# Bubble Elimination Device in Hydraulic Systems

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## Abstract

Bubbles in working fluids have much influence on the performance of hydraulic systems and cause some troubles. In this paper, the performance of the developed bubble elimination device concerning the effect of reducing the oil temperature rise is experimentally investigated. From a view point of energy balance in hydraulic systems, a simple mathematical model is proposed and validity of the model is studied.

## 1. Introduction

Bubbles in working fluids have much influence on the performance of hydraulic systems and cause major troubles such as bulk modulus change, cavitation and aeration inception, degradation of lubrication (Yano and Yabumoto, 1991), noise generation, oil temperature rise and deterioration of oil quality (Matsuyama and Takesue, 1996). When the bubbles in oils are compressed adiabatically at high pressure conditions, the temperature of the bubbles may rise sharply and the surrounding fluid temperature also rise (Backe and Lipphardt, 1976).

It is an important technical issue to eliminate the bubbles from the oil because of preventing a degradation of the oil and a damage of hydraulic components (Suzuki, 1994). However, it is a quite difficult problem how to separate the bubbles from the oils during the operating state of hydraulic systems. Recently, a device to eliminate bubbles by swirl flow has been developed (Suzuki and Yokota, 1994). The authors call this device “Bubble Eliminator”. By using this device, the hydraulic system obtains greater performances; especially useful for reducing oil temperature rises caused by the bubbles.

In this paper, the influence of bubbles increasing the oil temperature and the effects of the bubble eliminator are studied through experiments. Furthermore, from a view point of energy balance in hydraulic systems, a mathematical model concerning the effect of reducing the oil temperature rise by use of the bubble eliminator is proposed. A thermal time constant in the mathematical model is investigated through experiments and the validity of the proposed model is studied.

## 2. Nomenclatures

$A$: heat convection surface area [m$^2$]
$C$: specific heat of oil [J kg$^{-1}$ K$^{-1}$]
$h$: average heat transfer coefficient [W m$^{-2}$ K$^{-1}$]
$k$: constant (=$dQ_{in}/dt$) [J s$^{-1}$]
$m$: mass of oil [kg]
$Q_{in}$ : generated hydraulic energy [J]
$Q_{out}$: radiative heat energy [J]
$t$: time [s]
$T$: oil temperature [K]
$T_e$: ambient temperature [K]
$T_k$: rising temperature of oil (= $k / hA$) [K]
$T_\infty$: final temperature of oil [K]
$U$: internal energy of oil [J]
$\tau$ : thermal time constant [s]

## 3. Bubble eliminator

Figure 1 illustrates the principle of the bubble eliminator (Suzuki and Yokota, 1994). The tapered-tube type device is designed such that a chamber of cross-sectional round shape becomes gradually smaller and connected to a cylindrical shaped chamber.

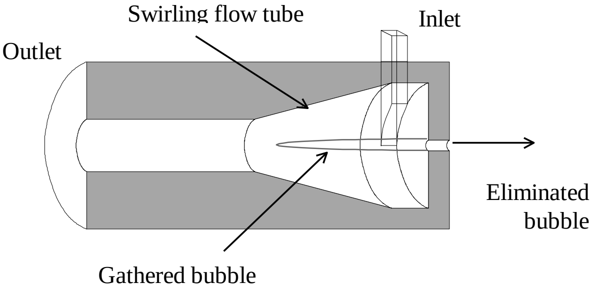

**Fig.1 Bubble eliminator**

Working fluids with bubbles flow tangentially into the tapered-tube from a inlet port and forms a swirl flow that circulates fluid through the flow passage. The swirl flow accelerates towards the downstream. Bubbles are trapped in the vicinity of the central axis because of a difference in the specific gravity of the oil and the bubble, and collected near the range of a vent port where the pressure is lowest. When some back pressure is applied by a check valve or an orifice located at the downstream side of the bubble eliminator, the bubbles are ejected oneself through the vent port. The dissolved gas in the fluid is also eliminated through the bubbles extracted at the pump suction side under the negative pressure. In the previous study (Suzuki and Yokota, 1994), it is experimentally confirmed that the bubble eliminator has been able to eliminate the entrained bubbles and dissolved gases from the working fluid efficiently.

## 4. Experimental investigation

### 4.1 Experimental setup

An experimental circuit of the hydraulic system is illustrated in Fig.2. The oil in a reservoir (the capacity of 20 *l* ) pressurized by a variable displacement-type piston pump flows through a restrictor and returns to the reservoir. A relief valve is set for a safety pressure in the pump delivery line. 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 through the bypass line in which the stop valve [2] is incorporated, and the flow meter to the reservoir. The needle valve [1] at the pump suction side is used to introduce external air into the hydraulic system. A thermistor type thermometer is installed in the reservoir.

