Technology Explanation

Research on Technology to Control Air Bubble Content in Hydraulic Fluid

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Abstract

In hydraulic pumps used in Continuously Variable Transmission (CVT) of automobiles, air is mixed from the surface of hydraulic fluid due to vibration of the hydraulic circuit, and also the dissolved the air appears in the working oil due to the cavitation. In CVT pumps, 10% to more than 30% of air bubbles are contained in the hydraulic fluid in the hydraulic circuit under the operating environment. These bubbles cause many problems such as pump discharge performance reduction, as well as degradation related to vibration, noise, and durability.

Therefore, when developing a pump, it is necessary to evaluate its performance under actual operating conditions, taking into account the bubble content. However, in general, there are no devices or methods to stably adjust the bubble content.

To solve this problem, KYB has developed a device and method to control the bubble content in the hydraulic fluid. First, we focused on a method using a swirling flow as a technique for removing bubbles from oil, and fabricated a bubble separation device. Second, we analytically and experimentally confirmed that the bubble separation effect of this device was sufficient.

Furthermore, we installed the bubble separator in the actual pump test equipment and verified whether the bubble removal effect could be obtained. Finally, to automatically control the bubble content, we verified it was possible to obtain the desired bubble content ratio by controlling the opening and closing of the valve on the outlet side of the bubble separator. In this report, the results of the above verification are described.

1 Introduction

A hydraulic fluid usually contains several percentages of air dissolved therein under atmospheric pressure. Inside a hydraulic pump like the one shown in Photo 1, the hydraulic circuit may have a local decrease in pressure to cause cavitation, generating voids or air bubbles (Fig. 1). Tiny bubbles appearing in this way will stay in the fluid for a certain period of time and may need considerable time to be dissolved in the fluid again or float up to collapse. The air can also be mixed into the hydraulic fluid from the outside of the fluid due to entrainment (sloshing) that occurs when the hydraulic circuit or the oil tank vibrates. The hydraulic circuit for continuously variable transmissions (hereinafter "the CVT") of automobiles is a typical example of those exposed to frequent opportunities for air intrusion in this mechanism. It is said that this type of hydraulic fluid contains 10% to, in some case, even more than 30% bubbles. The fluid with a high bubble content looks whitish as shown in Photo 2 compared to when it has a low bubble content. These bubbles contained in the fluid are often known as the third contaminant [2] of machinery, next to the particulates and water, and may cause the machinery to have vibration, noise or mechanical failure. The presence of air bubbles in the hydraulic fluid reduces the apparent elasticity of the fluid to impair the responsivity of the system. Research [3] has verified that aggressively decreasing the bubble content of the fluid will eventually lower the amount of air dissolved in the fluid to reduce cavitation. Taking into account the fact that

Photo 1 Example of KYB hydraulic pump

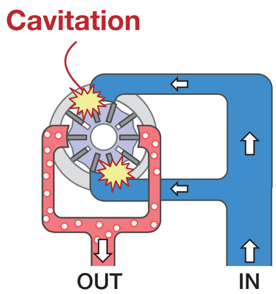
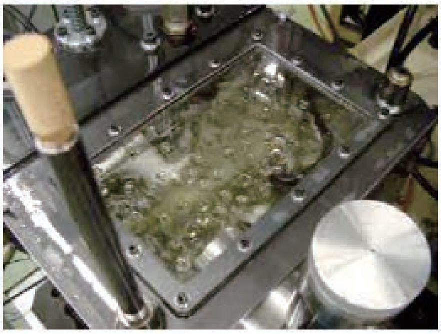
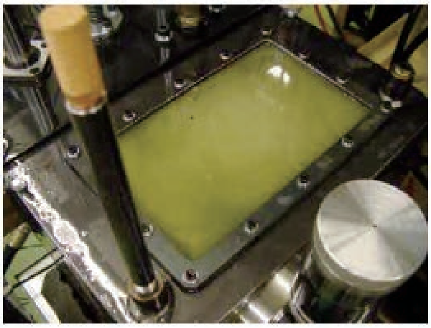


Fig. 1 How cavitation occurs (example)



(a) 0% bubble content



(b) 10% bubble content

Photo 2 Bubbles in a tank in a hydraulic circuit

one of the major causes of failures of hydraulic machinery elements is erosion caused by cavitation, reducing the bubble content of the hydraulic fluid will definitely help prevent machinery failures.

