A Study to Avoid the Dangers of High Speed Liquid Jets
(Perpendicular Jets from 5mm-long Small Circular Holes)

By Hiroshi KITAKURA** and Shigeru TSUJI***

An experimental research has been carried on to study the danger of a high-speed jet discharged from a hole in hydraulic equipment of very high pressure to the people working around the equipment. In this paper, the results of the research both on the time taken for a tested jet to inflict a piercing wound on the raw skin of an ox, when it was discharged from a hole of 5mm in length and hit the skin perpendicularly, and on the process of growth of a damage to a resin board of 1cm in thickness caused by the jet, such as when the hole have a relatively small diameter and the pressure is relatively low the place where the tested jet pierces through the skin most quickly is distant a little from the hole, are reported.

Key Words: Fluid Power System, Liquid Jet, Jet Cutting, Safety Engineering, Biological Engineering, Hydraulic Fluid, Danger, Breakdown, Ox, Skin

1. Introduction

Nowadays automatic machines such as a transfer machine are used in many factories. Hydraulic equipment is used in many of the machines. Pressure of hydraulic fluid in the equipment has been required to be higher because hydraulic loss of power in the equipment under higher pressure is usually lower than under lower pressure, so that recently it has reached 400MPa or more in some cases. Because of such a rise in the pressure the danger of a breakdown or mis-operation of the equipment has grown. Thus such an unfortunate accident as a high-speed liquid jet suddenly discharged from a small hole piercing a wall of the hydraulic equipment in its breakdown or mis-operation and hitting the people working around the equipment is increasingly real.

By the way, in case of ocean development, a submarine sometimes dives into the sea of 1000m in depth or more for a scientific research or a survey of natural resources. In this case, people in the submarine have to work next to a water of 10MPa or more in pressure with a sheet of wall between them, so that an accident like that around the hydraulic equipment is possible to happen when the wall is broken even a little.

The authors do not know of any past research to study the danger of an attack of a high speed liquid jet discharged from a hole in hydraulic equipment in the event of its breakdown or mis-operation, so they have been only able to infer the degree of the danger from the results of past research on jet cutting of metal, mineral or something else.[1] to [4] Therefore the danger of the high-speed liquid jet in a breakdown or mis-operation of the equipment to a human body has to be made clear quantitatively and the way to avoid the danger has to be sought.

In this research, the high speed jet of a petroleum-based hydraulic fluid of very high pressure which was suddenly discharged from a hole in hydraulic equipment was tested as the first step to make the danger of the liquid jet clear and to find out the way to avoid it, and effects of the diameter of the hole, the pressure in the upper reaches of the hole or the distance from the hole on a piercing wound on the raw skin of an ox when the jet discharged from a small circular hole, which is one of the most typical jets, hits the skin perpendicularly were made clear experimentally. All the experiments reported in this paper were done using the raw skin of an ox as a test piece to measure the degree of danger of a tested jet or a transparent resin board of polyvinyl chloride of 1cm in thickness as an example of test pieces of various kinds of protectors against the jet because the board is relatively easy to obtain and good for maintenance of the hydraulic equipment.

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** Research Associate, Tokyo Kogyo Daigaku (Tokyo Institute of Technology), Naguro-ku, Tokyo.
*** Professor Emeritus, Tokyo Kogyo Daigaku.
2. Symbols

\( \delta \) : Thickness of a test piece (unit : mm).

\( d \) : Diameter of a hole a tested jet is discharged from.

\( L \) : Depth of a damage to the test piece.

\( m \) : Mass drop in a test piece due to attack of a tested jet.

\( P \) : Absolute pressure in upper reaches of the hole a tested jet is discharged from.

\( P_r \) : Gauge pressure of \( P \).

\( Q \) : Flow rate of hydraulic fluid per unit cross sectional area of a tested jet.

\( Q_m/Q_{min} \) : Distance from the central axis of a tested jet.

\( S \) : Area of the upper surface of a test piece destroyed by a tested jet.

\( T \) : Time a tested jet takes to pass through the test piece.

\( T_m/T_b \) : Duration of a tested jet.

\( x \) : Distance between outer edge of the hole a tested jet discharged from and the upper surface of the test piece.

\( \rho \) : Density of hydraulic fluid.

3. Experimental Apparatus

Fig. 1 is a schematic diagram of a hydraulic circuit used in this research. For the jet to hit the test piece, the hydraulic fluid was made to flow from the main reservoir \( H \) to the part the jet is discharged from, \( I \), which was set in the top of the measuring part covered with transparent boards, \( G \), through the reservoir type filter \( A \), the line type filter \( C \), the electro-magnetic directional control valve \( E \) and the line type filter \( F \) by the supercharging pump \( B \) and the main pump \( D \), and then it was discharged vertically and downward from the hole in the part, \( I \). After that, the fluid was temporarily stored in the second reservoir \( J \) and returned to the main reservoir \( H \), through the reservoir type filter \( K \), the line type filter \( L \), and the oil cooler \( M \) by the pump \( H \). Before or after the jet was discharged from the hole \( I \), the fluid from the pump \( D \) was returned directly from the valve \( E \) to the main reservoir \( H \) through the variable throttling valve \( P \).

