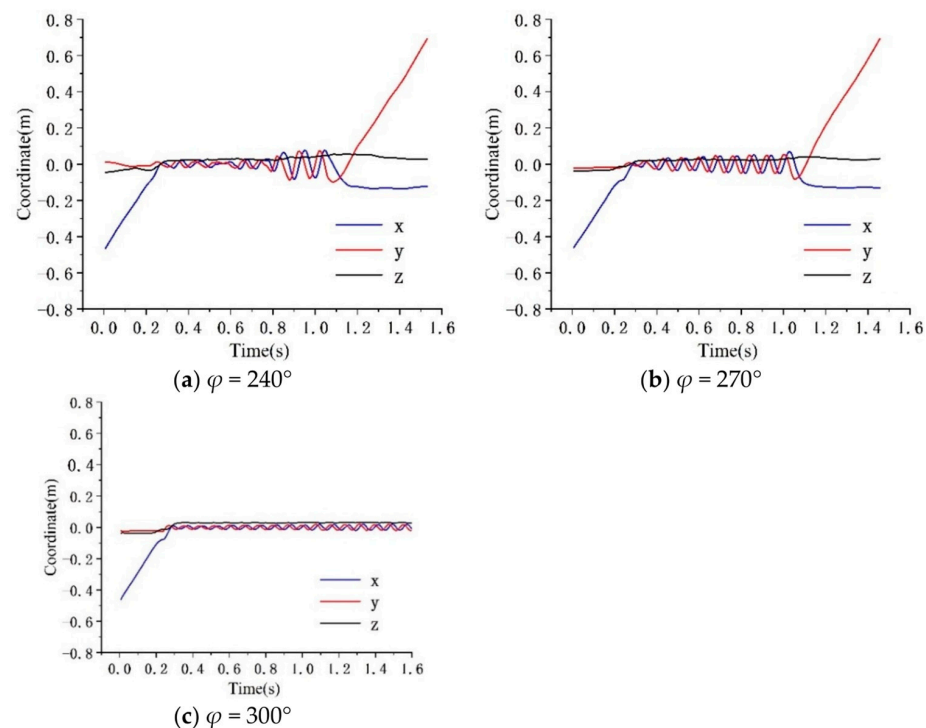


Figure 19. The average coordinates of the 250 mm long flexible fiber in the non-clogging pump.

When transporting fibers 250 mm in length, there is minimal difference in passage efficiency between double-blade non-clogging pumps with angles of 240° and 270° , with the 240° angle exhibiting slightly better performance. Fibers 250 mm in length cannot pass smoothly through a double-blade pump with a 300° angle. Therefore, for conveying fibers 250 mm in length, the double-blade pump with a 240° angle demonstrates the highest passage efficiency, followed by the 270° angle with a slightly lower performance, and the 300° angle with the poorest performance.

3.3. Influence of Blade Outlet Angles of Impeller on Long Flexible Fiber Passage Performance

(1) Fiber length L of 150 mm

Figure 20 depicts the flow characteristics of a flexible fiber with a length of 150 mm at the rated flow rate in a double-blade non-clogging pump with varying blade outlet angles. The flow behavior of the 150 mm flexible fiber is similar across different blade outlet angles upon entering the pump. The fiber swiftly moves away from the blade center towards

the impeller's outer edge. At a blade outlet angle (β_2) of 15° , the fiber enters the volute diffusion section twice, colliding with the tongue both times, remaining within the volute and continuing rotation post-collision. With a blade outlet angle of 20° , the fiber initially fails to enter the volute diffusion section upon passing through the tongue, but does so after one rotation, colliding with the tongue and remaining within the volute. At a blade outlet angle of 25° , the flexible fiber flows smoothly into the volute diffusion section on its first attempt without colliding with the tongue, and exits the double-blade non-clogging pump smoothly.

Figure 21 depicts the average coordinates of a 150 mm long flexible fiber flowing through a double-blade non-clogging pump at various blade outlet angles under rated flow conditions. In the case of a β_2 angle of 15° , the fiber exits the impeller after a single rotation and subsequently collides twice with the tongue within the volute. This collision causes the fiber to undergo two additional rotations before exiting. During the third rotation, the fiber momentarily halts at the position of the tongue, resulting in a flattening of the average coordinate peak. For the pump with a β_2 angle of 20° , the flexible fiber exits the impeller after two rotations, collides with the tongue inside the volute, and continues to rotate for one additional cycle before exiting. In the case of a β_2 angle of 25° , the fiber completes two rotations and exits into the volute diffusion section. During the initial rotation, the fiber bends along the inlet edge of the blade, leading to irregular fluctuations in its average coordinates.

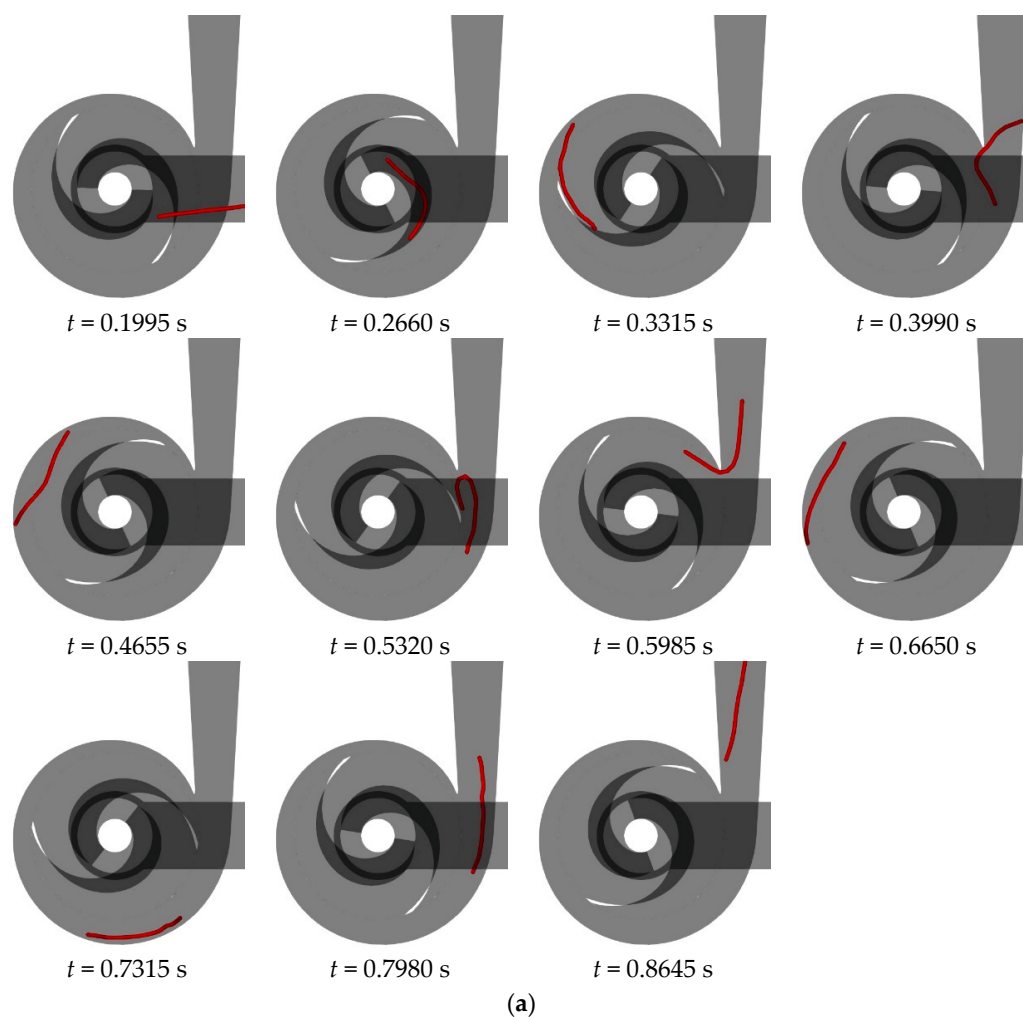


Figure 20. Cont.