A question: what is the fluid's bubble content that degrades the machinery performance to eventually cause a failure? Such a quantitative indication has not yet been determined. This is because you can barely measure or adjust the bubble content of the fluid in real time at a high accuracy under the present circumstances. Conventionally, the bubbles in the fluid have been removed predominantly by negative methods, such as spontaneous air purge of the oil tank or addition of anti-foam agent to the fluid.

In such situation, modern automobiles are required to have intermittent runs or stops of their engine more frequently for higher fuel efficiency. Accordingly, hydraulic pumps connected to the engines need to be started or stopped frequently as well. Air bubbles contained in the hydraulic oil are likely to stay or merge in various locations within the hydraulic circuit, which may cause the automobiles to generate noise or may make the hydraulic system unstable during the initial stage of the start-up process. The need to determine the effect of the bubble content of the fluid and to take measures has become urgent.

To respond to the need, we first tackled technical development to implement techniques for stable adjustment of the bubble content of the fluid. This report proposes a bubble separation device using a swirling flow and a method to control the bubble content of the fluid entering the separator. The separator has an air purge valve whose operation (closing/opening) can be controlled to adjust the bubble content of the fluid leaving the separator. Furthermore, the report explains the adequacy of this method by introducing the results of an experimental verification test.

2 Design and Fabrication of a Bubble Separator

2.1 Bubble Separator Using a Swirling Flow

Fig. 2 shows the operating principle and structure of a bubble separation device that uses a swirling flow to draw bubbles, which are distributed throughout the hydraulic fluid, and puts them together to be separated and removed by a simple mechanism. Using a swirling flow, the separator can draw bubbles distributed in the fluid and build them up around the central axis in a time as short as approximately 100 msec. The separator can remove and discharge these collected bubbles from a purge outlet to the outside by utilizing a slight difference in pressure between the fluid outlet and the purge outlet. [4] To implement this, a control valve should be installed downstream of the purge outlet to adjust the air purge by valve opening/closing. Controlling the period of time for the valve to be open or closed and/or the operation timing will adjust the volume of bubbles to be separated from the fluid. In this development, we began to fabricate the separator for building a system that can control the bubble content of the fluid at the fluid outlet of the separator.

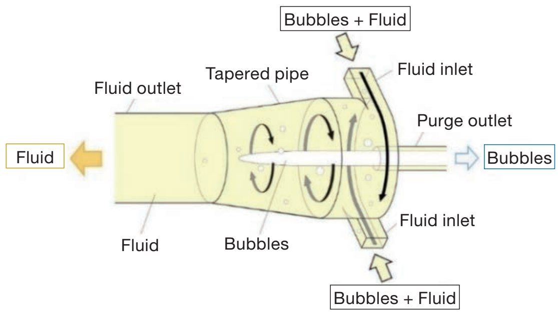


Fig. 2 Operating principle and structure of bubble separator

2.2 Simulation of Bubble Separation

For the method to be verified in this research, we set up a target range of the bubble content between 1% and 40%. To achieve this goal, the bubble separator must provide adequate bubble removal performance within the range. Since the performance of the separator heavily depends on the geometry of the fluid inlet and the diameter of the purge outlet, [5] it is very important to select appropriate parameters for flow conditions in designing the separator.

To verify the operating principle and select optimal geometry parameters, we used the computational fluid dynamics (CFD) to simulate and verify the bubble separation. For the purpose of CFD, we used a fluid duct shown in Fig. 3 and simulation conditions listed in Table 1. Within the target range, 20%, 30% and 40% bubble content levels were selected as examples for analysis purpose.

