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Bubble Elimination in Hydraulic Fluids: Part I

- Basic Principle and Technology Overview

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ABSTRACT

Eliminating bubbles from fluids, preventing degradation of liquids, as well as avoiding damages to fluid components are important engineering issues. One of the authors, Mr. R. Suzuki, has developed a new device that utilizes a swirling flow to eliminate bubbles in liquids and decrease dissolved gases. The device is called “Bubble Eliminator.” This paper offers a basic principle and technological overview of the bubble eliminator for fluids. The swirling flow pattern and pressure distributions in the bubble eliminator greatly affect performance of the bubble removal. In this paper the swirling flow pattern is shown in a transparent bubble eliminator. The result of it is compared with a numerical simulation and the effective bubble removal is verified. Additionally, this paper documents a removable rate of trapped air from the fluid Performance of the device is tested and evaluated by fluid temperature rise in a reservoir in a hydraulic test circuit.

INTRODUCTION

In recent years we are facing technical issues pertaining to environmental protection and energy conservation in fluid power systems. Because the earth is warming up and the cost of energy rising, we have to make a paradigm shift in design concept in fluid power technology.

Engineers often times overlook problems caused by bubbles in fluids. Bubbles in operating fluids greatly affect the performance of fluid power systems and sometimes cause major problems$^{1)}$. For instance, temperatures of fluid with bubbles increase significantly when the fluid is compressed and passes through pumps$^{2)}$. Compressed heat will have a major impact on the fluid temperature in hydraulic systems. Therefore, it is important to eliminate bubbles from fluids in order to maintain the integrity of high quality products and system performance while avoiding damages to the components.

The only solution is reducing the amount of air that is entrapped in the fluid. For eliminating bubbles from the fluid, a large reservoir with baffle plates is generally used, however, the drawback is that it takes a long time to eliminate small bubbles from the fluid by flotation alone.

Recently a novel device, bubble eliminator, that will eliminate bubbles in fluids successfully by utilizing swirl flow was developed$^{3)4)}$. It enables fluid power systems to function more efficiently. In some cases of hydraulic system with cavitated fluid, no use of the bubble eliminator is a feasible option today, but it often proves expensive. Troubles caused by bubbles and the principle of the bubble eliminator are explained in detail in this paper.

The swirling flow patterns and pressure distribution in the bubble eliminator are calculated by three-dimensional numerical analyses for single and multiple phase flows[5]. Time variant collected bubbles are shown by numerical simulation.

In this paper, performance of the bubble eliminator is demonstrated for elimination of bubbles from the fluid by utilizing a void meter that measures the percentage of bubbles in the fluid[4].

In our previous study, we have reported that the bubble eliminator is useful for preventing oil temperature rising as a result of bubbles being under low, moderate and high system pressure conditions[2] [6]. It has been confirmed through experiments and numerically that the Bubble Eliminator is useful for removing dispersed bubbles from the fluid in fluid power systems.

TROUBLES CAUSED BY BUBBLES

Bubbles in fluid power systems are generated when dissolved air is released, external air is introduced mechanically, improper bleeding is made, there is fluid contamination, a reservoir is designed improperly, and/or air vents are improperly installed.

If bubbles are present in hydraulic fluid in a reservoir, they may be sucked into a pump whereby the bubbles will increase in volume due to pressure decrease at the suction line and then be compressed when higher pressure is introduced. When bubbles in the fluid are compressed adiabatically at high pressure the temperature of the bubbles rises significantly and the surrounding fluid temperature also rises. In addition to these well known phenomena, cavitation may lead to formation of reactive chemical intermediates that will affect secondary oxidation. Cavitation occurs when hydraulic fluid pressure is less than the vapor pressure in the fluid.

In lubricating gears and bearings, a churning effect of the fluid as it flows through the gears or bearing assemblies may generate bubbles. In other words, various undesirable physical and chemical effects will occur during the said processes.

Bubbles in fluids greatly influence the performance of fluid power systems and may cause various problems such as:

Broad and high frequency vibration

Higher noise emission

Cavitation erosion

Material damage

Thermal degradation of oil[7]

Acceleration of oil degradation by oxidation[8]

Oil temperature rise

Lubricity reduction by air emulsion[9]

Reduction of thermal conductivity

Increase in compressibility

Decrease in dynamic characteristics

Decrease in pump output efficiency, and bulk modulus change

Thus, it is important to eliminate bubbles from the fluid in order to preserve quality of fluid, attain sound system performance and avoid damage to components.