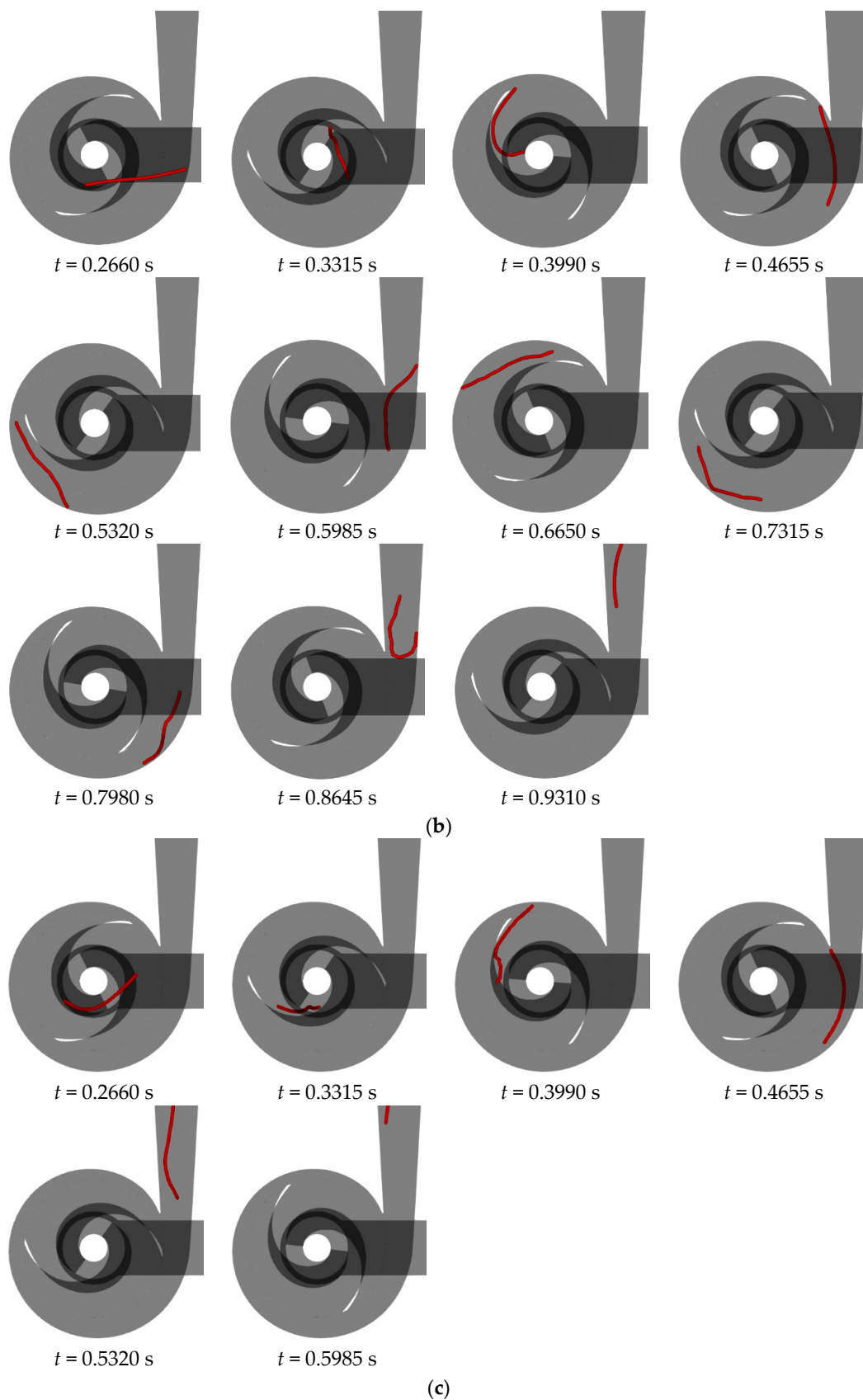


Figure 20. The flow behavior of the 150 mm long flexible fiber in the non-clogging pump with different outlet angles. (a) $\beta_2 = 15^\circ$, (b) $\beta_2 = 20^\circ$ [19], (c) $\beta_2 = 25^\circ$.

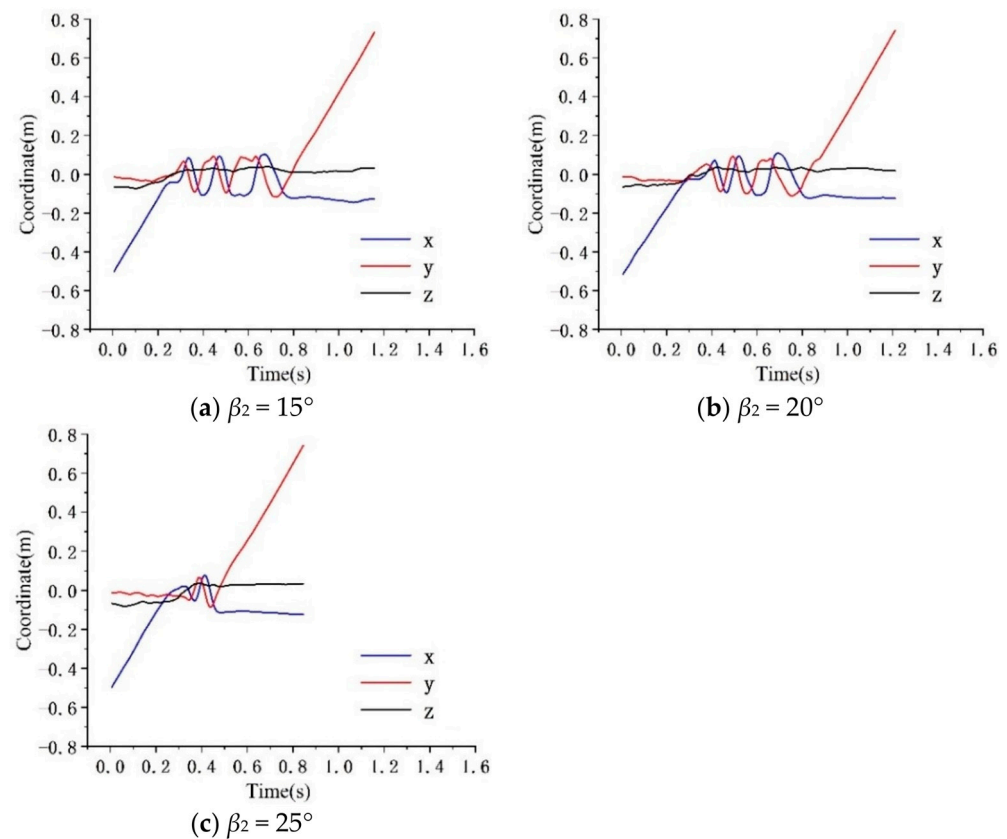


Figure 21. The average coordinates of the 150 mm long flexible fiber in the non-clogging pump.