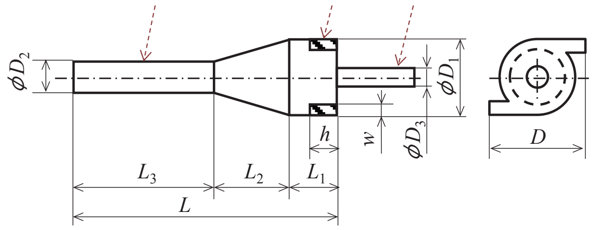
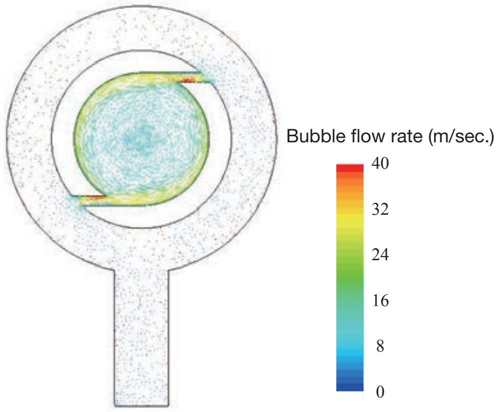


Fig. 3 Fluid duct for computational simulation

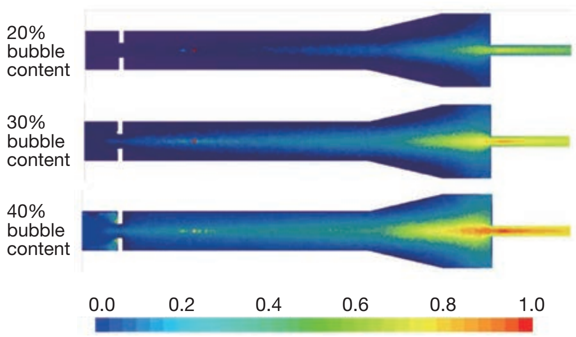
Table 1 Computational simulation conditions

Item		Value
Fluid flow at inlet (L/min)		30
Size of bubble particles (mm)		0.1
Physical properties of hydraulic fluid	Density (g/cm^3)	0.8474
	Dynamic viscosity (mm^2/sec.)	9.189
Bubble content (%)		20, 30, 40

The bubbles entering the separator via the fluid inlet has a higher flow rate around the perimeter of the inlet port and a lower flow rate in the center of the same as shown in Fig. 4(a). The figure represents how a swirling flow occurs. The volume fraction of the bubbles for the bubble content levels of 20%, 30% and 40% is higher in the center of the duct for any of the bubble content levels as shown in Fig. 4(b). It was verified that the bubbles flowed towards the purge outlet efficiently to be separated and removed from the fluid.



(a) Distribution of bubble flow rate
(for fluid with 40% bubble content)



(b) Volume fraction of bubbles

Fig. 4 Computational simulation of bubble flow

As a result of the CFD, an optimal set of geometry parameters for the bubble separator was obtained as shown in Table 2. Fig. 5 shows the resultant bubble removal rate of the separator with its fluid inlet sized to be 2.18 mm (width) x 4.35 mm (height), its air purge outlet sized to have an inside diameter of φ4.4 mm, and its fluid outlet sized to have an inside diameter of φ16 mm for the bubble content cases of 20%, 30% and 40%. Note that the bubble removal rate here refers to what percentage of the bubbles have been removed from the fluid that is discharged from the fluid outlet, not from the air purge outlet. The CFD proved that the simulated bubble separator with the optimal geometry parameters delivered a bubble removal performance as high as 90% or more for all the cases. These results were used as design parameters for an experimental bubble separation device.

Table 2 Optimal geometry parameters for bubble separator

Geometry parameter	Value [mm]
Inside diameter of tapered pipe section φD_1	30.0
Inside diameter of fluid outlet φD_2	16.0
Inside diameter of air purge outlet φD_3	4.4
Total Length L	150.0
Length of fluid inlet pipe L_1	20.0
Length of tapered pipe section L_2	30.0
Length of fluid outlet pipe L_3	100.0
Width of fluid inlet w	2.18
Height of fluid inlet h	4.35