BUBBLE ELIMINATION DEVICE

Figure 1 illustrates the principle of the bubble eliminator. The device consists of a tapered-tube that is designed such that a chamber of circular cross-section becomes smaller and is connected with a cylindrical shaped chamber. Fluid containing bubbles flows tangentially into the tapered tube from an inlet port and generates a swirling flow that circulates the fluid through the flow passage.

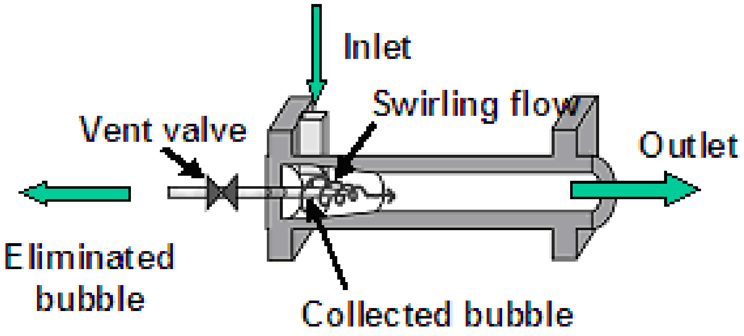


Fig.1 Principle of Bubble Eliminator

The swirling flow accelerates, and the fluid pressure along the central axis decreases as the fluid moves downstream. From the end of the tapered-tube, the swirl flow decelerates downstream and the pressure recovers as the fluid moves to the outlet

There are certain position-dependent centrifugal forces created in all parts of the swirl flow, and the bubbles tend to move toward the central axis of the bubble eliminator due to the difference in centrifugal force between the fluid and the bubbles. Small bubbles are trapped in the vicinity of central axis of the swirling flow and collected near the area where the pressure is the lowest. When backpressure is applied at the downstream side of the bubble eliminator, the collected bubbles are ejected through a vent port.

The dissolved air in the fluid is also eliminated through bubbles extracted at the pump's suction side under negative pressure10). The bubble eliminator has the advantage of a simple structure, a low level of the pressure drop (a few hundred Pa) and of being a passive element without any power supply.

The bubble eliminator has been used in many industrial machines using fluids such as hydraulic systems, food machines and coater machines in paper products11).

NUMERICAL SIMULATION

The swirl flow pattern and the pressure distribution in the tapered tube chamber of the bubble eliminator greatly influence the effectiveness of bubble removal. Geometry of the tapered tube chamber is important factor in design of the bubble eliminator.

Accordingly, the swirling flow of the bubble eliminator, by means of the numerical simulation, is investigated. The steps of our numerical investigation consist of calculating for a single-phase and a multi-phase flow analysis, and displaying with graphics.

The results obtained from the numerical calculation for the single-phase flow are available for an initial condition of the numerical calculation for the multi-phases flow analysis.

Figure 2 shows typical five definition blocks and cells for the numerical analysis of the bubble eliminator. The overall apparatus for the bubble eliminator is an inlet port, a peripheral inlet tube, tangential inlet ports, a tapered tube, and a downstream tube.

The two tangential inlet port regions are divided into smaller rectangles to account for the velocity and pressure value fluctuation. 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 the downstream tube regions are non-uniformly divided into 55 cells along the z-axis. The number of total cells for the studied configuration including the peripheral inlet tube and the inlet ports is 81,000. We perform a three-dimensional flow analysis of an incompressible viscous fluid using the commercially available numerical calculation software, RFLOW (Rflow Co. Ltd). Basic equations for the numerical analysis consist of the equation of continuity, the equations of motion and the energy equation. The basic equations are discretized by a finite volume method using boundary-fit coordinates and are solved by the successive over-relaxation (SOR) method. The numerical simulation has been performed for conditions of fluids having a kinetic viscosity of 30 mm^2 /s, a density of 857 kg/m^3 and a flow rate of 20 l/min.

