Abstract—A pump capable of transporting high-viscosity fluids and solid–liquid mixtures is required in various industrial settings, including cement plants, sewage treatment plants, and food plants. In addition, growing demand in the medical field. Turbine-type pumps, piston-type pumps and squeeze-type pumps are often used to transport high-viscosity fluids and solid–liquid mixture. However, these types of pumps have disadvantages. Turbine-type pumps cannot exert a high discharge pressure and turbine damage caused by stone; piston-type pumps are usually considerably large, because high pressure is needed to transport large quantities of fluid; squeeze-type pumps are a large and complex equipment. Furthermore, it can be difficult to arrange the bent pipes required by these systems because of high friction between the fluid and the pipe walls. Hence, an innovative transport system is desired.

In this paper, we focus on bowel peristalsis as a model for a mechanism that can transport fluids, such as sludge with little water. We developed a peristaltic pump based on the bowel mechanism by using an artificial rubber muscle, and confirmed its capabilities. In addition, we develop new tube to achieve a perfect close of the tube, and confirm the basic characteristics of the new tube. Finally, we measure the suction pressure and confirm the perfect close of the tube.

I. INTRODUCTION

A pump that is capable of transporting high-viscosity fluids and solid–liquid mixtures is required in various disasters such as flood that cause soil liquefaction, and in various industrial settings including sewage treatment plants and food processing. In addition, growing demand in the medical field. Moreover, it should be as easy as possible to install such a pump system. Turbine-type pumps, piston-type pumps and squeeze-type pumps are often used to transport high-viscosity fluids and solid–liquid mixture fluids. However, these types of pumps have disadvantages. Turbine-type pumps cannot exert a high discharge pressure; piston-type pumps are usually considerably large because high pressure is needed to transport large quantities of fluid; squeeze-type pumps are a large and complex equipment. Furthermore, it can be difficult to arrange the bent pipes needed by these systems because of high friction between the fluid and the pipe walls. Hence, an innovative transport system is desired.

Therefore, various peristaltic pumps have been proposed [1]-[4] to transport these fluids. Mangan proposed a peristaltic gripping device [3]. This device was inspired by the preying activity of *aplysia californica*, which is a type of ocean creature. However, this device cannot transport fluid, although they can transport solids, such as a small ball. Miki was prepared an artificial esophagus using a shape memory alloy [4]. However, this device is very small, and it is difficult to be larger. For this reason, usage environment is limited.

Therefore, we focus on bowel peristalsis as a model for a mechanism that can transport fluids, such as sludge that contains little water. Thus, we developed a peristaltic pump based on bowel peristalsis by using an artificial rubber muscle driven by pneumatic pressure [5]. In a previous study, we have successfully demonstrated transport of high-viscosity fluids (viscosity of 19000 mPa\(s\)) and solid–liquid mixtures (solid content rate of 50%) [6]-[8].

However, the cylindrical tube that is currently being used is not completely closed. Therefore, reverse of transport fluid was happening, and reverse of only fluid when transport solid-liquid mixtures. Thus, in this paper, we develop a new tube to achieve perfect closure. We also aim at determining the basic characteristics of the new tube. This includes measuring the suction pressure and confirming the perfect tube closure.

II. BOWEL PERISTALSIS

Bowel peristalsis is a motion that uses circular muscles located in the intestinal tract wall. This motion propagates toward the anus from the mouth [9]. Fig. 1 shows the motion resulting from bowel peristalsis. Bowel peristalsis can be described by the following three processes.

Fig. 1 Bowel peristalsis

- Bolus Stimulation
- Circular muscle contraction
- Circular muscle relaxation
- Direction of propagation
1) Bolus movement extends the circular muscle located in the intestinal tract wall and stimulates this muscle.
2) The circular muscle stimulated by the movement of the bolus contracts radially and pushes out the bolus.
3) After completely pushing out the bolus, the circular muscle relaxes and returns to its former state.

The bolus is conveyed in the intestines by repeating this process many times by using only the contractive force of the circular muscles. From this viewpoint, we consider that an evacuation mechanism based on bowel peristalsis could transport a solid–liquid mixture containing little water.

III. MECHANISM OF A UNIT

A. Overview of the Mechanism

The mechanism consists of many units; each unit imitates an intestinal circular muscle. Fig. 2 shows a cross section of a unit. Each unit consists of a cylindrical tube, a straight-fiber-type artificial muscle, and flanges. The cylindrical tube is arranged inside the artificial muscle, and the two ends are joined by the flanges. The space enclosed by the artificial muscle, the cylindrical tube, and the flanges forms a chamber. This chamber can be pressurized through an air vent.