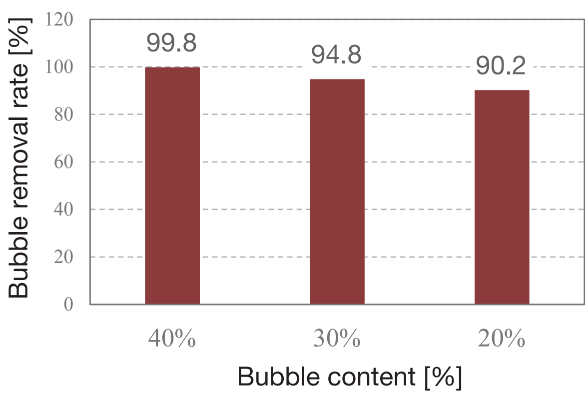


Fig. 5 Results of simulation of bubble separation

2.3 Separator Design and Fabrication

Based on the results of the CFD analysis stated in the previous section, we designed and fabricated a bubble separation device to be used in experiments of controlling the bubble content of the hydraulic fluid. Fig. 6 shows the bubble separator. The separator was designed in modulars so that the geometry parameters including the fluid inlet size, the fluid outlet size and the air purge outlet size can be adjusted later to be suited to the test conditions. Pieces of this modular device can be first inserted into a casing and then fixed together from both sides to be a one-piece structure. The peripheral casing and inserts are made of transparent acrylic.

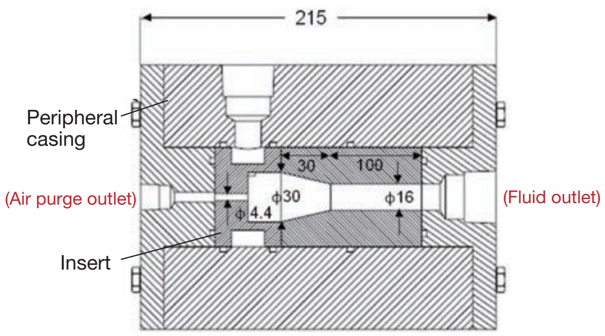


Fig. 6 Design and fabrication of bubble separator

3 Evaluation of Performance of Bubble Separator

To verify the bubble separation performance of the fabricated separator, a preliminary test was first conducted.

Fig. 7 shows the hydraulic circuit used in the preliminary test. The bubble separator was installed on the fluid circuit. A manually operated needle valve was mounted on the circuit line of the purge outlet side of the separator and a Coriolis-type flowmeter was on the circuit line of the fluid outlet side of the separator. The hydraulic fluid was forcefully mixed with bubbles from the air blown by an air compressor located on the discharge side of the pump. While the air was being blown into the fluid, the needle valve was manually controlled to deliver the fluid from the separator at different bubble content levels. The bubble content of the fluid was determined by measuring the density of the fluid at the fluid outlet against the degree of opening of the needle valve. [6] The fluid pressure at the fluid inlet of the separator was maintained at 0.5 MPa.

Photo 3 shows what happened inside the bubble separator during the preliminary test. With the purge outlet fully closed, the fluid looks whitish with great amounts of air bubbles over the entire duct in the separator as shown in Photo 3 (a) (Bubble separation with the purge outlet closed). With the purge outlet fully open, the air bubbles flowing into the separator from the fluid inlet quickly flowed toward the purge outlet. Few bubbles stayed in the separator for a while and then flowed toward the fluid outlet as shown in Photo 3 (b) (Bubble separation with the purge outlet open).

Fig. 8 shows the results of the preliminary test: the relationship between the degree of opening of the needle valve and the bubble content of the fluid at the fluid outlet. In fact, the specifications of the needle valve used in the test made it difficult to achieve precise control of the flow rate at the purge outlet by varying the degree of opening of the valve. Unfortunately, just slightly opening the valve at the purge outlet actually caused the separator to deliver the bubble removal effect more than expected, resulting in a substantially lower bubble content of the fluid at the fluid outlet. However, it was verified that the bubble content of the fluid at the fluid outlet can be controlled by changing the degree of opening of a valve installed at the purge outlet.

