Visualization and Analysis of Swirling Flow in Bubble Eliminator

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Abstract

Bubbles and the dissolved gases in liquids greatly influence the performance of fluid power systems, coating solutions, plants in the food industry and so on. Therefore, it is important to eliminate bubbles in liquids and to prevent degradation of the quality the system performance as well as to avoid possible damage of the components. These problems are often viewed with the knowledge of the difficulty of keeping out of the fluid power system. Recently, one of the authors has developed a newly device using swirling flow for elimination capable of eliminating bubbles and of decreasing dissolved gases. This devise is called “Bubble Eliminator”.

In this paper performance evaluation of a bubble eliminator is investigated through numerical analysis and visualization of the swirl flow in the bubble eliminator. The pressure distribution in the bubble eliminator is a calculated by a three-dimensional numerical analysis in the case of changing conditions of the fluid viscosity. The swirl flow pattern in a transparent bubble eliminator is visualized and processed as digital image by a high-speed video camera system. The results of the flow visualization are compared with experiments and numerical analysis. The performance evaluation of the bubble removal effectiveness is numerically verified.

Introduction

Bubbles in working fluids greatly influence the performance of fluid power systems and may cause major trouble because of cavitation and aeration inception, bulk modulus change, degradation of lubrication[1], noise generation, oil temperature rise[2] [3]and deterioration of oil quality[4][5]. When the bubbles in oil are compressed adiabatically at high-pressure condition, the temperature of the bubbles may rise sharply and surrounding fluid temperature also rises. Recent trends in industrial manufacturing are to compact machines and equipment in order to economize materials, energy consumption, required space, etc. Therefore, it is important to eliminate bubbles from the liquid and to prevent degradation of the quality products and the system performance as well as to avoid possible damage of the components. One of the authors has developed a newly device using swirling flow [6][7] for elimination capable of eliminating bubbles and of decreasing dissolved gases. This devise is called “Bubble Eliminator”. Using the bubble eliminator will enable the fluid power system to perform better.

In a previous study, the authors have reported that the bubble eliminate is useful for preventing oil temperature rise caused by the bubbles[8]. The swirling flow pattern in a tapered-tube chamber of the bubble eliminator greatly influences the effectiveness of bubble removal[3][4][5].

In this paper performance evaluation of bubble eliminator is studied through visualization and numerical analysis of the swirling flow. The swirling flow patterns in the bubble eliminator are calculated by a three-dimensional numerical analysis for single-phase flow and multi-phase. The performance of the bubble eliminator is evaluated by the numerical analysis under some working fluids conditions, too. The swirling flow pattern in a transparent bubble eliminator is also visualized and processed as the digital image by the high-speed video camera system. Time variant collected bubbles are presented by numerical simulation and flow visualization.

Principle of the bubble eliminator

Figure 1 illustrates the principle of the bubble eliminator. The bubble eliminator consists of three elements an inlet-tube and a tapered-tube, a straight tube. Liquids with bubbles flow tangentially into the tapered-tube from an inlet port and form a swirling flow that circulates through the flow passage in the tapered-tube. The swirling flow accelerates and the fluid pressure along the central axis decreases. From the end of tapered-tube, the swirling flow decelerates downstream and the pressure recovers toward the outlet. Small bubbles are trapped and make the large air column in the vicinity of central axis of the swirl near the area where the pressure is lowest. When back pressure is applied at the downstream side of the bubble eliminator, the collected bubbles are ejected through a vent port.

In the previous study [3], it is experimentally confirmed that the bubble eliminator has been able to eliminate babbles and dissolved gases from the working fluid. The swirling flow pattern and the pressure distribution in the tapered-tube chamber of the babble eliminator greatly influence the effectiveness the babble removal.