### 4.2 Test conditions

In order to investigate the effectiveness of the developed bubble eliminator experimentally, the oil temperature changes during several hours are measured under some conditions tabulated in Table 1. Different parameters such as the bubble eliminator “With” or “Without” and the air supply “On” or “Off” are set for the given pump delivery conditions.

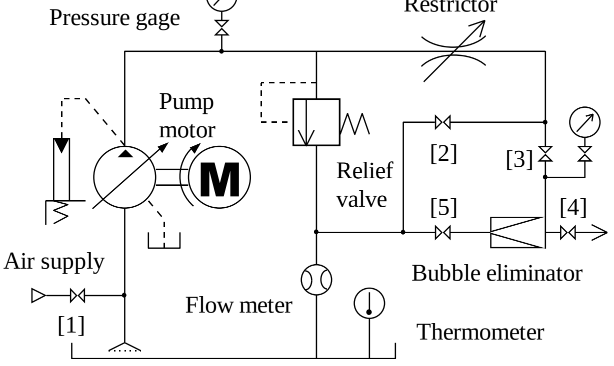

**Fig.2 Experimental hydraulic circuit**

**Table 1 Test conditions for experiments**

| Condition | Bubble eliminator | Air supply |
|---|---|---|
| A | Without | Off |
| B | With | Off |
| C | Without | On |
| D | With | On |

In the case of the bubble eliminator “With”, the operation of the bubble eliminator is carried out by the following manner; open the stop valves [3][4][5], close the stop valve [2] on the bypass line, squeeze the valve [5] to provide the bubble release pressure at 20 kPa and then discharge the bubbles through the vent valve [4]. In the case of the bubble eliminator “Without”, the stop valve [2] is opened and the valves [3][4][5] are closed.

In the case of the air supply “On”, the pump drives for few minutes under no load condition and the needle valve [1] is slightly opened for admission of an external air. Few minutes later, air bubbling is stopped and system pressure is adjusted at the experimental condition.

### 4.3 Experimental results for reduction of oil temperature rise

Figure 3 shows the oil temperature rise for the test conditions A-D as shown in Table 1. The pump delivery pressure and flow rate are adjusted at constant values of 6.0 MPa and 20 *l*/min, respectively. In the conditions C and D, the external air is supplied in the hydraulic system for first 10 minutes after the pump operates. The time interval of temperature measurement is every 30 seconds and the experiments are carried out during 1 hour under continuous running. The initial temperature of the oil is kept within a range of 10±4℃ 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, oil temperature increases significantly high. The highest temperature rise is measured in the condition C in which the bubble eliminator is not being used and air is infused for 10 minutes. It can be explained that the bubbles in the oil causes the oil temperature rise. The air bubbles are considered as some kind of a heat insulator, so the existence of the air bubbles causes reduction of thermal conductivity of the oil. The oil temperature rise in the condition A becomes lower than in the condition C, however, it remains higher than the conditions B and D. In the conditions A, only a cavitation air has much influence on the temperature rise of the oil.

The oil temperature rise with the bubble eliminator is reduced as shown in the conditions B and D. No significant difference is clarified between the conditions B and D. These results can be explained that the bubble eliminator removes both the infused

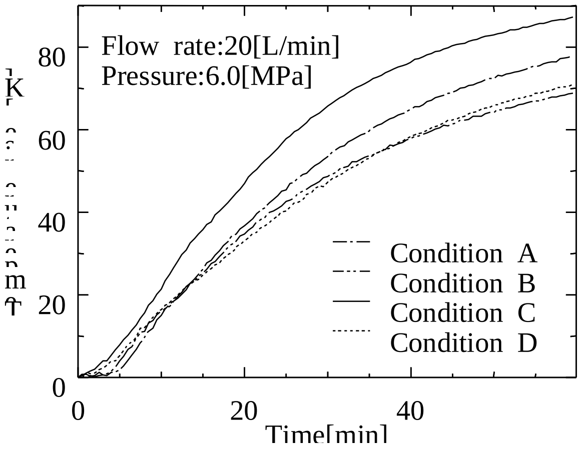

**Fig.3 Experimental results of oil temperature rise**

air and the cavitated air which is forced out from the oil. It is experimentally confirmed that the bubble eliminator is effective in reducing the oil temperature rise.

## 5. Energy balance of hydraulic system

## 5.1 Mathematical model

Considering the first principle of thermodynamics to the oil in hydraulic systems as a lumped-heat-capacity system shown in Fig.4, an internal energy balance of the oil is given as follows;

$$\frac{dU}{dt} = \frac{dQ_{in}}{dt} - \frac{dQ_{out}}{dt} \qquad (1)$$

where $U$ is the internal energy of the oil, $Q_{in}$ is the hydraulic energy generated by the pressurized pump and $Q_{out}$ is the radiated energy from the oil to an ambiance as the heat energy.