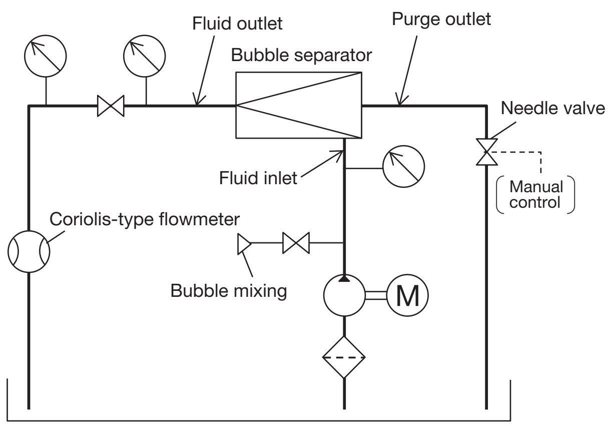


Fig. 7 Hydraulic circuit for testing of manual control of bubble content

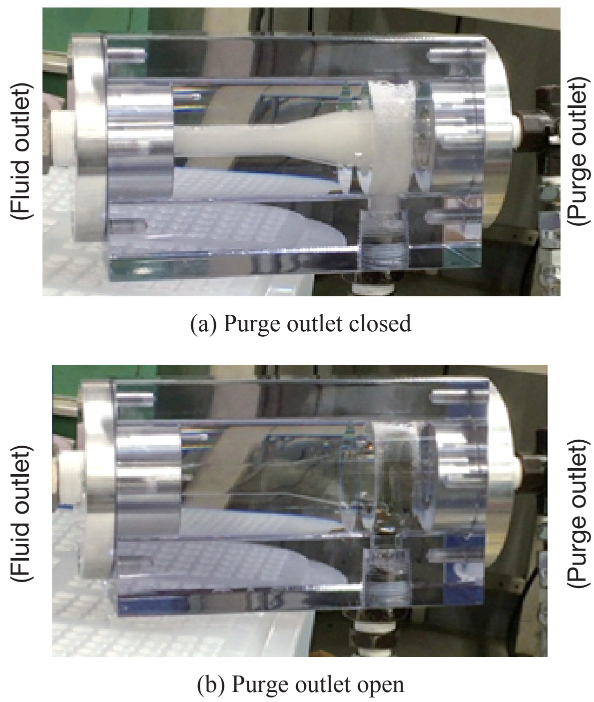


Photo 3 Inside the bubble separator

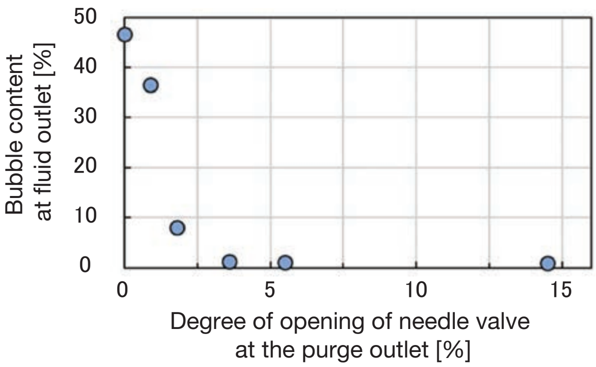


Fig. 8 Manually controlled bubble content

4 Evaluation of Performance of Bubble Separator on Actual Machine

To verify that the bubble separator developed can also be applied to evaluation of actual pumps, we carried out an experimental test on the bubble separator installed on an actual pump test unit. Note that the bubble separator used for this test was another unit made of metal, not the original separator.

Fig. 9 shows the hydraulic circuit of the actual machine test equipment. In order to determine the effect of the bubble content of the hydraulic fluid on the pump, a device to mix the air into the hydraulic fluid in a tank upstream of the target pump to be evaluated was provided to increase the bubble content of the fluid. This air mixing device was designed to be able to control the air discharge rate for mixing. The bubble separator was installed downstream of the target pump. On the purge outlet line a needle valve was provided to be able to be opened or closed freely in the same manner as for the preliminary test. On the fluid outlet side an orifice of any round shape was inserted as a back pressure control. Further downstream, an inline impedance-type bubble content measuring device was installed to measure the bubble content in real time. The oil temperature was maintained at 100°C by a cooler and a heater provided on the circuit.