Numerical simulation

Single-phase flow analysis

The first step of our numerical investigation consists of the calculation for single-phase flow. The results obtain from the numerical calculation of the single-phase flow are available for an initial condition of multi-phases flow analysis. The swirling flow pattern, the velocity profile and the pressure distribution in the bubble eliminator are calculated by three-dimensional numerical analysis for incompressible viscous fluid. Figure 2 shows the typical five definition blocks for the numerical analysis of the bubble eliminator. The overall apparatus for the bubble eliminator is Inlet port, Peripheral inlet tube, Tangential inlet ports, Tapered-tube, and Downstream tube. The two tangential inlet port regions are divided into smaller rectangles to account for the velocity and pressure value changes. There are 900 cells on the x-y plane of the tapered-tube divided by use of the boundary-fit coordinate. The tapered-tube and downstream tube regions are non-uniformly divided into 55 cells along the z-axis. The number of total cells for the configuration, including the peripheral inlet tube and inlet port, has 81000 cells. We perform a three-dimensional flow analysis of an incompressible viscous fluid using the commercially available numerical calculation software, RFLOW (Rflow Co. Ltd). The basic equations for the numerical analysis consist of the equation of continuity, the equations of motion and energy equation. The basic equations are discretized by the finite volume method using boundary-fit coordinates and are solved by the successive over-relaxation (SOR) method.

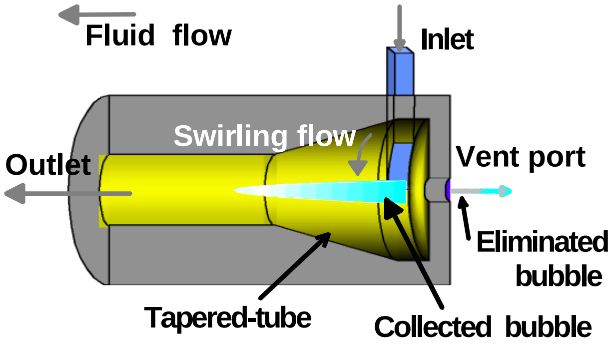

Fig.1 Principle of the bubble eliminator

We investigate influence in the bubble eliminator in the case of the difference conditions of the working fluid. The numerical simulation has been performed for conditions of working fluids having kinetic viscosity of 30, 60, 90[mm^2/s], a density of 857[kg/m^3] and flow rate condition of 20[l/min]. For the flow rate of 20[l/min], the outlet side of the downstream tube has an average viscosity of 1[m/s] and the Reynolds number of 700.

Figure 3 shows that pressure distributions along the central axis of the bubble eliminator are plotted. All pressure date is plotted from the reference at the end of the downstream tube. The pressure at the center of the swirl continuously decreases as the working fluid flows downstream. There are minimum pressure points of a close end the tapered-tube. After that, the pressure makes a gradual

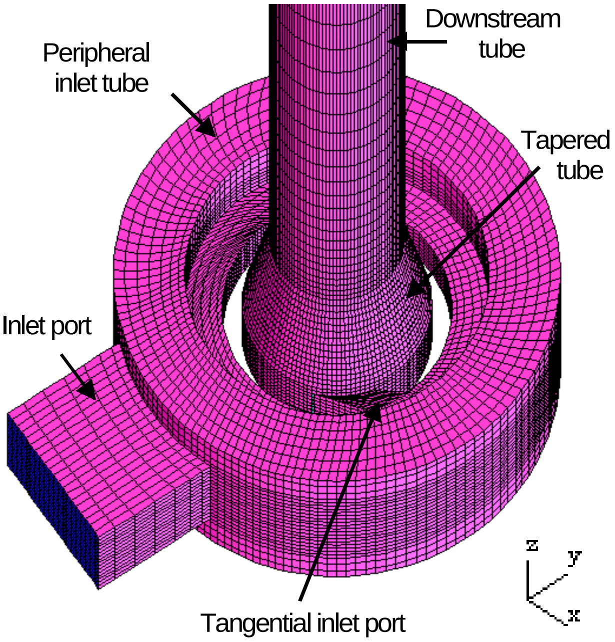

Fig.2 Definition of Blocks for Numerical Analysis

recovery at the center of the adjoining straight downstream tube, because the velocity of the swirl flow is decreased by the viscosity of the fluid. The recovery pressure gradient in the kinetic viscosity of 30[mm^2/s] becomes larger than in one in 60[mm^2/s] and 90[mm^2/s]. The recovery pressure gradient depends on the viscosity of working fluid. Pressure distribution across the cross section at the end of tapered-tube is plotted in Fig.4. As the centrifugal effect at this potion become larger as the fluid viscosity decreases, the difference of pressure between at the tube wall and the center axis decreases because the fluid viscosity decreases the swirling flow. The pressure distribution will drive the bubbles to move toward the central axis.