Figure 22 depicts the transit time of 150 mm long flexible fiber in a non-clogging pump at various blade outlet angles. From the graph, while the fiber's flow time T_1 in the double-blade non-clogging pumps with a β_2 of 15° and a β_2 of 20° is longer, excluding the impact of tongue collisions, the pumps are ranked by T_0 time from shortest to longest for a β_2 of 15° , β_2 of 25° , and β_2 of 20° , respectively. Thus, when transporting 150 mm long flexible fiber, the pump with a β_2 of 15° exhibits the highest performance, followed by a β_2 of 25° , with the pump which has a β_2 of 20° showing the poorest performance.

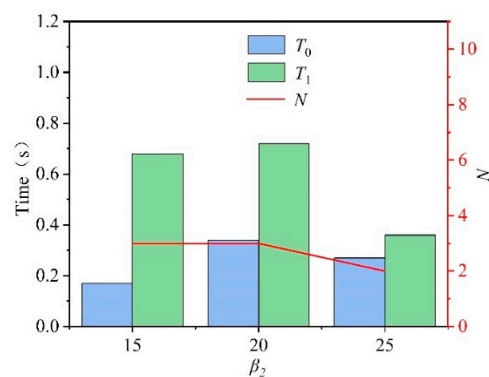


Figure 22. The transit time of the 150 mm flexible fiber.

(2) Fiber length L of 200 mm

Figure 23 depicts the flow characteristics of a 200 mm long flexible fiber at the rated flow rate in a double-blade non-clogging pump with varying blade outlet angles (β_2). The flow behavior of the 200 mm long flexible fiber is similar for blade outlet angles of $\beta_2 = 15^\circ$ and $\beta_2 = 20^\circ$ upon entry into the pump, characterized by an initial collision with the suction

surface of the blade, leading to aggregation at the fiber's front end. As the liquid phase progresses, the fiber's front end extends and shifts from the outer side of the blade towards the impeller's outer edge. However, at $\beta_2 = 15^\circ$, the fiber takes more time to detach from the impeller's center and, upon entering the volute diffusion section, avoids collision with the tongue, proceeding directly into the outlet extension section. In contrast, at $\beta_2 = 20^\circ$, the fiber collides with the tongue upon initial entry, resulting in bending and an additional rotation cycle inside the volute before exiting.

In a double-blade non-clogging pump with a blade outlet angle (β_2) of 25° , the flexible fiber does not agglomerate upon colliding with the suction surface of the blade. Instead, it moves along the suction surface towards the central position. Compared to pumps with β_2 angles of 15° and 20° , the fiber exits the impeller and enters the volute more rapidly in the pump with a β_2 of 25° . It collides with the tongue, continues rotating for an additional cycle, and successfully exits the pump.

Figure 24 illustrates the average coordinates of a 200 mm flexible fiber flow at various blade outlet angles in a double-blade non-clogging pump operating at its rated flow rate. For a blade outlet angle (β_2) of 15° , the fiber enters the impeller at a t of 0.25 s and reaches the volute diffusion section after four cycles, at a t of 0.70 s. For a β_2 of 20° , the fiber enters the impeller at a t of 0.26 s, completes three rotations, collides with the tongue at a t of 0.55 s, continues rotating within the volute for an additional cycle, and enters the diffusion section at a t of 0.73 s. For a β_2 of 25° , the fiber enters the impeller at a t of 0.27 s and reaches the volute diffusion section after two rotations, at a t of 0.63 s.

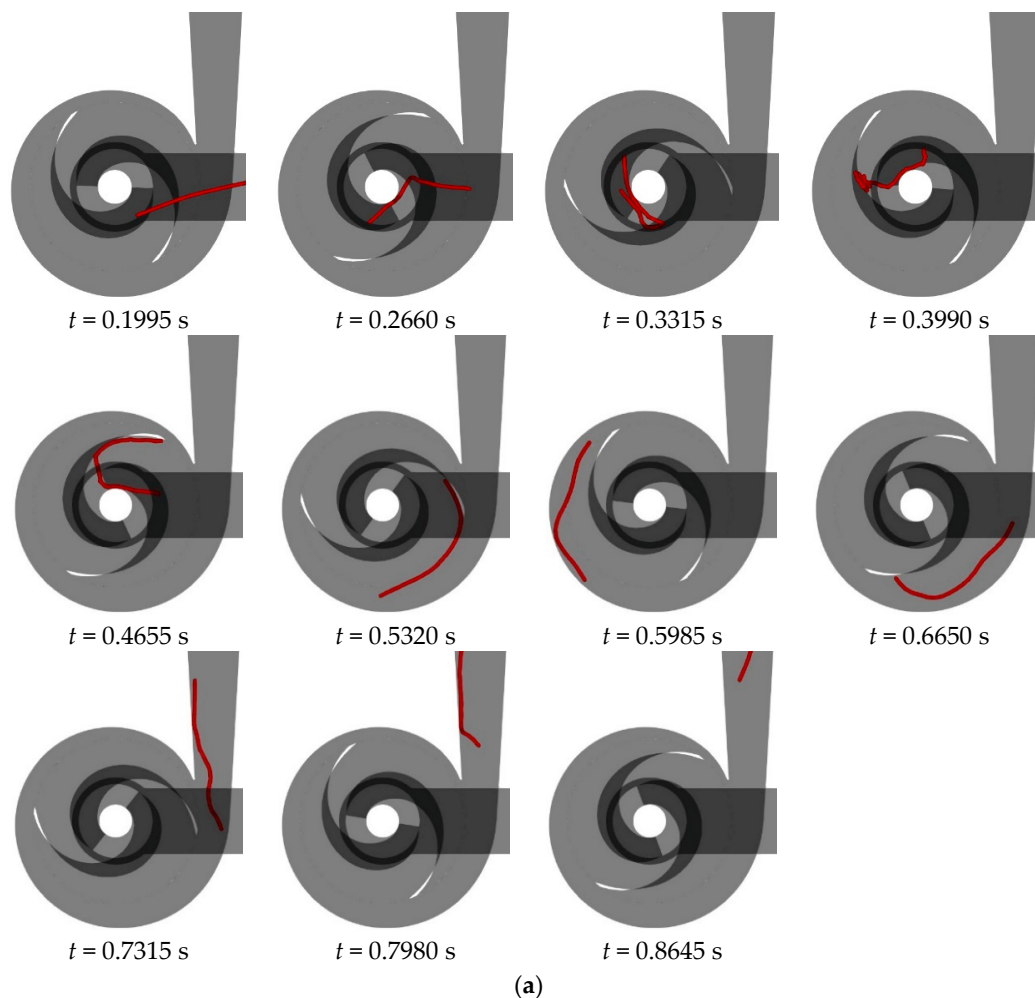


Figure 23. Cont.