Fig. 3 shows how the appearance of the unit changes when the unit is pressurized. Both the artificial muscle and the cylindrical tube expand during pressurization; the artificial muscle expands only in the radial direction, and the unit contracts in the axial direction. The cylindrical tube is composed of four guide trenches. These trenches trigger a dilation deformation when pressurizing the unit. Therefore, the cylindrical tube is divided into four parts by these trenches. As seen from the axial direction, upon expansion, the cylindrical tube takes the shape of four quarter circles that push out toward the center.

![Fig. 2 Cross section of a unit](image)

B. Straight-Fiber-Type Artificial Muscle

Fig. 4 shows a straight-fiber-type artificial muscle [7]. The artificial muscle consists of a tube made of low-ammonia natural rubber latex and a carbon roving sheet. This artificial muscle has the carbon sheet arranged parallel to the axial direction of the tube. The carbon sheet is made of thin carbon fibers, and spreads across its width as rubber layers expand during pressurization. When the artificial muscle is pressurized, it expands only in the radial direction because the carbon fibers do not readily expand axially; thus, the artificial muscle contracts in the axial direction. The contractive force at this time serves as an actuator.

![Fig. 4 A straight fiber muscle](image)

C. Cylindrical Tube

Fig. 5 shows the cylindrical tube that includes carbon fibers (old tube). Fig. 6 shows the cylindrical tube composed of guide trenches (new tube), and its specifications are shown in Table 1. These cylindrical tubes are made of low-ammonia natural rubber latex. The old cylindrical tube includes four carbon fibers that become constrained when pressurizing the unit.

The new cylindrical tube is composed of equiangular guide trenches which trigger a dilation deformation when pressurizing the unit. Fig. 7 shows the pattern diagram of power that acts on the cylindrical tube. The air pressure applied to the outside of the cylindrical tube acts perpendicularly to an action side. Therefore, the cylindrical tube begins to bend from the guide trench. After that, the cylinder side expands.

![Fig. 5 Cylindrical tube](image)

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>SPECIFICATIONS OF NEW UNIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length [mm]</td>
<td>90</td>
</tr>
<tr>
<td>Diameter [mm]</td>
<td>60</td>
</tr>
<tr>
<td>Excrescence height [mm] angle [deg.]xlength [mm]</td>
<td>3x80x2x0</td>
</tr>
<tr>
<td>Guide trench depth [mm]angle [deg.]xlength [mm]</td>
<td>1.5x90x65</td>
</tr>
<tr>
<td>Thickness [mm]</td>
<td>1.5</td>
</tr>
</tbody>
</table>
The optimum number of guide trenches is considered in the model shown in Fig. 8. The figure presents an axial view when the tube expands uniformly. The dashed line represents the shape of the rubber part in its initial state, the solid line indicates the shape during the expansion, and the red line shows the shape in the final state. The green circle shows the guide trench arrangement, which is in a counterclockwise direction on the circumference. To close the inside of the unit completely, there can be no slack in the cylindrical tube. In other words, the final length of the rubber part must be longer than its initial length. This condition is expressed as

\[ d \geq \frac{\pi d}{n} \]  \hspace{1cm} (1)

where \( n \) is the number of guide trenches and \( d \) is the diameter of the cylindrical tube. In (1), \( n \) is an integer. Therefore, the minimum integral value \( n \) is derived as

\[ n \geq 4 \]  \hspace{1cm} (2)

As the number of guide trenches increases, the amount of rubber expansion required to reach the final expanded shape increases. Moreover, as the number of guide trenches increases, the interference of each expanding part can become significant because of the reduction of the expansion progression angle. Thus, we assume that the required pressure tends to increase as the number of guide trenches increases, and \( n \) should be as small as possible. We will set \( n \) to 4 in this study. The condition for determining the axial length of the cylindrical tube is that no fold lines should occur on the rubber part between guide trenches, and the inside of the unit should close completely. First, we consider the condition that no fold lines should occur on the rubber part between guide trenches. Fig. 9 shows a schematic of the rubber part divided by guide trenches.