As an example of verification of the bubble removal effect, Fig. 10 shows changes in bubble content of the fluid over time for the case of a constant mixing rate of bubbles in the tank, a fluid outlet size of φ10, and a pump discharge rate of 18 L/min. At the time point of 0 seconds, the separator has its purge outlet closed and the duct contains the fluid with bubbles mixed in as sufficient as around 30% with the mixing tank being operated. When the purge outlet is opened, the bubble content immediately dropped and became stable at around 10% about 4 minutes later.

This bubble content level was obtained when the bubble mixing device in the tank and the bubble separator were both operated. The air content of the hydraulic fluid may be adjusted to any given level by controlling the air mixing rate and/or the air purge rate of the bubble separator.

Now we have verified that using the bubble separator in the actual pump test unit enables quick, stable adjustment of the bubble content of the fluid in the circuit.

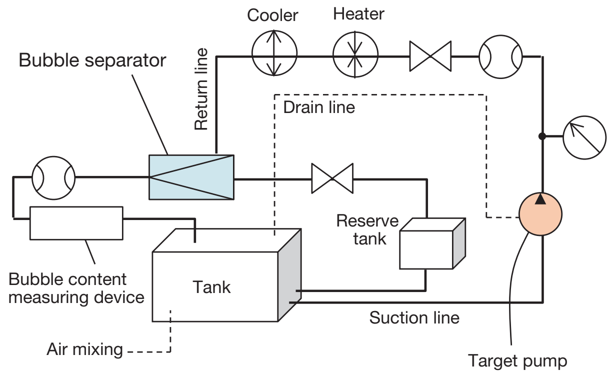


Fig. 9 Hydraulic circuit of actual machine test equipment

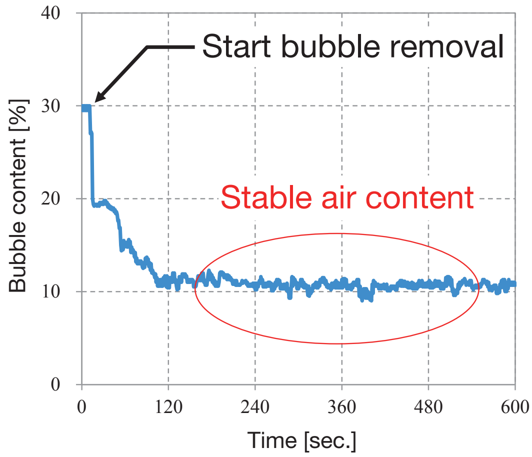


Fig. 10 Bubble content of hydraulic fluid on actual machine

5 Evaluation of Performance of Automatic Bubble Content Control

After verifying that controlling the degree of opening of the purge outlet of the bubble separator can adjust the bubble content of the hydraulic fluid in the circuit, we further tried to determine the possibility of automatically controlling the bubble content to any given level. To this end, we installed an on-off control solenoid at the purge outlet and carried out a test to control the bubble content of the fluid at the fluid outlet by adjusting the on/off time or the switching timing of the solenoid.

Fig. 11 shows the hydraulic circuit used in the control test. The bubble separator was installed on the fluid circuit similar to the one shown in Fig. 7. A Coriolis-type flowmeter was installed at the fluid inlet and a bubble content measuring device installed at the fluid outlet. Then, the bubble content of the fluid was measured in real time for various cases. Air mixing into the fluid was attained by keeping the suction port of the pump open to the atmosphere. An on-off control solenoid was installed at the purge outlet of the separator. The solenoid control (opening/closing) was implemented by a sequencer using a relay according to the deviation of bubble content measurements at the fluid outlet from the target level.

Fig. 12 shows an example of the results of the bubble content control tests. When the incoming fluid had about 29% bubble content, the outgoing fluid had about 28% bubble content with the purge outlet closed. Then, the target bubble content was set to 18%. With the on-off control solenoid operation frequency 1s and the duty ratio between 10% and 100%, the bubble separator automatically controlled the duty ratio to attain the target level as indicated by the figure. Table 3 shows the average bubble content for each duty ratio and its relative deviation from the target bubble content for a certain period of time (19.2 seconds to 25 seconds) after the bubble content became stable at around the target level. In general, the smaller the duty ratio is, the lower the control accuracy and responsivity are. However, this test demonstrated that the relative deviation from the target level was within 9.4% for small duty ratios, proving a certain level of control accuracy.