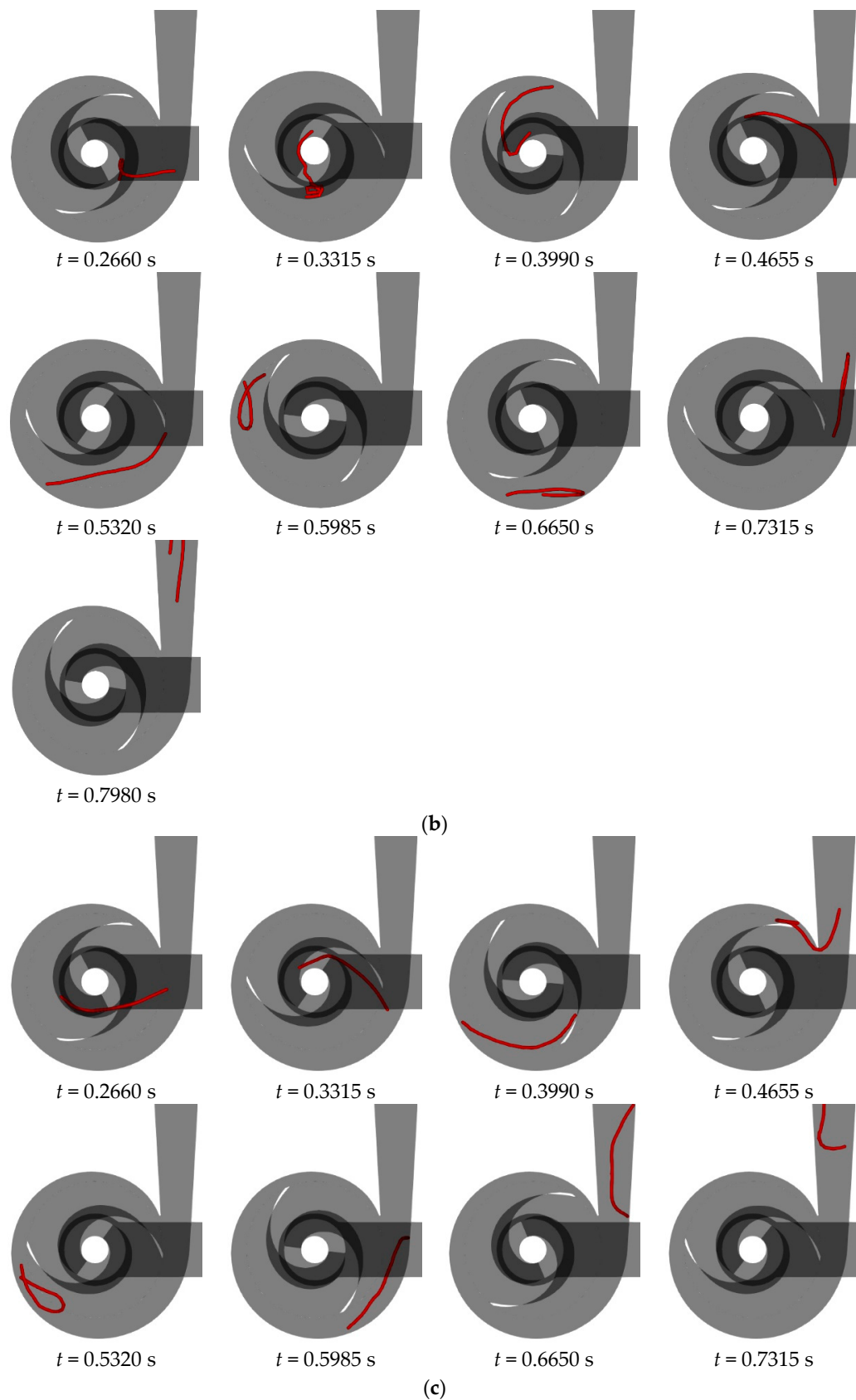


Figure 23. The flow behavior of the 200 mm long flexible fiber in the non-clogging pump with different outlet angles. (a) $\beta_2 = 15^\circ$, (b) $\beta_2 = 20^\circ$ [19], (c) $\beta_2 = 25^\circ$.

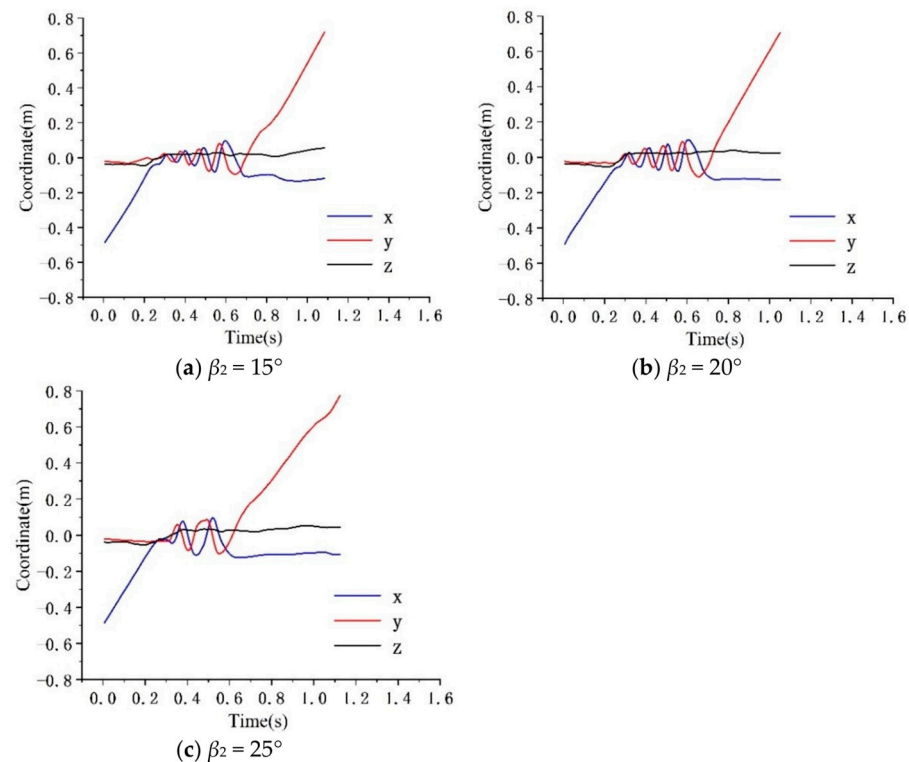


Figure 24. The average coordinates of the 200 mm long flexible fiber in the non-clogging pump.