The divided rubber part of the cylindrical tube is clearly a rectangle. According to the expansion experiment, we have performed by changing the aspect ratio of the divided rubber part. To prevent the generation of fold lines on the rubber part, the side parallel to the axial direction of the rectangle must be the long side at the time of pressurization. This condition can be expressed as

\[ l \geq \frac{\pi d}{n} + x \]  \hspace{1cm} (3)

where \( l \) is the axial length of the cylindrical tube and \( x \) is the amount of contraction at the time of pressurization. Next, we consider the condition that the inside of the unit closes completely. Fig. 10 shows the radial view when the tube expands under ideal conditions. In this case, we assume that the rubber part expands while maintaining a circular shape. To close the inside of the unit completely, at the time of pressurization, the axial length of the cylindrical tube must be greater than its diameter. This condition can be expressed as

\[ l > d + x \]  \hspace{1cm} (4)

Here, \( x \) is derived from the approximation constant obtained from a pressurization experiment.
The central position of two guide trenches, namely, the top section when pressurizing the unit, is composed of a mountain type excrescence. These excrescences gathering in the center, and fill the hole in the center when the unit is pressurized.

IV. PERFORMANCE EVALUATION PARAMETERS

The prototype is shown in Fig. 11. In this study, we define the closing area and volume exclusion rates as performance evaluation parameters of the unit. Fig. 10 shows the schematic diagram of the closing area and volume exclusion rates.

The closing area rate $C_a$ is defined using the percentage as

$$C_a = \frac{S_0 - S}{S_0} \times 100$$  \hspace{1cm} (5)

where $S_0$ is the unit-opening space viewed from the axial direction at the initial state, and $S$ is the unit-opening space viewed from the axial direction at the time of pressurization. The closing area rate shows the performance of the unit as a valve. The volume exclusion rate $E$ is defined using the percentage as

$$E = \frac{V_0 - V}{V_0} \times 100$$  \hspace{1cm} (6)

where $V_0$ is the internal volume of the unit at the initial state, and $V$ is the internal volume of the unit at the time of pressurization. The volume exclusion rate becomes an index of the transportation efficiency of the peristaltic pump.

A. Pressure response

Fig. 12 shows the relationship between pressure and closing area rate, and Fig. 13 shows the relationship between pressure and volume exclusion rate. The final closing area rate of the old tube is 99.6%. However, the new tube is achieved 100% by excrescences. Therefore, the new tube can reduce the backflow. In addition, the new tube performances at 0.01 MPa, the new tube performs at a lower pressure than the old tube.

B. Time response

Fig. 15 and 16 show the time response of the closing area rate of pressured and exhaust cases. When pressurizing the unit, the old tube has a more rapid response than the new ones, but the time to complete the transformation is the same. The same trend is also seen in the exhaust case. Therefore, the new tube has reduced resilience. This is probably because a cross-section of the new tube is not a perfect circle.

V. PERISTALTIC PUMP

The peristaltic pump developed in this study is shown in Fig. 17, and its specifications are shown in Table II. Each unit of this pump can be contracted toward the center annularly similar to that in the intestinal tract. The peristaltic action of the pump can be carried out by contracting each unit according to a pattern of regular motion. It is possible to transport an inclusion by this peristaltic action. In this study, we constructed a peristaltic pump having six units.
TABLE II

<table>
<thead>
<tr>
<th>Specifications of the Peristaltic Pump</th>
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<tbody>
<tr>
<td>Maximum length [mm]</td>
</tr>
<tr>
<td>Minimum length [mm]</td>
</tr>
<tr>
<td>Mass [g]</td>
</tr>
</tbody>
</table>

The internal structure of a unit is shown in Fig. 18, and its specifications are shown in Table III. When the units are connected, the chamber contains an air tube supplying air to each unit; the air tube is arranged such that it saves space. Moreover, it is circularly arranged to prevent it from breaking when the unit contracts. This structure prevents the air channel from being cut. In this unit, flanges A and B form a pair. The cylindrical tube is fixed in place by interleaving one end of each unit between flanges A and B. By adopting this method, we can eliminate transport losses due to the influence of the thickness of the flanges.

