Water Hammer in the Pump Discharge Line
Equipped with Semi-open End Valve*

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This study aims at obtaining data on the pressure rise due to water hammer caused by the impact to the semi-open valve at the end of a discharge pipe by the water flow that starts flowing in the distribution pipe at the time when the pump starts.

Experiments were conducted to measure the pressure variation by oscillograph in the following two cases, namely the first case was in the end valve opening with the velocity of impact kept constant and the second case was in the velocity of impact with the end valve opening kept constant.

(1) The pressure rise becomes greater, when the end valve opening is smaller and the impact velocity is larger.

(2) Velocity measured at the impact coincides well with the calculated velocity which is obtained from the cross point of the heat capacity curve and pipe resistance curve.

(3) We could get the relationship between the experimental value and the calculated value by a graphical method.

1. Introduction

When water starts to flow into the empty discharge line at pump start, we experience a failure (breaking) of a pump or discharge line by the impact of flow to the semi-open valve located at the end of the discharge line.

Experimental study was carried out to obtain some numerical data on the amount of pressure rise due to water hammer. This report studies the influences on the maximum pressure rise of the end valve opening and impact velocity. Furthermore, experimental pressure rises are compared with theoretical values calculated by the graphical method. And it is shown that the maximum pressure rises in any pipe line can be predicted by knowing the frictional loss head of pipe line and semi-open valve.

2. Experimental method and apparatus

Fig. 1 shows the experimental apparatus. A test pump was single suction volute pump with 75 mm bore diameter, and a 3 in suction pipe (80.7 mm diameter) of 1.4 m length having a foot valve at the suction end. A discharge line of 3 in pipe 32 m length having a rising gradient of 2 degrees and two gate valves was installed in the pump discharge line. One valve was at the pump discharge nozzle to regulate the flow and the other was at the discharge end of the pipe line. The end valve was made to indicate the accurate valve opening by an index spindle fitted to the valve disc through the valve body. Vertical head of discharge end from suction level was apart as much as 3 m.

Pressure detecting pick-ups for oscillograph were installed at both the pump discharge nozzle and the front of end valve to detect the pressure transition at water hammer, and the Bourdon tube pressure gauges A and B were prepared at the same taps as pick-ups. Furthermore, taps were made for electrical pick-ups on the discharge line at 5 m intervals to detect the velocity of flow which starts to flow into the empty discharge pipe at the pump start. Impact velocity to the end valve was taken from the mean velocity of the last section of taps closed to the end valve. Before each test, water in the discharge pipe was directed to the branch pipe to have it empty.

Prior to the test for water hammer, characteristics
of the test pump were measured (using a booster pump for test), and then a loss of head of end valve at each opening and the resultant loss of head of discharge pipe and regulating valve (excluding end valve) were measured using the other pump. Pump capacities were measured by an orifice meter made in accordance with JIS standards and pressures were measured by the Bouldon type pressure gauge and U-tube manometer. (Fig. 2)

Transient pressure changes due to water hammer were recorded on the recording paper of the oscillograph and stabilized pressures were measured by the Bouldon tube pressure gauge, and maximum pressure rises were calculated from the pressure by proportion.

It is expected that maximum pressure rise due to the above-mentioned water hammer mainly depends on the opening of end valve and impact velocity of flow, therefore we measured maximum pressure rises under several end valve openings and several impact velocities obtained by changes in regulating valve opening.

3. Notation

$B_V$ : coefficient of head loss of end valve

$B_V = \frac{V}{\sqrt{H}}$

$B_{PL}$ : coefficient of resultant head loss of regulating valve and discharge pipe (excluding end valve)

$V_I$ : mean velocity at the last section of flow
measuring tap (where impact velocity to the end valve) m/sec

\[ a = \frac{1}{\sqrt{1 + (k/E)(D/t)}} \]

\[ D : \text{inner diameter of discharge pipe} \]
\[ t : \text{thickness of pipe} \]
\[ k : \text{bulk modulus of water} = 2.07 \times 10^8 \text{kg/m}^2 \]
\[ E : \text{Young's modulus of pipe material} \text{kg/m}^2 \]

In this test apparatus

\[ k/E = 0.01 \]
\[ D/t = 19.2 \]

then \( a = 1.310 \text{ m/sec} \)

4. Test results

Values of \( B_v \) and \( B_{PL} \) tested by the above-mentioned method are shown in Fig. 3 and Fig. 4.

Fig. 3 shows \( B_v \) against end valve opening and Fig. 4 shows \( B_{PL} \) against regulated valve opening. In Fig. 4 \( B_{PL} \) at 100\% regulating valve opening means the head loss of discharge pipe alone, and in this test apparatus this value \( B_{FPL} \) was 1.368.

Fig. 5 is one example of an oscillogram showing transient pressure which was recorded against several end valve openings under constant regulated valve openings. In Fig. 6, maximum pressure rise \( H_{\text{max}} \) obtained from the oscillograph is shown against head loss coefficient \( B_v \). From this figure we can see that maximum pressure rise becomes higher as the end valve opening becomes smaller i.e. as head loss of end valve becomes larger.