Figure 25 depicts the transit time of a 200 mm flexible fiber in a non-clogging pump with various blade outlet angles. The figure reveals that for a 200 mm fiber, the T_0 times in the double-blade non-clogging pumps with a β_2 of 15° and a β_2 of 20° are nearly identical, both showing a transit time of four cycles ($N = 4$). There is minimal difference in throughput capacity between these configurations. In contrast, the T_0 in the double-blade non-clogging pump with a β_2 of 25° is the shortest, at two cycles ($N = 2$), indicating a superior throughput capacity compared to the pumps with a β_2 of 15° and β_2 of 20° .

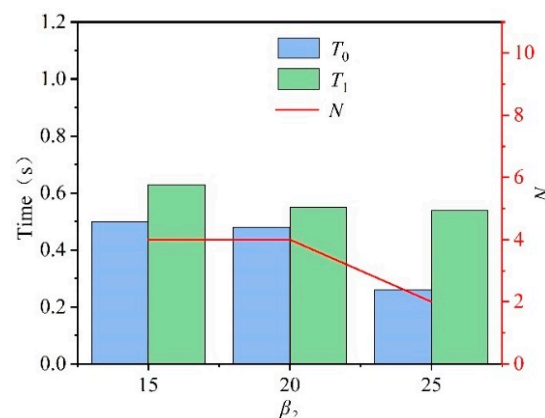


Figure 25. The transit time of the 200 mm flexible fiber.

(3) Fiber length L of 250 mm

Figure 26 illustrates the flow characteristics of a 250 mm flexible fiber in a double-blade non-clogging pump at various blade outlet angles under rated flow conditions. At a blade outlet angle β_2 of 15° , the fiber collides with the suction surface of the blade upon entering the impeller. Driven by the blade's inlet edge, the fiber aggregates and subsequently detaches from the outer side of the inlet edge, moving towards the middle of the blade.

As the fiber continues, it gradually expands and flows towards the outer edge of the impeller, eventually entering the volute. Within the volute, the fiber maintains a smooth flow, proceeding into the diffusion section and exiting the double-blade non-clogging pump without obstruction.

When the blade outlet angle β_2 is 20° , the flexible fiber enters the impeller with the anterior half flowing toward the outer side of the blade, while the posterior half wraps around the pump shaft, inhibiting further movement towards the outer blade side. This configuration causes continuous collisions between both ends of the fiber and the blade wall, leading to bending or agglomeration. Consequently, the fiber remains centrally positioned within the impeller. Over time, the fiber gradually shifts laterally. At $t = 0.7980$ s, the anterior half of the fiber returns to the outer side of the blade, while the posterior half is drawn towards the blade's outer edge. During this transition, the fiber assumes a circular shape due to eddy currents, gradually extending and unfolding. Following adequate centrifugal action within the volute, the fiber exits the volute smoothly.

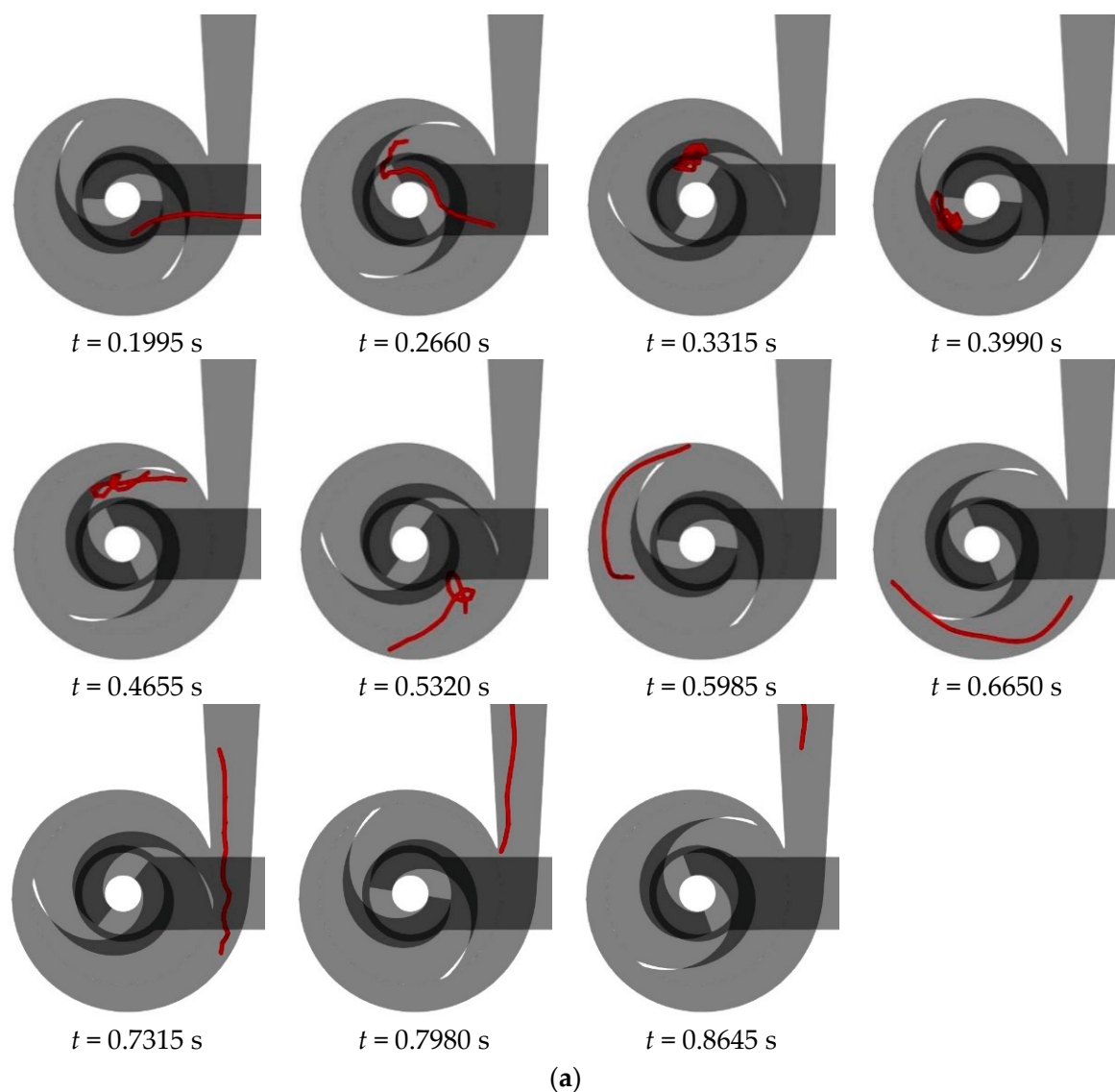


Figure 26. Cont.