For some duty ratio settings, however, the bubble content may fail to be stable at around the target level and may continue fluctuating in some cases. This is because the on-off solenoid at the purge outlet can only deliver low responsivity while the bubble separator has highly responsive bubble removal performance. This can be probably improved by using a more responsive proportional valve.

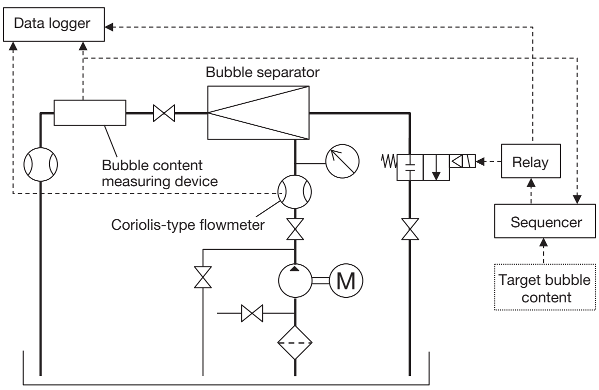


Fig. 11 Hydraulic circuit for automatic bubble control test

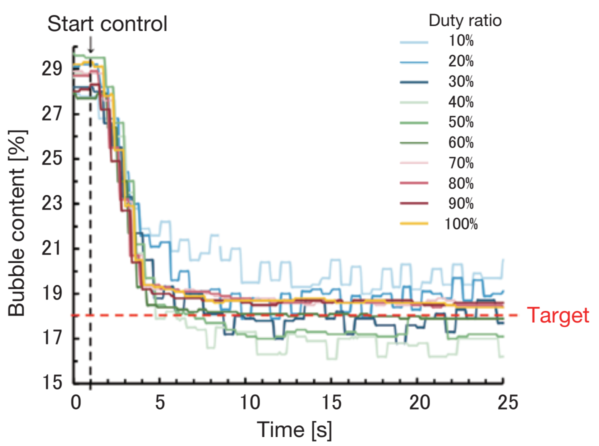


Fig. 12 Automatically controlled bubble content

Table 3 Bubble content for various duty ratios

Duty ratio [%]	Average [%]	Relative deviation [%]
10	19.7	9.4
20	18.8	4.4
30	17.9	0.5
40	16.8	6.7
50	17.3	3.9
60	18.0	0.0
70	18.6	3.3
80	18.6	3.3
90	18.6	3.3
100	18.6	3.3

6 Future Prospects

We will apply the technology that controls the bubble content of the hydraulic fluid developed in this research to evaluation of our pumps under actual operating conditions, thereby developing high-function and high-quality products, although the control stability is still a challenge.

On the other hand, we aim to deploy the technology in such a manner that our pump products including CVT could be improved in performance by focusing the feature of the technology that can remove the bubbles contained in the fluid, which may be called "the third contamination" as stated in the beginning of this report.

By improving our capability of technical development like this, we will be able to offer even-higher-efficiency pumps that could improve the fuel efficiency of automobiles for instance. These products will help create a carbon neutral society or achieve the sustainable development goals (SDGs).

7 Concluding Remarks

This report has introduced the verification of the method that freely controls the bubble content of the hydraulic fluid with the bubble removal technology using a swirling flow, toward establishment of such a bubble content control system. The verification has produced the following conclusions:

(1) A bubble separator has been developed and fabricated that can adequately remove air bubbles from the hydraulic circuit to obtain a bubble content between 1% and 40%.

(2) It has been verified that the bubble separator mounted on the actual pump test unit can control the bubble content in the hydraulic circuit quickly and stably.

(3) Testing has proven that adjusting the flow rate at the purge outlet of the bubble separator can control the bubble content of the fluid at the fluid outlet of the separator.

This research was carried out in cooperation with Professor TANAKA Yutaka, Hosei University, who designed the bubble separation device using a swirling flow, and Associate Professor SAKAMA Sayako, Aoyama Gakuin University (currently belonging to National Institute of Advanced Industrial Science and Technology), who carried out various element tests. Finally, we would like to take this opportunity to sincerely thank them.

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