Energy Absorption Characteristics of Conical Threaded Tubes Under Oblique Loading: Postprint

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Abstract

Thin-walled structures have found widespread application in transportation and other fields due to their advantages of light weight, low manufacturing cost, and high energy absorption efficiency. To improve the energy absorption performance of traditional straight tubes and corrugated tubes, a tapered thin-walled tube with a spiral corrugated pattern—namely, a tapered threaded tube—was proposed. The crushing behavior and energy absorption characteristics of tapered threaded tubes under oblique loading were investigated using the finite element method, analyzing the influence of different geometric parameters and loading angles on performance indicators such as initial peak force, mean crushing force, energy absorption, and specific energy absorption. It was found that oblique loading limits the energy absorption performance of structures, while tapered tubes can effectively withstand oblique loading just as they do axial loading. The introduction of threads significantly reduces the initial peak force of tapered tubes, with a maximum reduction of 78% compared to straight tapered tubes. The crushing force efficiency is improved by up to 50%, significantly reducing load fluctuation; however, the specific energy absorption decreases. The research results provide theoretical guidance for the design of related energy absorption structures.

Full Text

Preamble

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Research on Energy Absorption Characteristics of Spiral Tapered Tubes Under Oblique Loading

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Abstract: Thin-walled structures are widely used in transportation and other fields due to their advantages of light weight, low manufacturing cost, and high energy absorption efficiency. To improve the energy absorption performance of traditional straight tubes and corrugated tubes, this paper proposes a novel tapered thin-walled tube with a spiral corrugated pattern, named the spiral tapered tube (STT). The crushing behavior and energy absorption characteristics of STT under oblique loading are investigated using the finite element method. The effects of different geometric parameters and loading angles on performance indicators including initial peak force, mean crushing force, energy absorption, and specific energy absorption are analyzed. The results reveal that oblique loading can limit the energy absorption performance of the structure, but tapered tubes can effectively withstand oblique loads just as they do axial loads. The introduction of spiral corrugation significantly reduces the initial peak force of the tapered tube by up to 78% compared with conventional tapered tubes, while increasing the crushing force efficiency by up to 50% and markedly reducing load fluctuation. However, the specific energy absorption is somewhat reduced. These findings provide theoretical guidance for the design of related energy-absorbing structures.

Keywords: thin-walled structure; oblique loading; energy absorption; spiral tapered tube

Introduction

Thin-walled structures are widely employed as energy absorption devices in transportation and other fields due to their light weight, low cost, and high energy absorption efficiency. Traditional tube geometries such as circular and square tubes have been extensively studied, leveraging their regular deformation patterns under compressive loads to absorb substantial energy [1]. However, these conventional thin-walled structures suffer from excessive initial peak force, unstable deformation processes, and significant load fluctuations, resulting in suboptimal energy absorption performance.

To achieve superior energy absorption, researchers have introduced pre-existing defects to induce controlled deformation, including holes, origami patterns, dents, and corrugations as triggering mechanisms, which effectively reduce initial peak force and enhance energy absorption. SONG et al. [2] investigated square tubes with rectangular window patterns, achieving a 63% reduction in initial peak force and a maximum 54% increase in specific energy absorption while reducing structural mass. In addition to perforated tubes, studies on origami-patterned tubes [3] have shown that introducing pre-folded diamond creases on conventional square tubes effectively lowers initial peak force, while a stable complete diamond deformation mode significantly improves energy absorption. ZHANG et al. [4] incorporated longitudinal grooves into square tubes, increasing specific energy absorption by 82.7% and reducing peak force by 22.3%. ISAAC et al. [5] examined a novel external pattern with press-fitted rings on the tube surface, demonstrating higher energy absorption than conventional tubes. Compared with traditional structures, corrugated patterns enable more controllable collapse and smoother deformation processes. Consequently, extensive research has been conducted on corrugated structures. SINGACE et al. [6] experimentally demonstrated that corrugations force plastic deformation to occur at predetermined intervals along the tube generator, resulting in smoother load-displacement curves. LIU et al. [7] investigated waveform-patterned structures, finding that such patterns enhance specific energy absorption and crushing force efficiency. WU et al. [8] studied straight tubes with sinusoidal corrugation patterns, effectively reducing initial peak load and optimizing corrugated tube parameters. LUO et al. [9] proposed a novel energy-absorbing structure with equally spaced continuous corrugations, achieving a 14.31% reduction in initial peak force. ZHANG et al. [10] designed a thin-walled circular tube with a sinusoidal spiral structure, significantly improving platform crushing force stability and specific energy absorption.