It is assumed that the oil is non-compressible and no work is carried out by the hydraulic pressure change instead of heat transfer. As a result of the constant pressure and flow rate conditions at the pump, the hydraulic energy differentiated with respect to time is kept at a constant value and defined as follows;

$$\frac{dQ_{in}}{dt} = k \qquad (2)$$

Based on the Newton's law of cooling between the oil and the ambiance, the differential radiative heat energy $Q_{out}$ with respect to time is derived as follows;

$$\frac{dQ_{out}}{dt} = hA(T - T_e) \qquad (3)$$

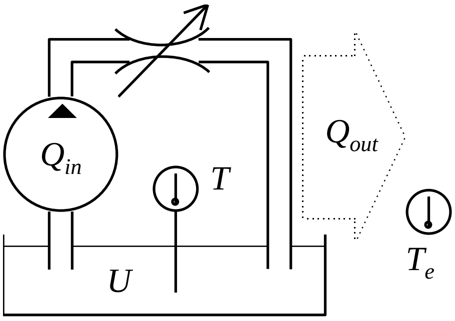

**Fig.4 Energy balance of hydraulic system**

where $h$ is the averaged heat transfer coefficient and $A$ is the surface of the hydraulic system for heat convection.

Using the equations (1) to (3), the differential oil temperature change with respect to time can be derived as follow:

$$\frac{dT}{dt} = \frac{hA}{mC}\left(\frac{k}{hA} + T_e - T\right) \qquad (4)$$

By solving this differential equation (4), the following expression for the oil temperature change can be obtained.

$$T = \frac{k}{hA}\{1 - \exp(-\frac{t}{\tau})\} + T_e \qquad (5)$$

where $\tau$ is the thermal time constant and defined as follows.

$$\tau = \frac{mC}{hA} \qquad (6)$$

Consequently, equation (5) can be regarded as the first order time-lag which has the initial value of $T_e$ and the final value of ($T_e$ + $k/hA$), respectively. Let a rising temperature $T_k$ denote as:

$$T_k = \frac{k}{hA} \qquad (7)$$

The thermal time constant defined by the equation (6) depends on the convection heat transfer coefficient which changes with time. So the thermal time constant is determined by the experimental results of the temperature changes for a heat equilibrium test. Figure 5 shows a typical example of the oil temperature rise as the result of the condition B. The oil temperature is measured until the energy balance attains thermodynamic equilibrium during 4 hours. The thermal time constant is estimated from the time which takes value 63.2 % of the rising temperature $T_k$.

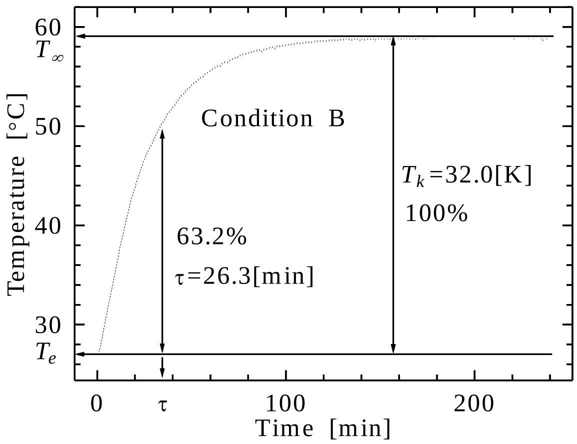

**Fig.5 First order time lag**

## 5.2 Experimental result of heat equilibrium

In the heat equilibrium tests, the pump delivery pressure and flow rate are adjusted at moderate values of 3.0 MPa and 13 *l*/min, respectively. The time interval of the temperature measurement is every 6 seconds and the tests are carried out for 4 hours under continuous running. The initial oil temperature is in the range of 26±2℃. In the conditions C and D, the external air is infused in the oil for 2 minutes before testing. The volume % of the infused bubble in the oil of reservoir is measured by Picno meter and the 2 % air in the oil is contained.

Figure 6 and 7 show the experimental results of the oil temperature rise for the heat equilibrium test. These figures also show comparative results for the mathematical model calculated by the equation (5) under the test conditions A, B and C, D respectively. The experimental results and calculations of the mathematical model indicate good similarity as a function of the operating time. Table 2 shows the thermal time constant $\tau$ and the rising oil temperature $T_k$ estimated from the experimental results in Fig.6 and Fig.7 under the test conditions A to D. It is noticeable in the conditions B and D, the rising temperature is little reduced comparing to the conditions A and C.