A pressure distribution along the central axis C-D of the bubble eliminator is plotted in Figure 3. A pressure contour is also graphically shown in Figure.3. The pressure data 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 is a minimum pressure point near the end of the tapered tube indicated by a blue color region in the pressure contour. Subsequently, the pressure makes a gradual recovery along the center of the adjoining straight downstream tube, because the fluid swirl falls in decay. Stagnant particles with the fluid are not carried downstream because of the positive pressure gradient. Finally, the pressure gradient returns to negative because of the pressure drop.

The photo of Figure 4 shows a transparent bubble eliminator for the flow visualization. The device is made from an acrylic pipe in order to understand the situation of the collected bubbles. Small bubbles gather to make a large air column around the central axis at the downstream end of the tapered tube. The fluid properties in the experimental flow visualization are the same as those in the numerical simulation. A flow rate is set at the condition of 20 l/min.

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-phase flow analysis, it is assumed that small air particles are mixed with the fluid in the bubble eliminator. The diameter of the mixed particles keeps at a constant value of 1 mm. Surface tension and buoyancy of the air particle is neglected.

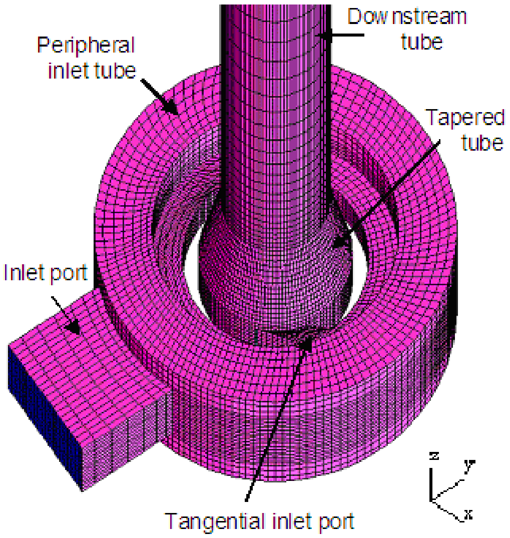


Fig.2 Typical five definition blocks and cells for the numerical analysis of the bubble eliminator

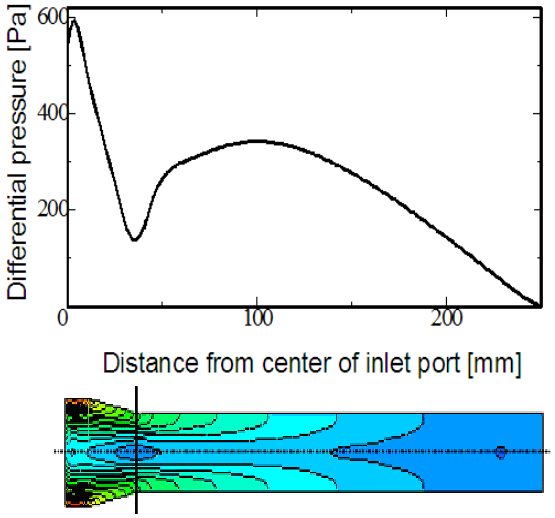


Fig.3 pressure contour is also graphically

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 0.1ms. A calculated content ratio of air particles along the central axis of the bubble eliminator is plotted in Figure 5.

The content ratio at the center of the swirl continuously increases as the fluid flows downstream. There is a maximum value at the downstream end point of the tapered tube. Fig. 5 also graphically illustrates the typical numerical results of the percentage of the air content contour as a function of time for the multi-phase flow analysis.

The distribution of the content ratio of the air particles is demonstrated at time intervals of 0.01 second. At the initial stage when an elapsed time is zero, the fluid contains 3% air particles by volume all over the blocks.

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

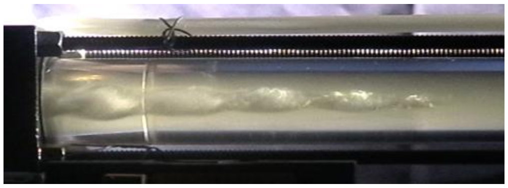


Fig.4 Flow visualization

In the numerical calculation for the multi-phase flow analysis, the bubbles are regarded as solid spheres that never merge or collapse.

The volume of a sphere occupies 52% of total volume of a cube having each side equal to the diameter of the sphere. In other words the fluids numerically contains a maximum of 52% air particles by volume. In the numerical analysis, therefore, 52% of air content ratio becomes the maximum efficiency of the trapped bubbles.