The ability of structures to absorb energy under oblique loading represents a critical performance metric, as the inclination angle can suppress energy absorption capacity. Tapered tubes are widely used for energy absorption under oblique loads because they exhibit lower initial peak force, more stable deformation modes, better oblique load resistance, and greater design flexibility compared with straight tubes [11]. NAGEL et al. [12] found that tapered square tubes exhibit elastic global bending under oblique loading and provide more stable crushing force reduction than conventional straight tubes. AHMAD et al. [13] demonstrated that foam-filled tapered tubes can effectively withstand oblique impact loads as efficiently as axial impact loads. Similar to research on straight tubes, dents and external ribs have been applied to tapered tubes [14]. REZVANI et al. [15] experimentally and analytically investigated the axial crushing behavior of tapered tubes with annular grooves, showing that grooves effectively control axisymmetric deformation modes, reduce maximum collapse load, and improve crushing force efficiency. ASANJARANI et al. [16] optimized tapered tubes with different surface rectangular indentations, finding that surface indentations can enhance specific energy absorption and crushing force efficiency. ZHANG et al. [17] studied functionally graded thickness tapered tubes, achieving 30%-40% increases in specific energy absorption. ALKHATIB et al. [18-19] introduced corrugations into conical tubes, identifying corrugation amplitude and thickness as the most influential geometric factors, and subsequently conducted numerical studies on the crushing behavior and energy absorption of tapered corrugated tubes under oblique loading, revealing higher specific energy absorption than conventional tapered tubes. AHMADI et al. [20] developed analytical models for predicting the mean crushing force of tapered corrugated tubes under quasi-static axial and oblique loading, demonstrating that corrugated structures increase specific energy absorption more effectively than simple tapered structures under oblique loading.

Existing research demonstrates that tapered tube structures exhibit certain resilience across different loading angles and can effectively resist oblique loads. However, conventional straight tapered tubes have excessive initial peak force and low crushing force efficiency, while corrugated tubes suffer from low mean crushing force and specific energy absorption due to independent corrugations. Spiral patterns connect the corrugations, enabling continuous threads to act collectively during crushing and generate more plastic hinges, thereby further enhancing energy absorption. This study designs a tapered tube with spiral corrugations—the spiral tapered tube (STT)—and employs finite element analysis to investigate the effects of geometric parameters (amplitude, pitch, thickness, taper angle) on deformation modes and energy absorption characteristics under various oblique loading angles, providing clear insights into the energy absorption performance of STT.

1. Design Method of Spiral Tapered Tube

As shown in [Figure 1: see original paper], inspired by the spiral structure of seashells in nature, the STT is generated by sweeping a sinusoidal curve along a helical path on the surface of a straight tapered tube. The sinusoidal curve is expressed as:

$$y' = A \sin\left(\frac{x' \cdot 2\pi}{P}\right)$$

The STT is primarily defined by four geometric parameters: thread amplitude (A), thread pitch (P), wall thickness (t), and tube taper angle (α). As listed in , each geometric parameter is assigned two values to investigate its influence on the mechanical performance of STT. In this study, the tube height (L) and top diameter (D) are fixed at 120 mm and 40 mm, respectively, while the bottom diameter varies with the taper angle. Based on these geometric variations, a total of 16 STT configurations are obtained. Each configuration is simulated under five different loading angles: 0° (axial loading), 10°, 20°, 30°, and 40°.

2. Finite Element Model and Validation

2.1 Finite Element Model

Quasi-static compression analysis of STT is performed using Abaqus/Explicit. As shown in [Figure 2: see original paper], the spiral tapered tube is placed between two rigid plates, with the tube fixed to the bottom rigid plate while the top rigid plate translates only along the tube axis. To ensure quasi-static compression with a kinetic energy to internal energy ratio below 5%, the loading time is set to 0.05 s to achieve accurate and efficient analysis, with a compression distance of 70% of the tube height. The finite element model employs 4-node S4R shell elements with 5 integration points through the thickness and a mesh size of 1 mm. Surface-to-surface contact is defined between the tube and rigid plates, and self-contact is employed for the tube walls with a friction coefficient of 0.25 [3, 10].