Multi-phase flow analysis

In the second step of our numerical analysis, multi-phases flow patterns are calculated and distributions of the collected particles are presented. In the multi-phases flow analysis, it is assumed that small air particles are mixed with the working fluid in the bubble eliminator. The diameter of the mixed particles keeps at a constant value of 1[mm]. A surface tension and buoyancy of the air particle is neglected.

Time variant distribution of the collected air particles is calculated by the results of single-phase flow analysis for the initial values. A time interval of numerical simulation for the multi-phase flow analysis is 0.1[ms]. The content ratio of the air particle under the kinetic viscosity of 30[mm^2/s], 60[mm^2/s], 90[mm^2/s] along the central axis of the bubble eliminator is plotted in Fig.5. The content ratio at the center of the swirl continuously increases as the oil flows downstream. There is a maximum value at the downstream end point of the tapered-tube. The maximum value of the content ratio of the air particle decreases in accordance with the viscosity of working fluid. In this numerical analysis, bubbles are regarded as a solid ball which will not mix or collapse, occupying 53 percentage volume of cube having each side as same as a diameter of the particles. Then 53 percentage of air content ratio becomes maximum efficiency of bubble elimination and in case of 30[mm^2/s], 47 percentage of air content ratio of the data means excellent performance. In the case of the highest kinetic viscosity, it is found that it takes the most time to collected bubbles in the end of tapered tube. Figure 6 illustrate the typical numerical results of the percentage of the air content as a function of time for the multi-phase flow analysis under the flow rate condition of 20[l/min] and the kinetic viscosity of 30[mm^2/s]. The distribution of content ration of air particles is demonstrated at every time interval of 0.01[s]. In the initial stage when an elapsed time is 0[s], the fluid contains 3-percentage air particle by volume all over the