A growth rate of the air column is investigated with the elapsed time from the results of the numerical and the experimental flow visualization.

The trapped bubbles behavior of the numerical analysis is qualitatively in agreement with the experimental results of the flow visualization.

The trapped bubbles behavior of the numerical analysis is qualitatively in agreement with the experimental results of the flow visualization. Therefore, it is numerically and experimentally verified that the bubble eliminator collects bubbles effectively near the end of the tapered tube.

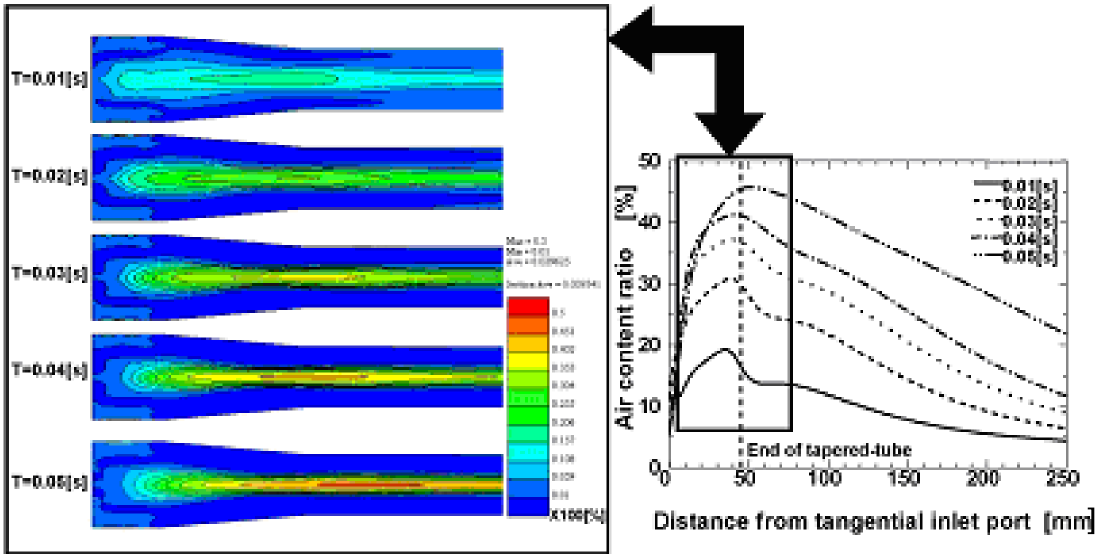


Fig.5 Content ratio of air particles along the central axis

MONITORING OF BUBBLE CONTENT

Sampling and time-consuming methods had been conventionally used to determine the bubble content of the oil. One method is to introduce sample oil into a vertical glass pipe or a syringe, let the sample stand for a sufficiently long period to have the bubbles separated from the oil, and finally measure the volumes of the air and the liquid. Another method is to let the oil with the bubbles flow though a small separation of two glass plates, take photographs of the oil, and analyze the photos to determine the distribution of the size and number of the bubbles. These methods take taken a long time to determine the bubble content in the oils.

Recently an in-line type of a void meter; MOC Void Meter VA-III, for monitoring and determining bubble content of running oils has been commercially available (Yano and Yabumoto, 1991). The basic layout for this device is shown in Figure 6.In the MOC void meter a mass flow rate and a volumetric flow rate of the running oil with bubbles are measured with a Coriolis type flow sensor and with a volumetric type flow sensor, respectively. The mass and volumetric flow rate data allow us to determine the average density of the running oil. A temperature and a pressure sensor are also installed in the void meter. The bubble content of the oil is calculated by a microprocessor from the data of the four sensors. The void meter is able to measure the bubble content of the running oil on line and in real time without diverting a main flow path for collecting samples.