2.2 Material Parameters

The STT thin-walled structure is made of Q235 low-carbon steel, using the elastic-plastic constitutive model and parameters from reference [3]. The mechanical properties are listed in .

2.3 Performance Indicators

The performance of tubular thin-walled structures is evaluated based on overall crushing behavior and the following metrics:

The **initial peak force (FIPF)** is the maximum crushing force required to initiate deformation and collapse of the energy-absorbing structure. A lower FIPF is desirable as it reduces reaction forces and prevents injury to occupants in safety applications such as automotive crashworthiness.

Energy absorption (EEA) evaluates the ability of an energy-absorbing structure to dissipate crushing energy through plastic deformation. The absorbed energy is represented by the area under the force-displacement curve:

$$\mathrm{EEA} = \int_0^{d_{\max}} P(s)ds$$

where $P(s)$ is the instantaneous crushing force and $d_{\max}$ is the effective compression stroke at maximum deformation.

The **mean crushing force (Pm)** is the average force experienced by the energy-absorbing structure during crushing:

$$P_m = \frac{1}{d_{\max}} \int_0^{d_{\max}} P(s)ds$$

Crushing force efficiency (ECFE) is defined as the ratio of Pm to the maximum peak force, measuring load fluctuation during crushing:

$$\mathrm{ECFE} = \frac{P_m}{P_{\max}}$$

where $P_{\max}$ is the maximum peak force experienced during crushing.

Specific energy absorption (ESEA) is the ratio of total absorbed energy to structural mass, representing energy absorption per unit mass for comparing different materials and structures:

$$\mathrm{ESEA} = \frac{1}{m}\int_0^{d_{\max}} P(s)ds$$

where m is the mass of the energy-absorbing structure.

2.4 Finite Element Validation

As experimental results for STT compression were unavailable, the accuracy of the finite element analysis was verified by analyzing the compression of sinusoidal spiral tubes [10] and oblique loading of tapered tubes [13], with comparisons to experimental results. The deformation modes and force-displacement curves obtained from the present finite element analysis and literature experiments are shown in [Figure 3: see original paper] and [Figure 4: see original paper]. The deformation modes are essentially identical, and the force-displacement curves show consistent trends (according to reference [10], local fracture at the tube end and base in the sinusoidal spiral tube experiments caused a ring deformation mode in the straight section, resulting in a higher maximum peak force in the experimental results). The errors between finite element simulation and experimental results for performance indicators are listed in , confirming the accuracy of the finite element model and results.

3. Results and Discussion

3.1 Force-Displacement Characteristics

To compare the energy absorption performance of STT under different loading angles, Appendix Tables 1-4 summarize the crushing simulation results for STT under various loading conditions. Performance indicator values are calculated at a displacement of 84 mm, selected because all tubes have undergone sufficient deformation for performance comparison at this point.

[Figure 5: see original paper] shows the force-displacement characteristics of a representative STT ($A = 1$ mm, $P = 10$ mm) and a straight tapered tube under different loading angles. The platform force of STT is clearly lower than that of the straight tapered tube due to the spiral surface acting as a deformation trigger. All tubes experience an initial peak force, with STT exhibiting lower FIPF. As the loading angle increases to 10°, both the initial peak force and force oscillation amplitude tend to decrease. When the loading angle further increases to 40°, the force-displacement curve shifts downward, reducing the platform force because tubular structures undergo global bending deformation under oblique loading, particularly at high angles.

Research on conical tapered tubes (CTT) [19] revealed that CTT significantly reduces FIPF and improves compression stability and ESEA. [Figure 6: see original paper] compares the force-displacement curves of STT and CTT with identical specifications ($A = 1$ mm, $P = 5$ mm) under quasi-static oblique loading at different angles, with ESEA values listed in . The results show that STT not only maintains low load fluctuation but also achieves higher EEA and ESEA (with maximum ESEA increase of 31%). Thus, STT exhibits superior energy absorption performance compared with CTT, making further comparison with CTT unnecessary.