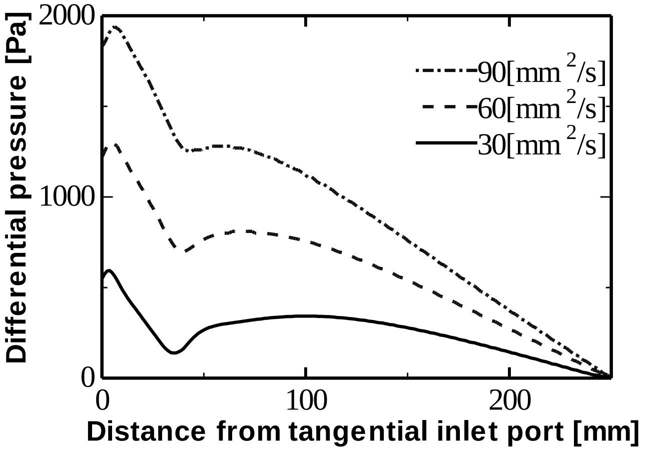

Fig.3 Pressure distribution along central axis for kinetic viscosity

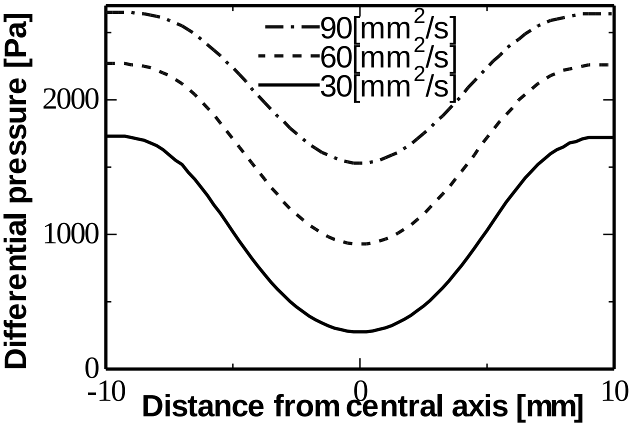

Fig.4 Pressure Distributions across the cross section at the end of tapered-tube

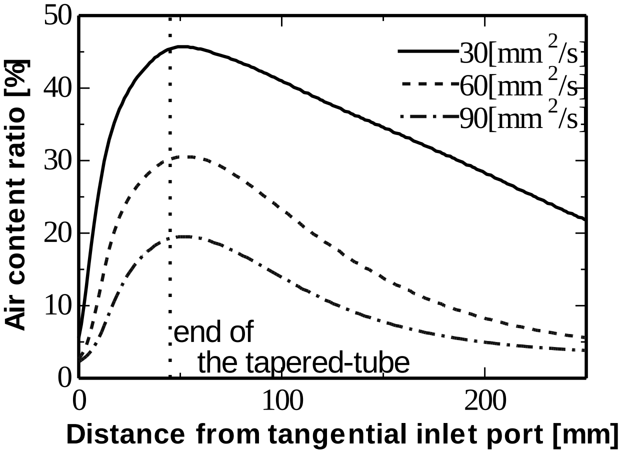

Fig.5 Air particle content along central axis for kinetic viscosity

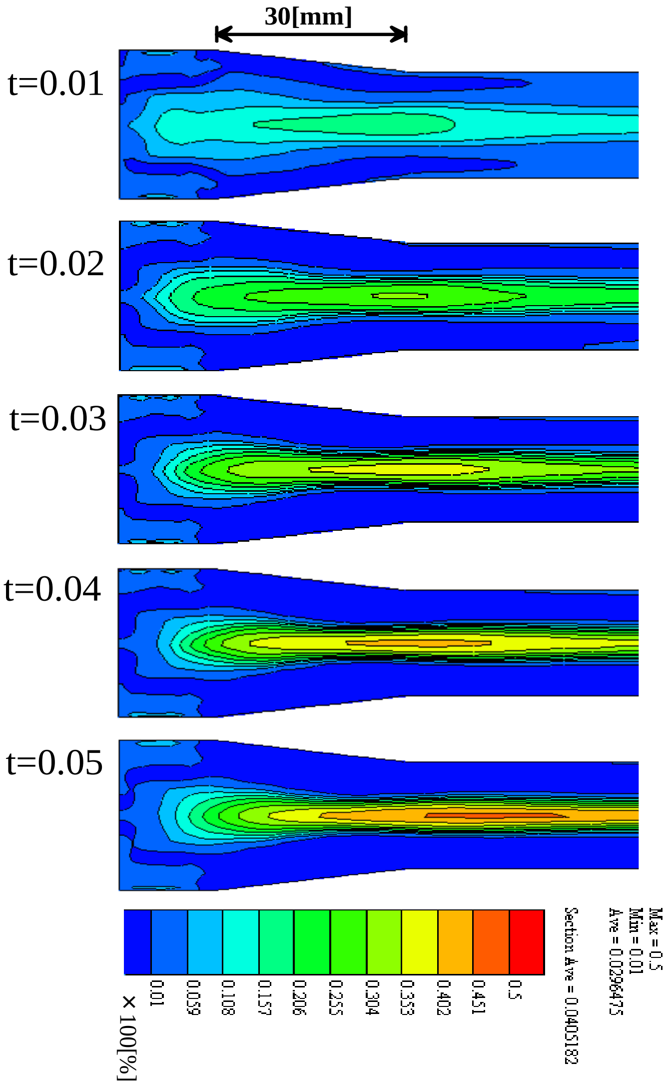

Fig.6 Air particle content as a function time

blocks. The air particles have been collected near the end of the tapered-tube and a column of the air particles has grown up near the central axis of the tube to downstream.

Experimental Investigation

Flow visualization

Figure 7 illustrates an experimental circuit of oil hydraulics for flow visualization. Working fluid in a 20L reservoir fed by a variable displacement-type piston pump flows to a transparent bubble eliminator. The tapered-tube of the transparent bubble eliminator for flow visualization is made form an acrylic pipe. A needle valve at the pump suction side is used experimentally to introduce air into the system. The needle valve is slightly opened and external air is admitted in the system for bubbling. A relief valve is set for the purpose the safety pressure in the pump delivery line. Flow rate is measured by flow meter in the downstream of the fluid circuit. A solenoid-type on-off valve is installed on the vent port side of the bubble eliminator. The time interval of closing the vent valve is adjusted and monitored by a control circuit of the on-off valve. In the usual case the on-off valve is opened, and the trapped and collected bubbles are ejected through the vent line. When the on-off valve is closed, the trapped bubbles make a large air column in a flash time. The high-speed camera (FASTCAM-ultima: maximum recording rate of 4300 flame per second) or the digital video camera is set at a flank of the transparent bubble eliminator. We can observe a growth pattern of the trapped bubbles by the swirling flow at the tapered-tube in the bubble eliminator. Working fluid is Daphne Super Hydraulic Fluid 32 in the experiment for flow visualization of the bubble eliminator. Flow rate set up the condition of between 17[l/min] and 20[l/min].