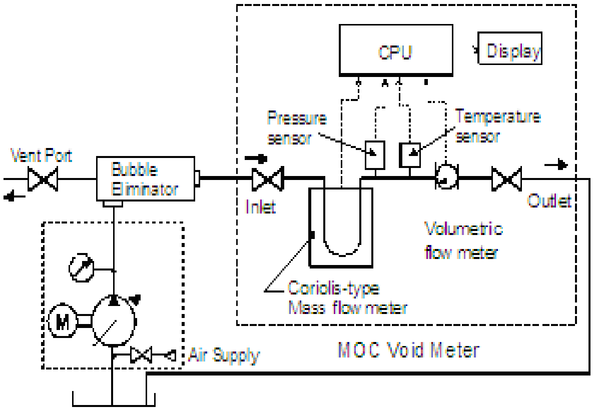
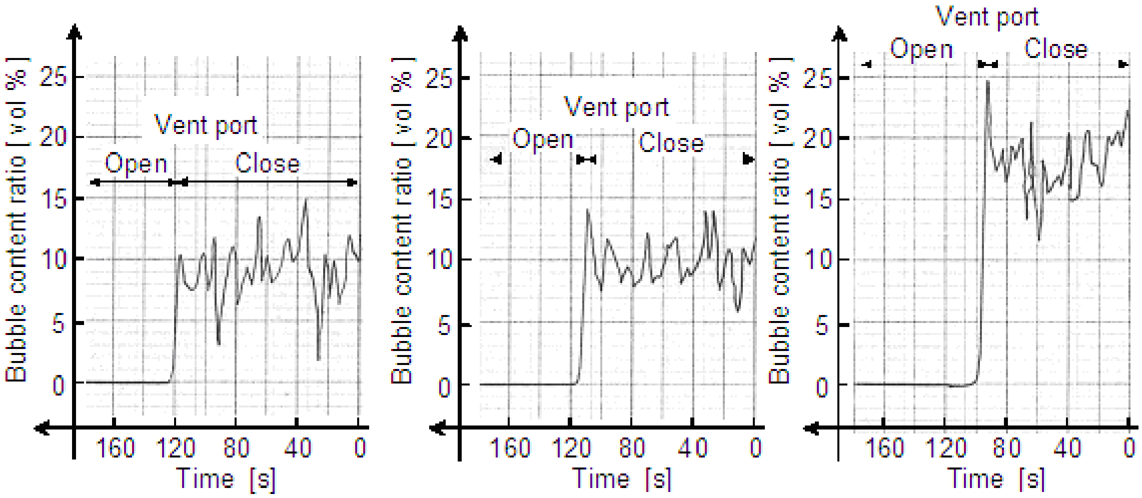


Fig.6 Basic layout of the Void Meter

The void meter is installed in the downstream side of the bubble eliminator in the hydraulic circuit and the change of the bubble content ratio using the bubble eliminator is measured. An untreated mineral oil with a viscosity of 0.13



Flow rate: 30 litter/min

Flow rate: 50 litter/min

Flow rate: 60 litter/min

Fig.7 Experimental results for real-time measurement of bubble content

cm^2/s is used. External air is introduced into the oil through the suction side of a vane pump, churning and mixing until the initial bubble content of 9% to 18 % in volume of the oil is reached.

Figure 7 shows the recorded output of the change of the bubble content ratio as a function of time with the void meter. The pump delivery flow rates are set at the volumetric flow rate of 30.0, 50.4, and 60.0 liter/min, respectively. These experiments are carried out at 180 second interval under continuous running. The vent port of the bubble eliminator is initially closed and the collected bubbles are not ejected and not discharged out of the bubble eliminator. After 100 - 120 seconds of the continuous running, the vent port is quickly opened and the collected bubbles are removed and ejected from the oil. It is clear that the bubble content ratio with the void meter is immediately reduced to almost zero in all three cases. It is experimentally verified that the bubble eliminator proves to be significantly effective in separating the bubbles from the oil.

EXPERIMENTAL INVESTIGATION FOR OIL TEMPERAURE RISE

In our previous paper, it has been experimentally verified that the bubble eliminator is effective in reducing the oil temperature rise. When bubbles in oil are compressed adiabatically at high pressure, the temperature of the bubbles rises sharply, and the surrounding fluid temperature also rises.

In order to verify a reduction of thermal conductivity of oil by eliminating bubbles in the oil, oil temperature rise in a hydraulic circuit is measured with and without the bubble eliminator. An experimental circuit of the hydraulic system is illustrated in Figure 8. The oil in a 20 liter reservoir pressurized by a piston pump flows through a restrictor and returns to the reservoir. The pump delivery flow rate is adjusted at a constant value of 20 liter/min. A relief valve is set at a supply pressure of 6 MPa. The downstream line of the restrictor is divided into two lines. One goes through the stop valve[3], the bubble eliminator, the stop valve[5] and the flow meter to the reservoir. Another goes though the bypass line, in which the stop valve[2] is incorporated, and the flow meter to the reservoir. A needle valve[1] at the suction side of the pump is used to introduce external air into the hydraulic circuit. A thermistor type thermometer is installed in the reservoir. Oil cooling devices are not intentionally installed in the experimental hydraulic circuit.