![Fig. 18 Internal structure of a unit](image)

TABLE III

<table>
<thead>
<tr>
<th>Specifications of Each Unit</th>
</tr>
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<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>Extension</td>
</tr>
<tr>
<td>Length [mm]</td>
</tr>
<tr>
<td>Maximum diameter [mm]</td>
</tr>
<tr>
<td>Bore [mm]</td>
</tr>
<tr>
<td>Mass [g]</td>
</tr>
<tr>
<td>Contraction rate [%]</td>
</tr>
</tbody>
</table>

VI. EXPERIMENT

A. Motion pattern

Fig. 19 shows a schematic of the motion pattern. In this figure, A–F show the states of the pump motion pattern. Each state moves to the next state at a regular time which we call motion interval. Transport of the fluid becomes possible when each unit is pressurized according to this motion pattern. The motion pattern has three parameters, wavelength, wave propagation and wavenumber. Wavelength is the number of expanding units adjacent to each other. Wave propagation refers to the number of wavelengths that move during one step. Finally, Wavenumber is the number of Wavelength which moves at the same time. As shown in Fig. 19, the motion pattern is represented as two wavelengths, one wave propagation, and one wavenumber. In the case of this pattern is express 2-1-1. In the experiment, we examined the pump characteristics by changing these parameters.

![Fig. 19 Schematic of the motion pattern (2-1-1)](image)

B. Suction pressure experiment

We performed a suction pressure experiment by using a peristaltic pump. Fig. 20 shows a schematic of the experimental system when the peristaltic pump is placed perpendicular to the floor. In this system, pneumatic pressure is controlled by using voltage signals. The pressure supplied to each unit is independently controlled using six electromagnetic proportional valves. The transportation of the fluid is enabled by supplying a controlled pressure to the peristaltic pump according to a specified motion pattern. With the pressure sensor, we measured the suction pressure while water is transported. The pressure sensor is connected to the bottom of the peristaltic pump. This experiment is conducted in the following steps.

1) Operating the peristaltic pump 2 cycle.
2) Keep the operation immediately before pressurizing the bottom unit.
3) Measure the pressure while keeping the step-2 states for constant time.

In this experiment, measurements are performed for three motion patterns: 2-1-1, 2-1-2, and 3-1-1. Each motion pattern has intervals 3.0 s. The applied pressure is 0.04 MPa, and the pump units are numbered 1, 2, and 3 from the bottom.

![Fig. 20 Schematic of the discharge pressure experiment](image)

Fig. 21 shows the new tube and old tube pressure of motion pattern 2-1-1, Fig. 22 shows motion pattern 3-1-1, Fig. 23 shows motion pattern 2-1-2.
From the result of Fig.21-23, we can see that, first, the pressure rises. At this time, the first unit on the bottom the peristaltic pump expands. Thereafter, the pressure in a tube drops rapidly. At this time, constriction of the first unit of the peristaltic pump occurs. Then, the pressure in a tube rises again. In addition, negative pressure has occurred when the pressure in a tube dropped. This pressure is the suction pressure.

The maximum pressure value in the new tube is higher than in the old one. This phenomenon is believed to affect the closing area rate. The new tube completely closed when pressurizing the unit. Therefore, the fluid flow in the tube does not reverse itself, and the pressure in the tube does not drop. However, the old tube leaves a hole, even after pressurizing the unit. Because of that hole, the pressure in the tube drops.

The minimum pressure value in the old tube is lower than in the new tube. This phenomenon is believed to affect the resilience of the tube. The unit exhausts air at atmospheric pressure. However, when the unit exhausts air, the pressure in the tube causes a negative pressure, which is lower than the atmospheric pressure. Therefore the unit is not completely restored to its original shape, the unit is only restored to the extent of balancing the negative pressure and resilience. Thus the higher the resiliency of the tube, the more the unit is restored and the more volume in the tube is expanded, and the negative pressure in the tube is lowered.

After stopping the motion, the pressure in the new tube is maintained the discharge pressure. However, the pressure in the old tube is not maintained at the discharge pressure, it becomes immediately equal to atmospheric pressure. Thus, old tube is not possible to keep the suction pressure. But, the pressure in the new tube hardly changes after stopping the motion, and the closing area rate remains at 100%, this is, the tube stays perfectly closed.

VII. CONCLUSION

In this paper, we improve closing area rates. And, we conducted suction pressure measurement. Details show in below.

1. We developed a new cylindrical tube, and confirmed the basic characteristics of this.
2. We measured the suction pressure at the pump.
3. We confirmed the perfect close in the tube.

In the future, we will improve the resilience which was reduced in the new cylindrical tube. Therefore, we will consider how to evacuate the air forcibly in the unit

REFERENCES