We assume in the mathematical model that the thermal time constant expressed in the equation (6) is a time invariant value. However, it is our opinion that the heat transfer coefficient is varied by the air bubble content in the oil. As a result, the thermal time constant is a time variant value under different test conditions. In order to investigate the oil temperature change in more detail, the variation of the logarithm of the ratio of the oil temperature with the time is introduced. The following equation is obtained from equation (5).

$$\ln\frac{T_e+T_k-T}{T_k}=-\frac{t}{\tau} \qquad (8)$$

Figure 8 shows the variation of the logarithm of the ratio of the measured oil temperature in the left side of the equation (8) with the times. According to the equation (8), the mathematical model which has the time invariant constant is shown as a straight line with a constant gradient. In the conditions A and C without the bubble eliminator, the experimental results differ from the mathematical model significantly. On the contrary, in the conditions B and D with the bubble eliminator, the experimental results are similar to the calculation of the mathematical model. In the conditions B and D, the dissolved and infused air is eliminated from the oil by the bubble eliminator and not affected on the change of the thermal time constant. The gradient change in the condition C as shown in Fig.8 results from the averaged heat transfer coefficient changed by the infused and cavitated air. The above results lead to the conclusion that the existence of the air bubbles in the oil has influence on the heat transfer coefficient and the thermal time constant.

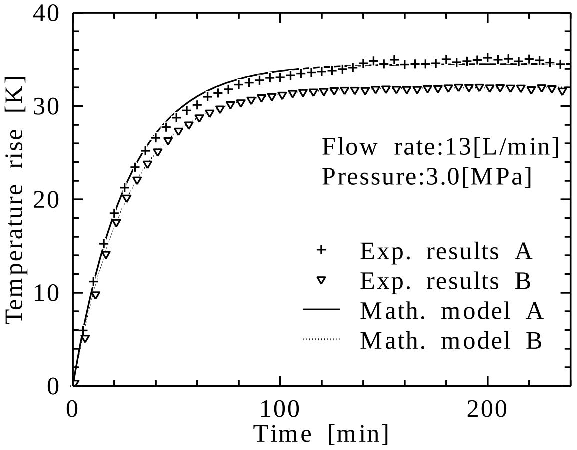

**Fig.6 Comparison of experiment and mathematical model in conditions A and B**

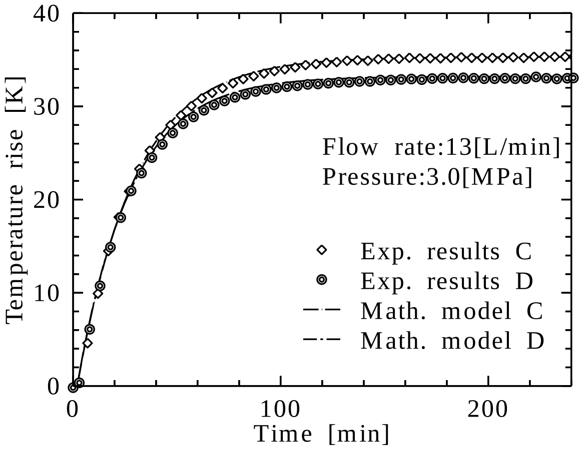

**Fig.7 Comparison of experiment and mathematical model in conditions C and D**

**Table 2 Thermal time constant and rising temperature**

| Condition | τ [min] | $T_k$ [K] |
|---|---|---|
| A | 26.1 | 34.5 |
| B | 26.3 | 32.0 |
| C | 27.9 | 35.3 |
| D | 25.6 | 33.2 |

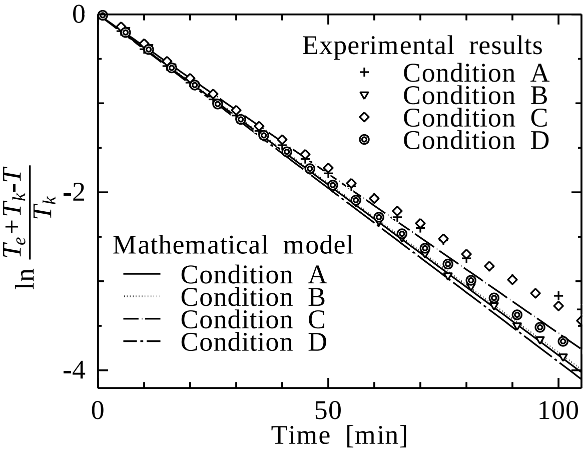

**Fig.8 Variation of logarithm of ratio of oil temperature with time**

## 6. Conclusions

In this paper, the authors have examined the influence of the air bubble and the effect of the bubble eliminator to prevent temperature rise through the experimental investigations by using the oil hydraulic system. Furthermore, from a view point of energy balance in hydraulic systems, the mathematical model concerning the effect of reducing oil temperature rise by use of the bubble eliminator is experimentally investigated. The validity of the proposed mathematical model is verified. It can be considered that many problems caused by the entrained bubbles in hydraulics and lubrication oils are solved by the bubble eliminator.

## Acknowledgments

The authors would like to thank Mr. S. Suzuki for his valuable assistance with experiments.

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