3.2 Deformation Modes

[Figure 7: see original paper] shows the final deformation modes of a representative STT ($t = 1$ mm, $\alpha = 5°$) under different amplitudes and pitches. Under oblique loading, STT primarily exhibits axial progressive crushing and global bending deformation modes. At low loading angles (0°-10°), STT undergoes axial progressive crushing; at higher angles (20°-40°), the axial deformation mode tends to shift laterally, resulting in global bending that reduces energy absorption capacity and limits maximum impact energy absorption [18-19].

Although all STT specimens transition from axial progressive crushing to global bending with increasing loading angle, this transition varies for each structure depending primarily on STT geometry. To understand the influence of geometric parameters on the bending transition, summarizes the critical loading angles at which bending transition occurs for different geometric parameters.

When the taper angle $\alpha = 5°$, the transition to global bending occurs at larger loading angles (20°-30°). When the taper angle is 2°, transition occurs at smaller loading angles (10°-20°). With an amplitude of 1 mm, increasing pitch from 10 mm to 20 mm shifts the bending transition to larger loading angles because larger pitch reduces the number of threads, making the tube more similar to a straight tube and diminishing the thread triggering effect. At an amplitude of 2 mm, the bending transition loading angle does not change with pitch, indicating that pitch has insignificant influence on the transition to global bending when thread amplitude is large. With a pitch of 20 mm, increasing amplitude from 1 mm to 2 mm enhances thread triggering effect and advances the onset of global bending. Therefore, reducing amplitude and increasing pitch are beneficial for delaying global bending deformation to larger loading angles.

3.3 Parameter Influence

Oblique loading suppresses energy absorption performance because structures experience two load types under oblique impact: bending and axial compression. Tapered tubes improve load-bearing capacity under oblique loading, while spiral corrugations enhance compression stability. The influence of each geometric parameter on STT energy absorption performance is analyzed in [Figure 8: see original paper]-[Figure 10: see original paper], which describe performance metrics (FIPF, Pm, EEA, and ESEA) at different loading angles.

The effect of loading angle on all performance indicators (FIPF, Pm, EEA, and ESEA) follows a similar trend: FIPF is maximum at 0° (axial loading), gradually decreases at 10°, and continues to decrease significantly with increasing loading angle.

[Figure 8: see original paper] illustrates the influence of geometric parameters on FIPF. [FIGURE:8(a)] shows that an amplitude of 2 mm results in lower FIPF, indicating that FIPF decreases with increasing amplitude due to enhanced triggering effect of more pronounced threads. [FIGURE:8(b)] demonstrates that smaller pitch yields lower FIPF. [FIGURE:8(c)] reveals that thickness significantly affects FIPF, with greater thickness producing higher FIPF. Notably, for 2 mm thick tubes, FIPF decreases more substantially at loading angles exceeding 20°, indicating that loading angle has more pronounced influence on FIPF for thicker tubes. Finally, [FIGURE:8(d)] shows that FIPF increases with taper angle, with the 5° taper angle exhibiting slower FIPF reduction, suggesting that larger taper angles provide better resistance to FIPF reduction at high loading angles.

[Figure 9: see original paper] describes the influence of geometric parameters on Pm, which represents the average crushing force over total effective deformation and higher values indicate greater energy absorption. [FIGURE:9(a)] shows that tubes with 1 mm amplitude have higher Pm because smaller amplitude requires greater force for deformation. A sudden decrease in Pm occurs when loading angle increases from 10° to 20° due to global bending deformation, which generates plastic hinges only locally and limits energy absorption. [FIGURE:9(b)] shows the effect of pitch on Pm: at loading angles below 20°, 10 mm pitch yields higher Pm, while at angles above 20°, 20 mm pitch produces higher Pm, indicating that smaller pitch is beneficial at low loading angles. [FIGURE:9(c)] and [FIGURE:9(d)] demonstrate that Pm increases with both thickness and taper angle across the loading angle range. Notably, for the same thickness, Pm values under axial and 10° loading are nearly equal, indicating that STT provides the same crush resistance as axial compression at low loading angles (0°-10°).

The influence of geometric parameters on EEA and ESEA follows the same pattern as for Pm. As shown in [FIGURE:10(c)], STT exhibits equally excellent ESEA under low loading angles as under axial compression. The only difference appears in the effect of taper angle on ESEA: [FIGURE:10(d)] shows that at loading angles below approximately 15°, the 2° taper angle yields higher ESEA because, despite similar Pm and EEA values, the smaller taper angle has lower mass. As loading angle increases, the EEA gap widens, resulting in higher ESEA for larger taper angles across the test range.