Figure 8 shows the photographs for the flow visualization by the digital video camera. Bubbles are collected along the central axis. Figure 9 shows the series of the photographs at the flow visualization in swirling flow by the high-speed video camera. In

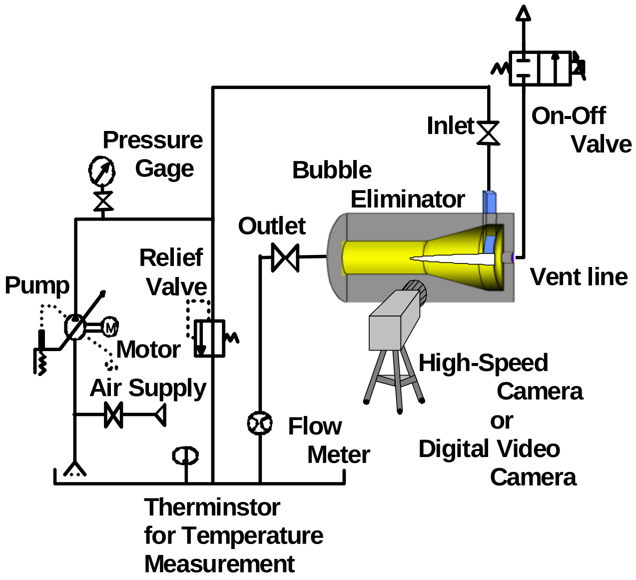

Fig.7 Experimental hydraulic circuit for flow visualization

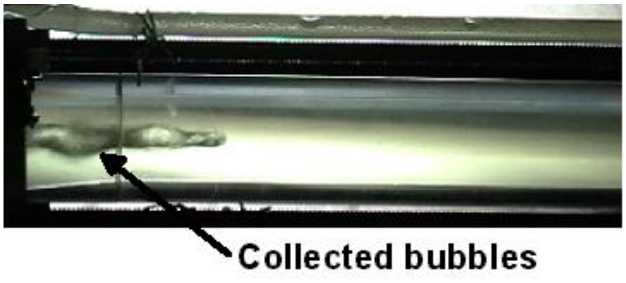

Fig.8 Flow visualization by digital video camera

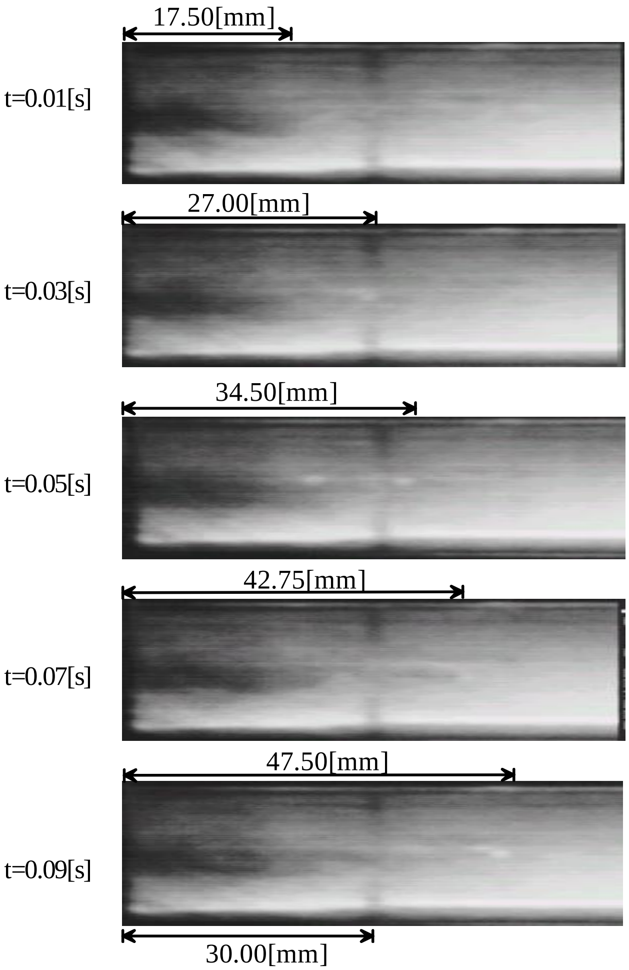

Fig.9 Flow visualization of trapped bubbles by high-speed camera

the initial stage when an elapsed time is 0[s], the on-off valve in the vent line is closed. When the on-off valve is closed, the trapped bubbles are collected at the moment and make a large air column along the central axis of chamber toward downstream. In a series of photographs, it is found that the air column grows up within 0.1[s]. The length from inlet port to the top of the air column is 17.5[mm], 27.0[mm], 34.5[mm], 42.75[mm], and 47.50[mm], respectively in accordance with the elapsed time.

Comparison of between flow visualization and numerical analysis

Figure 10 shows the length of air column comparing to the results of numerical analysis and the experiment of the flow visualization. The length of air column in the case of the numerical analysis is defined as the length between the inlet port and the point of the largest air content ratio at each time obtained from Fig.6. The trapped bubbles behavior of numerical analysis are qualitatively in good agreement with the experimental results of the flow visualization. It is numerically verified that the bubble eliminator collects bubbles effectively near the end of tapered-tube.

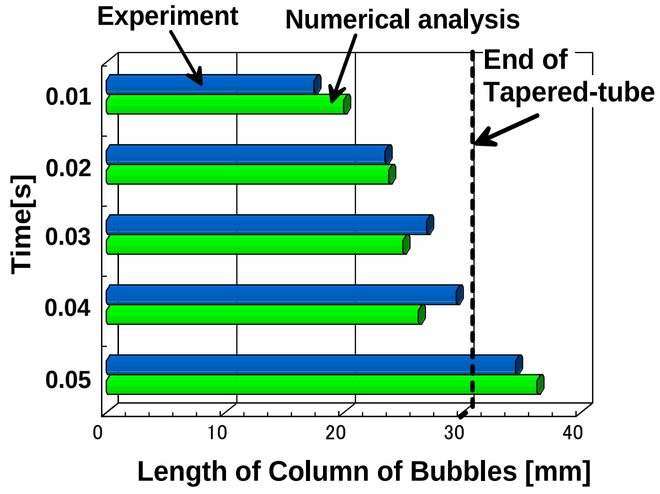

Fig.10 Comparison of the flow visualization of the results of experiment and numerical analysis

Conclusions