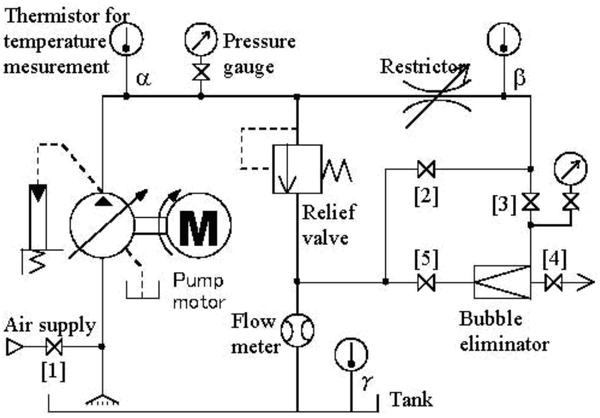


Fig.8 Hydraulic circuit for oil temperature rise

Figure 9 shows the oil temperature rise for the test cases A to D as shown in Table 1. In cases C and D, the external air is supplied in the hydraulic system for the first 10 minutes after the pump operates. The experiments are carried out for 1 hour under continuous running. The initial temperature of the oil is kept within a range of 279 K to 287 K which is almost the same as atmospheric temperature. The temperature data are plotted as the values relative to the initial temperature.

After 1 hour of continuous running, the oil temperature increases significantly. The highest temperature rise is measured in case C in which the bubble eliminator is not being used and air is infused for 10 minutes. The bubbles in the oil are considered as some kind of a heat insulator, so the existence of the air bubbles causes reduction of the thermal conductivity of the oil. The oil temperature rise in condition A becomes lower than in case C, but it remains higher than that in the cases B and D. In case A only cavitation air at the restrictor has much influence on the temperature rise of the oil. If the bubble eliminator is used, the infused bubbles from the suction side of the pump are perfectly eliminated, and the temperature rise can be prevented comparing to not operating the bubble eliminator. It can be explained that the bubbles in the oil causes the oil temperature rise.

CONCLUSION

As a result of the numerical analysis, it is verified that the bubble eliminator collects bubbles effectively near the end of the tapered-tube. Numerical analysis is one of the effective means to study behavior of the swirl flow in the bubble eliminator. The trapped bubbles behavior of numerical analysis are qualitatively in agreement with the experimental results of the flow visualization.

In fluid power systems loss of power turns to thermal energy to heat working fluids and system components. It is numerically and experimentally verified that the bubble eliminator can effectively reduce the fluid temperature rise. It must be borne in mind that the reduction of the entrained bubbles should be considered as one of the important design factors for the fluid power system.

Concrete benefits obtained from the use of the bubble eliminator for the systems are:

1. A reservoir with lighter weight, smaller space, simpler configuration, lower cost
2. Slow fluid degradation, which extends lifetime of fluid
3. Prevent pump and valve cavitation and noise
4. Decrease in compressibility of oil
5. Shorter heating time in cold environment

   easier contamination control

Table 1

Case	Air Supply	Eliminator
A	Off	Without
B	Off	With
C	On	Without
D	On	With

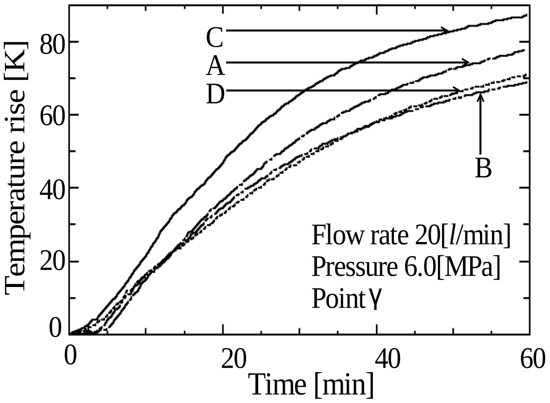


Fig.9 Experimental results for oil temperature rise

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