3.4 Performance Comparison

To directly compare FIPF, ECFE, and ESEA characteristics of all STT configurations with straight tapered tubes, [Figure 11: see original paper]-[Figure 12:

see original paper] present these values at different loading angles, with different STT categories indicated by taper angle and thickness. The results show that STT exhibits much lower FIPF and higher ECFE than straight tapered tubes at all loading angles, though sacrificing some ESEA.

[Figure 11: see original paper] depicts performance indicators for tubes with 2° taper angle and 1 mm thickness. [FIGURE:11(a)] shows that STT with 2 mm amplitude and 10 mm pitch has the lowest FIPF, and that increasing amplitude while decreasing pitch is beneficial for reducing FIPF in 1 mm thick tubes. [FIGURE:11(b)] demonstrates that STT has higher ECFE than straight tapered tubes, indicating improved load fluctuation. At loading angles below 20°, 1 mm amplitude with smaller pitch increases ECFE, while 2 mm amplitude with smaller pitch decreases ECFE. At angles above 20°, ECFE increases with amplitude and decreases with pitch, with 2 mm amplitude and 10 mm pitch providing the highest ECFE. [FIGURE:11(c)] shows that STT has reduced ESEA compared with straight tapered tubes. At low loading angles (0°-10°), STT with 1 mm amplitude and 10 mm pitch exhibits better ESEA performance, while at high loading angles (20°-40°), STT with 1 mm amplitude and 20 mm pitch performs better. Thus, 1 mm amplitude yields higher ESEA, with small pitch suitable for low loading angles and large pitch for high loading angles.

[Figure 12: see original paper] presents performance indicators for 2 mm thick tubes (same taper angle as [Figure 11: see original paper]), showing different trends. [FIGURE:12(a)] indicates that unlike 1 mm thick tubes, STT with 2 mm amplitude and 20 mm pitch has lower FIPF at loading angles below 20°, suggesting that both increasing amplitude and pitch are beneficial for reducing FIPF. [FIGURE:12(b)] shows that at loading angles below 20°, 1 mm amplitude with larger pitch increases ECFE, contrary to the 1 mm thickness case. [FIGURE:12(c)] demonstrates that at loading angles of 30°-40° with 1 mm amplitude, smaller pitch yields greater ESEA. Across all loading angles, STT with 1 mm amplitude and 10 mm pitch has higher ESEA.

Investigation of increased taper angle (5°) reveals the same trends as for 2° taper angle.

4. Conclusions

This study numerically investigated the crushing behavior and energy absorption characteristics of STT under various oblique loads. Sixteen STT configurations were simulated under five different loading angles, examining deformation modes and performance indicators across the loading angle range. The main conclusions are:

1. Under certain loading angles, spiral tapered tubes transition from axial progressive crushing to global bending deformation. The axial crushing mode is nearly unaffected by loading angle in terms of energy absorption, while global bending reduces initial peak force and energy absorption. This transition occurs at smaller loading angles (10°-20°) for small taper angles

(e.g., 2°) and at larger loading angles (20°-30°) for larger taper angles (e.g., 5°). Increasing taper angle helps resist bending deformation and improve energy absorption.

2. Increasing thread amplitude and decreasing pitch are beneficial for obtaining lower initial peak force. Decreasing amplitude yields higher specific energy absorption, with small pitch suitable for low loading angles and large pitch appropriate for high loading angles.
3. Compared with conical tapered tubes, STT achieves higher energy absorption and specific energy absorption, with maximum specific energy absorption improvement of 31%.
4. Compared with straight tapered tubes, STT significantly reduces initial peak force by up to 78%, exhibits smaller load fluctuation with maximum crushing force efficiency improvement of 50%, and provides good compression stability, though with some reduction in specific energy absorption.

References

[1] MEN Heng, CHEN Weidong, TIAN Xiaogeng. Energy absorption of prefolded tube with stiffness gradient[J]. Journal of mechanical strength, 2021, 43(3): 651-659 (in Chinese).

[2] SONG J, CHEN Y, LU G X. Light-weight thin-walled structures with patterned windows under axial crushing[J]. International journal of mechanical sciences, 2013, 66: 239-248.