But when the end valve opening is too small, i.e. in the case of \( B_v < 0.08 \) the air in the discharge
pipe is not adequately vented because the valve resistance is too large, therefore the impact velocity of water to the end valve \( V_f \) becomes smaller and maximum pressure rise becomes rather low. We found that the critical value of \( B_v \), at which the maximum pressure rise becomes low as mentioned above, depends on the valve setting. Namely the air at the discharge end was vented with ease when valve was set to close to the upward movement of valve disc. On the contrary air venting was difficult when the valve positioning was in the downward movement of the valve disc. After finding this phenomenon, the tests were carried out under the former valve positioning.

Fig. 7 to Fig. 10 are the oscillograms showing the

\[ \text{Fig. 6 Maximum pressure rise against head loss coefficient } B_v \]

\[ \begin{align*}
(a) & \quad B_{PL}=1.386 \\
& \quad V_f=3.46 \text{ m/sec} \\
(b) & \quad B_{PL}=0.55 \\
& \quad V_f=2.05 \text{ m/sec} \\
(c) & \quad B_{PL}=0.685 \\
& \quad V_f=2.48 \text{ m/sec} \\
(d) & \quad B_{PL}=0.42 \\
& \quad V_f=1.64 \text{ m/sec} \\
\end{align*} \]

\[ \text{Fig. 7 Transient pressure under change in opening of regulating valve provided that } B_v=0.64 \text{ (end valve opening)} \]
maximum pressure rises under several $V_f$ values. Experiments were carried out on the four kinds of end valve opening, and Fig. 7 to Fig. 10 show pressure transients at $B_v=0.64$, $B_v=1.3$, $B_v=0.39$ and $B_v=0.25$ respectively. Fig. 11 shows the relation between maximum pressure rise $H_{max}$ and $V_f$, then it is understood that maximum pressure is higher as $B_v$ becomes smaller or $V_f$ larger.

Practically, the impact velocity to the end valve is decided from the intersecting point of the pump head capacity curve and the resistance curve of discharge line (excluding the end valve). Fig. 12 shows the measured impact velocity $V_f$ against the same velocity obtained from the above-mentioned method. It is supposed from this test result that the calculation is correct practically.

5. Consideration on the maximum pressure rise

Maximum pressure rise due to water hammer in the pump discharge line equipped with semi-open end valve is calculated graphically as shown in Fig. 13 (1). In the first place, the head capacity curve $B$ in front of the end valve, namely the head capacity curve which is calculated by the reduction of pipe loss from the actual pump head capacity curve, is shown in the graph. Then the actual head line $h_a$ measured from suction level to end valve is drawn and the intersecting point of $B$ and $h_a$ is decided as $P$. Finally an inclined line is drawn from point $P$.

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with the gradient \( a/g \) (in this apparatus \( a/g = 1.310/9.8 = 0.138 \)), and the intersecting point \( Q \) of this line with the resistance curve of end valve \( C \) gives the maximum pressure rise. Fig. 14 shows the ratio \( k \) of measured maximum pressure rise \( H_{\text{max}} \) to the calculated value \( H_{\text{max}} \). From Fig. 14, it is known that \( k < 1 \) when \( B_v < 0.8 \) and \( k \) value becomes smaller as \( B_v \) smaller.

We believe that \( k \) is smaller than 1 when \( B \) is small, because of smaller velocity of pressure propagation. We checked the velocity of pressure propagation from the time lag of pressure rise at the two pick-up points. These are set at two separate points of 8 m and 16 m from the end valve. From this test, we found the velocity of the pressure propagation was 400 to 600 m/sec when the end valve opening was small. This is far smaller than the calculated value 1310 m/sec.

In such case the air shall be rolled in front of flow and turn into bubbles, and the residual air shall cushion the pressure rise. It is known that the velocity of the pressure propagation in the water involving air bubbles becomes far smaller \( ^1 \). Therefore the reason for the smaller a value and \( k \) value at the smaller end valve opening is understood easily.

6. Conclusion

As mentioned above, we investigated and obtained numerical data on the pressure transition of the water-hammer at the pump start, with a semi-open

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Fig. 9 Transient pressure under change in opening of regulating valve provided that \( B_v = 0.39 \) (end valve opening)
valve at the end of discharge line. Based on the data collected we are able to estimate and predict the maximum pressure rise that will occur in similar pipe line systems. Namely:

(a) When the impact velocity to the end valve is constant, maximum pressure rise due to waterhammer is larger as the end valve opening becomes smaller.

(b) When the opening of the end valve is constant, the maximum pressure rise is higher as the impact velocity becomes larger.

(c) Starting velocity of flow at the starting of pump (impact velocity) coincides practically with the theoretical velocity calculated from the intersecting point of the pump head capacity curve and pipe

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Fig. 10 Transient pressure under change in opening of regulating valve provided that $B_L=0.25$ (end valve opening)
Fig. 11 Relation between maximum pressure rise \( H_{\text{max}} \) and \( V_f \)

Fig. 12 Relation between \( V \) and \( V_f \)

Fig. 13 Graphical solution

Fig. 14 Comparison between graphical solution and test results

actual pressure rise and the pressure rise obtained by the graphical method. In this investigation, actual pressure rise was smaller than calculated pressure rise when \( Br < 0.8 \) and the difference becomes larger as \( Br \) smaller.

(d) We obtained the relation between the resistance curve.

References

(1) For example, R.W. Angus: Water-hammer in pipes, including those supplied by centrifugal pumps: Graphical treatment(1938), Bulletin 152, University of Toronto Press.