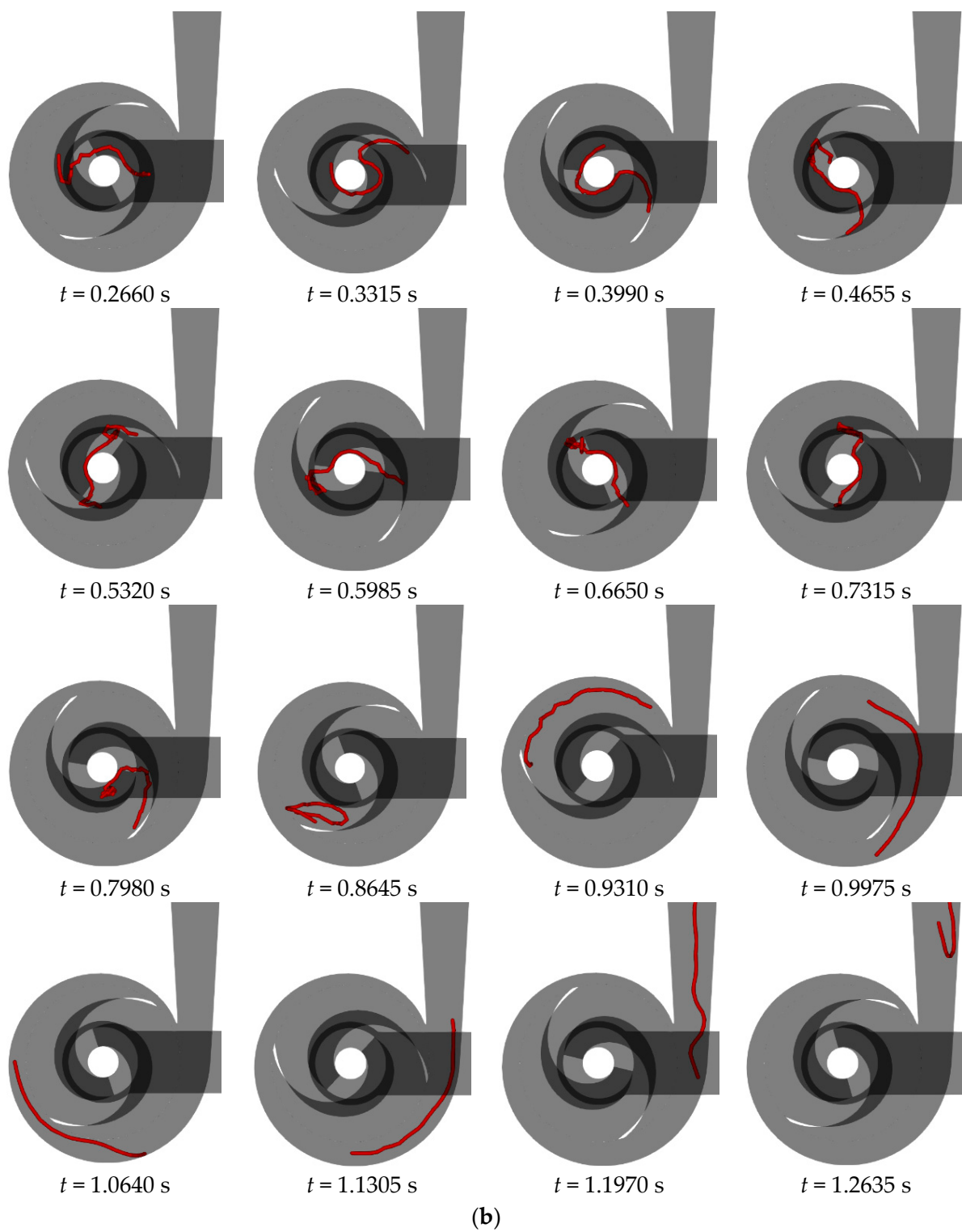


Figure 26. Cont.

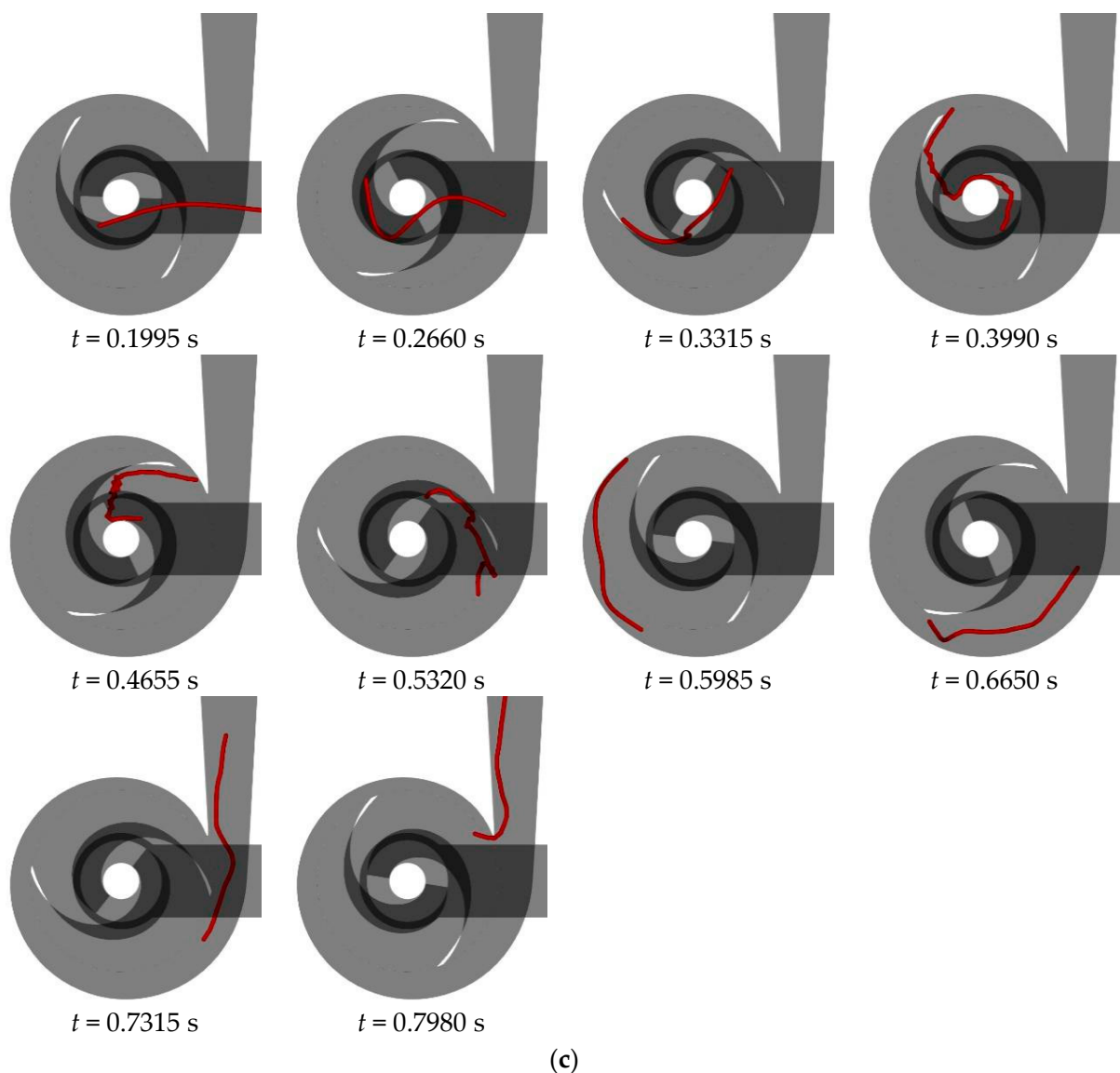


Figure 26. The flow behavior of the 250 mm long flexible fiber in the non-clogging pump with different outlet angles. (a) $\beta_2 = 15^\circ$, (b) $\beta_2 = 20^\circ$ [19], (c) $\beta_2 = 25^\circ$.