[3] MA J Y, YOU Z. Energy absorption of thin-walled square tubes with a prefolded origami pattern—part I: geometry and numerical simulation[J]. Journal of applied mechanics, 2014, 81(1): 011003.

[4] ZHANG X, HUH H. Energy absorption of longitudinally grooved square tubes under axial compression[J]. Thin-walled structures, 2009, 47(12): 1469-1477.

[5] ISAAC C W, OLUWOLE O. Energy absorption improvement of circular tubes with externally press-fitted ring around tube surface subjected under axial and oblique impact loading[J]. Thin-walled structures, 2016, 109: 352-366.

[6] SINGACE A A, EL-SOBKY H. Behaviour of axially crushed corrugated tubes[J]. International journal of mechanical sciences, 1997, 39(3): 249-261.

[7] LIU Z F, HAO W Q, XIE J M, et al. Axial-impact buckling modes and energy absorption properties of thin-walled corrugated tubes with sinusoidal patterns[J]. Thin-walled structures, 2015, 94: 410-423.

[8] WU S Y, LI G Y, SUN G Y, et al. Crashworthiness analysis and optimization of sinusoidal corrugation tube[J]. Thin-walled structures, 2016, 105: 121-134.

[9] LUO Geng, ZHAO Jiannan, CHEN Liang, et al. Research on the crashworthiness of a novel crush box with corrugated structures[J]. Journal of automotive safety and energy, 2022, 13(3): 453-462 (in Chinese).

[10] ZHANG N, TIAN X G. Energy absorption of thin-walled circular tubes with a sinusoidal spiral structure[J]. International journal of applied mechanics, 2022, 14(8): 2250086.

[11] BAROUTAJI A, SAJJIA M, OLABI A G. On the crashworthiness performance of thin-walled energy absorbers: recent advances and future developments[J]. Thin-walled structures, 2017, 118: 137-163.

[12] NAGEL G M, THAMBIRATNAM D P. Dynamic simulation and energy absorption of tapered thin-walled tubes under oblique impact loading[J]. International journal of impact engineering, 2006, 32(10): 1595-1620.

[13] AHMAD Z, THAMBIRATNAM D P, TAN A C C. Dynamic energy absorption characteristics of foam-filled conical tubes under oblique impact loading[J]. International journal of impact engineering, 2010, 37(5): 475-488.

[14] ALTINA M, HALISA S, YÜCESUA H S. Investigation of the effect of corrugated structure on crashing performance in thin-walled circular tubes[J]. International journal of automotive science and technology, 2017, 1(2): 1-7.

[15] REZVANI M J, DAMGHANI NOURI M. Analytical model for energy absorption and plastic collapse of thin-walled grooved frusta tubes[J]. Mechanics of advanced materials and structures, 2015, 22(5): 338-348.

[16] ASANJARANI A, DIBAJIAN S H, MAHDIAN A. Multi-objective crashworthiness optimization of tapered thin-walled square tubes with indentations[J]. Thin-walled structures, 2017, 116: 26-36.

[17] ZHANG X, ZHANG H, WEN Z Z. Axial crushing of tapered circular tubes with graded thickness[J]. International journal of mechanical sciences, 2015, 92: 12-23.

[18] ALKHATIB S E, TARLOCHAN F, EYVAZIAN A. Collapse behaviour of thin-walled corrugated tapered tubes[J]. Engineering structures, 2017, 150: 674-692.

[19] ALKHATIB S E, TARLOCHAN F, HASHEM A, et al. Collapse behaviour of thin-walled corrugated tapered tubes under oblique impact[J]. Thin-walled structures, 2018, 122: 510-528.

[20] AHMADI A, ASGARI M. Efficient crushable corrugated conical tubes for energy absorption considering axial and oblique loading[J]. Proceedings of the institution of mechanical engineers, part c: journal of mechanical engineering science, 2019, 233(11): 3917-3930.

Appendix Table 1. Tube geometry and numerical simulation results ($A = 1$ mm, $P = 10$ mm)

Appendix Table 2. Tube geometry and numerical simulation results ($A = 1$ mm, $P = 20$ mm)

Appendix Table 3. Tube geometry and numerical simulation results ($A = 2$ mm, $P = 10$ mm)

Appendix Table 4. Tube geometry and numerical simulation results ($A = 2$ mm, $P = 20$ mm)

Note: Figure translations are in progress. See original paper for figures.

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