In this paper, the performance evaluation of bubble eliminator is studied through numerical analysis and visualization of the swirling flow.

As the results of the numerical analysis, the pressure distribution of the device for the swirl flow has a large influence on the performance of the bubble eliminator. It is confirmed that pressure distribution changes in the case of the kinetic viscosity. As the experimental results of the flow visualization, the results are qualitatively in good agreement with the results of numerical analysis. Numerical analysis is one of the effective means to study behavior of the swirl flow in the bubble eliminator. As we have examined in this paper, the efficiency of the bubble elimination can be calculated by means of numerical simulation for a certain bubble eliminator of appropriate design for the given, parameters of the fluid viscosity, flow rate and bubble diameter. The results of the numerical analysis bring forth much hope to establish design standards of the bubble eliminators. It can be considered that many problems caused by the entrained bubbles in fluid power systems are solved by the bubble eliminator.

Concrete benefits obtained from the use of the bubble eliminator for the systems are : the minimization of oil reservoirs size, prolonging oil life, and elimination of the power loss caused by entrained bubbles.

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Fig.1 Principle of the bubble eliminator

Fig.7 Experimental hydraulic circuit for flow visualization

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Fig.5 Air particle content along central axis
for kinetic viscosity

Fig.6 Air particle content as a function time

Fig.8 Flow visualization by digital video camera

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Fig.9 Flow visualization of trapped bubbles by high-speed camera