When the blade outlet angle β_2 is 25° , the anterior portion of the flexible fiber advances toward the central position along the suction surface of the blade upon entering the impeller. Concurrently, the posterior portion of the fiber wraps around the pump shaft as the anterior portion reaches the blade's tail area. As the fiber progresses towards the impeller's outer edge, the middle section folds due to compression from the suction surface and inlet edge of the blade, causing the fiber to bend within the flow channel. With the continued flow of the liquid phase, the bent fiber gradually expands and transitions into the volute, smoothly entering the diffusion section and exiting the double-blade non-clogging pump.

Figure 27 illustrates the average coordinates of the flow of a 250 mm long flexible fiber through a double-blade non-clogging pump at various blade outlet angles under rated flow conditions. The data indicate that at a blade outlet angle β_2 of 15° , the fiber undergoes five rotations before reaching the diffusion section of the volute. At a β_2 of 20° , the fiber completes 10 rotations prior to entering the diffusion section. Conversely, at a β_2 of 25° , the fiber accomplishes four rotations before entering the volute diffusion section.

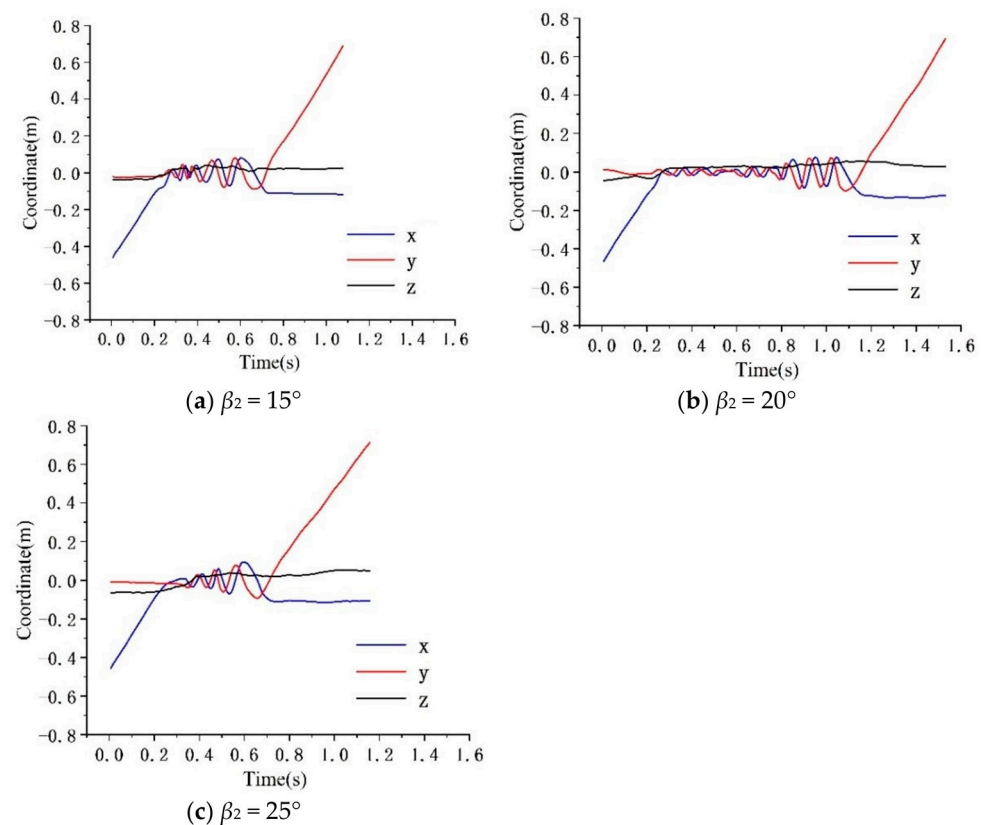


Figure 27. The average coordinates of the 250 mm long flexible fiber in the non-clogging pump.

Figure 28 illustrates the transit time of a 250 mm long flexible fiber through a non-clogging pump at various blade outlet angles. The data reveal that both T_0 and T_1 exhibit the shortest passage times in the double-blade non-clogging pump with a β_2 of 25° . The pump with a β_2 of 15° demonstrates a slightly longer passage time, while the pump with a β_2 of 20° shows the longest passage time. Consequently, it can be inferred that for a 250 mm long flexible fiber, the pump with a β_2 of 25° provides the highest passage capacity, followed by the pump with a β_2 of 15° , with the pump with a β_2 of 20° exhibiting the lowest capacity.

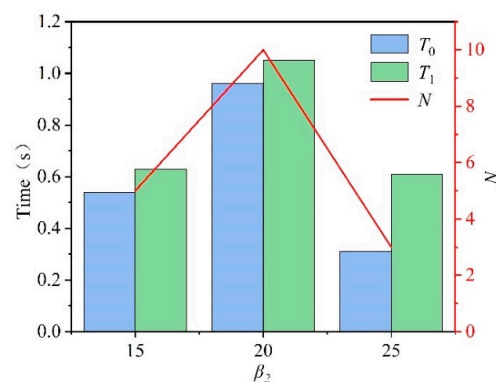


Figure 28. The transit time of the 250 mm flexible fiber.

4. Conclusions

The influence of the impeller blade number, blade wrapping angle, and blade outlet angle on the conveying capacity of a double-blade non-clogging pump was examined in this study. The principal findings are as follows:

- (1) As the blade number z increases, the fiber-conveying capacity of the non-clogging pump decreases, with longer fibers experiencing a more pronounced reduction in carrying capacity. When conveying 150 mm fibers with a $z = 2$, the time T_0 for flexible fibers to pass through the volute diffusion section from entering the impeller to completely exiting is 0.34 s, with a rotation cycle N of 3. For $z = 3$, T_0 increases to 0.47 s with $N = 4$. When conveying 200 mm fibers with $z = 2$, T_0 is 0.48 s with $N = 4$, and for $z = 3$, T_0 extends to 0.94 s with $N = 9$. Fibers of 250 mm length cannot smoothly pass through a non-clogging pump with $z = 3$ due to entanglement on the pump shaft.
- (2) When conveying flexible fibers of 150 mm length, the double-blade pump with a 270° angle exhibits the highest passing performance, whereas the double-blade non-clogging pump with a 240° angle shows poorer performance, and the one with a 300° angle performs the worst, with respective T_0 values of 0.27 s, 0.34 s, and 0.46 s. For fibers of 200 mm length, the double-blade pump with a 240° angle performs the best. The passing performance of the pumps with 270° and 300° angles does not show significant differences, with T_0 values of 0.48 s, 0.55 s, and 0.55 s, respectively. When the fiber length increases to 250 mm, the passing performance between the pumps with 240° and 270° angles is not significantly different, though the pump with a 240° angle performs slightly better. In the double-blade non-clogging pump with a 300° angle, fibers tend to wrap around the pump shaft and cannot detach, thereby preventing normal flow out of the pump. Hence, the passing performance of the pump with a 300° angle is inferior to those with 240° and 270° angles.
- (3) When conveying flexible fibers of 150 mm length, the non-clogging pump with double-blades at a β_2 of 15° demonstrates the highest performance, followed by a β_2 of 25° , while the pump with double-blades at a β_2 of 20° exhibits the lowest performance. For fibers 200 mm in length, the T_0 values within the double-blade non-clogging pumps at a β_2 of 15° and a β_2 of 20° are nearly identical, with both showing four rotation cycles, N , indicating no significant difference in throughput performance. The double-blade non-clogging pump at a β_2 of 25° shows the shortest T_0 with an N of 2, indicating stronger throughput performance compared to a β_2 of 15° and a β_2 of 20° . When conveying flexible fibers 250 mm in length, the throughput performance of the double-blade pump at a β_2 of 15° surpasses that of a β_2 of 20° , but both are inferior to the double-blade pump at a β_2 of 25° .

Author Contributions: Conceptualization, K.W.; methodology, K.W.; software, K.W.; validation, K.W.; formal analysis, K.W.; investigation, K.W.; resources, K.W.; data curation, K.W.; writing—original draft preparation, R.L. and S.Z.; writing—review and editing, Q.Z. and K.W.; visualization, K.W.; supervision, K.W.; project administration, K.W.; funding acquisition, K.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: Author Qiang Zhang was employed by the company Suzhou Xidian Intelligent Technology Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. The company Suzhou Xidian Intelligent Technology Co., Ltd. had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

References

1. Fairbank, L.C. Effect on the Characteristics of Centrifugal Pump. *Trans. Am. Soc. Civ. Eng.* **2020**, *107*, 1564–1575. [[CrossRef](#)]
2. Walker, C.I.; Wells, P.J.; Bodkin, G.C. *The Effect of Flow Rate and Solid Particle Size on the Wear of Centrifugal Lifting Pumps*; American Society of Mechanical Engineer: New York, NY, USA, 1994.
3. Charoenngam, P.; Subramanian, A.; Kadambi, J.R.; Wernet, M.; Courtwright, R. PIV Investigations of Particle Velocities in the Tongue Region of a Lifting Pump. In Proceedings of the ASME 2002 Joint US-European Fluids Engineering Division Conference, Montreal, QC, Canada, 14–18 July 2002.

4. Salim, B.; Bajawi, H.Y.; Suhaibani, Z. Performance of a Centrifugal Lifting Pump with Clinker Slurry. *Indian J. Sci. Technol.* **2015**, *12*, 1–9.
5. Tarodiya, R.; Gandhi, B.K. Numerical Simulation of a Centrifugal Lifting Pump Handling Solid-liquid Mixture: Effect of Solids on FlowField and Performance. *Adv. Powder Technol.* **2019**, *30*, 2225–2239. [[CrossRef](#)]
6. Tan, M.G.; Zhang, K.K.; Wu, X.F.; Liu, H.L. Experimental Study on Large Particle Solid-liquid Two-phase Flow in a Centrifugal Pump. *Trans. Chin. Soc. Agric. Eng.* **2021**, *37*, 62–67.
7. Wang, Z.; Qian, Z. Effects of concentration and size of silt particles on the performance of a double-suction centrifugal pump. *Energy* **2017**, *123*, 36–46. [[CrossRef](#)]
8. Zhang, Q.; Zhang, W.; Yan, Z.; Kang, S.; Xie, Z. Experiment on the straw particle flow in a centrifugal pump. *Proc. Inst. Mech. Eng. Part E J. Process Mech. Eng.* **2020**, *10*, 1989–1996. [[CrossRef](#)]
9. Pagalthivarthi, K.V.; Gupta, P.K.; Tyagi, V. CFD Prediction of Erosion Wear in Centrifugal Lifting Pumps for Dilute Slurry Flows. *J. Comput. Multiph. Flows* **2011**, *3*, 225–246. [[CrossRef](#)]
10. Pagalthivarthi, K.V.; Gupta, P.K.; Tyagi, V. CFD Predictions of Dense Slurry Flow in Centrifugal Pump Casings. *Int. J. Aerosp. Mech. Eng.* **2011**, *5*, 16–28.
11. Datta, S. *Numerical Investigation of Flow-Field Inside a Centrifugal Lifting Pump Casing*; Jadavpur University: Kolkata, India, 2012.
12. Shi, B.; Wei, J. Numerical simulation of 3D solid-liquid turbulent flow in a low specific speed centrifugal pump: Flow field analysis. *Adv. Mech. Eng.* **2014**, *6*, 814108. [[CrossRef](#)]
13. Chaumeil, F.; Crapper, M. Using the DEM-CFD method to predict brownian particle deposition in a constricted tube. *Particuology* **2013**, *15*, 94–106. [[CrossRef](#)]
14. Azimian, M.; Lichti, M.; Bart, H.J. Investigation of particulate flow in a channel by application of CFD, DEM and LDA/PDA. *Open Chem. Eng. J.* **2014**, *8*, 1–11. [[CrossRef](#)]
15. Yamamoto, S.; Matsuoka, T. A Method for Dynamic Simulation of Rigid and Flexible Fiber in a Flow Field. *J. Chem. Phys.* **1993**, *98*, 644–650. [[CrossRef](#)]
16. Skjetne, P.; Ross, R.F.; Klingenberg, D.J. Simulation of Single Fiber Dynamics. *J. Chem. Phys.* **1997**, *107*, 2108–2121. [[CrossRef](#)]
17. Ross, R.F.; Klingenberg, D.J. Dynamic Simulation of Flexible Fiber Composed of Linked Rigid Bodies. *J. Chem. Phys.* **1997**, *106*, 2949–2960. [[CrossRef](#)]
18. Schmid, C.F.; Switzer, L.H.; Klingenberg, D.J. Simulations of Fiber Flocculation: Effects of Fiber Properties and Inter fiber Friction. *J. Rheol.* **2000**, *44*, 781–809. [[CrossRef](#)]
19. Liu, J.; Xu, J.W.; Zhuang, S.G.; Wang, K. Influence of Long Flexible Fiber on the Transport Capability of Non-clogging Pump. *Processes* **2024**, *12*, 934. [[CrossRef](#)]
20. Geng, F.; Yuan, Z.L.; Wang, H.S.; Li, B.; Xu, D.Y. Numerical Simulation on the Distribution Characteristics of Flexible Slender Particles in a Circulating Fluidized Bed. *Proc. CSEE* **2009**, *29*, 102–108.
21. Kang, S. *Study on Flow Characteristics of Flexible Fiber Suspension in Centrifugal Pulp Pump with Open Impeller*; Jiangsu University: Zhenjiang, China, 2021. (In Chinese)

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.