The main pump \( D \) was a variable-displacement axial plunger pump of tilting cylinder block type and directly driven by an alternating-current electric motor of 24\( \text{rpm} \) in revolution speed. The maximum displacement of it was 69cm\(^3\), the maximum delivery pressure of it was 261MPa and the number of plungers in it was 7. The suction pressure of the pump \( D \), which was just the same as the delivery pressure of the pump \( B \) of external gear type, was kept at about 0.8MPa using the relief valve \( Q \) and some other valves. The pressure in the part \( I \) during the jet being discharged from the hole, \( P_r \), was adjusted by an adjustment of the set pressure of the relief valve \( E \) and tilting angle of the pump \( D \) using the pressure gauge at the part, \( I \).

In this research, as the first step in a series of studies using holes of various shapes from which the jets are discharged, an experiment was done using a small circular hole of 5mm in length looking like a pressure tap on the wall of hydraulic equipment. The diameter of the hole was set from 0.5mm to 2mm.

Structure of the part the jet is discharged from used in this research is shown in Fig. 2. Hydraulic fluid used in this research was a petroleum-based hydraulic fluid of VG10 and which was kept at 308K to 318K in temperature.

4. Structure of the Jet Tested in This Research

A photograph of the jet tested in this research is shown in Fig. 3. In the case that the diameter \( d \) is relatively small and the pressure \( P \) is relatively
low, the jet may be divided into the following 3 regions as shown in this photograph. The regions are:

* Region 1 where the jet is a continuous flow and looks like a transparent slender rod, the cross sectional area of which is constant anywhere;
* Region 2, transient region, where the cross sectional area of the jet starts to increase and the jet gradually changes from the continuous flow to a droplet flow;
* Region 3 where the jet is a fully-developed droplet flow anywhere in any cross sectional area;

with the axis of the jet from the hole the jet is discharged from to the lower reaches.

Fig. 4 shows spatial distributions of flow rates of hydraulic fluid in the jets measured by the means shown in one of the past reports of the authors[6]. Vertical axes in these figures indicate the dimensionless values

\[ \hat{Q} = \frac{Q}{\sqrt{ \rho P_{10}^2} \bar{r}} \]

of the flow rate of hydraulic fluid per unit cross-sectional area of the jets, \( \bar{Q} \), and horizontal axes in the figures indicate the distances from the central axes of the jets, \( \bar{r} \).

5. The Case that a Jet Hits the Raw Skin of an Ox

In this section the results of an experimental study on the piercing wound of the raw skin of an ox hit by the jet are described.

Fig. 3 A photograph of a tested jet. (\( d=0.5 \text{mm}, P=15 \text{MPa} \))

Fig. 4 Measurements of the spatial distributions of flow rates of hydraulic fluid in the tested jets. (\( d=2 \text{mm} \))
5.1 Method of experiment

All the experiments described in this section were done as follows. A piece of the skin of a grown-up ox of 2mm to 4mm in thickness from which the fat under the skin and the hair on it were removed was used for measurement. Past literature[5] states that the tensile strength of an abdominal skin of an ox is about 7N/mm and that of a human skin is from 30N/mm to 14N/mm depending on the part of his body. All the measured pieces had a square shape of 8cm x 8cm and were set in the part shown in Fig. 5 during the experiments.

The time when the pressure \( P \) reached its set value to the time when the jet just passed through the piece, \( T \), which is considered the length of time the jet needs to pass through it in this research, was measured in the experiment. The discharging of the jet did not take more than 5min even if the jet could not pass through the piece.

The experiments as mentioned above were done repeatedly at various distances between the hole and the piece, \( x \), the diameter of the hole, \( d \), or the pressure in upper reaches of the hole, \( P \).

By the way, the reasons why the authors chose the length of time the jet needs to pass through the piece, \( T \), for measurement are not only that the characteristics of the skin of an ox is similar to that of the human skin but also that the length of time \( T \) is considered more important for human safety and measured more accurately than the depth of a wound or the mass drop in the piece which are usually used in research on jet cutting.

5.2 Experimental results and discussions

Fig. 6 shows photographs of measuring pieces which were taken just after the jets passed through them.

Fig. 7 to Fig. 9 show results of the experimental studies on the relation between the distance \( x \) from the hole the jet was discharged from to the upper surface of the skin of an ox, and the length of time \( T \) the jet needs to pass through the skin. In these figures, the piercing time \( T = \frac{T_0}{6} \) which means the length of time the jet needs to pass through the measuring piece of 1mm in thickness, which was chosen because the thickness of the human skin is roughly equal to 1mm, was applied to the vertical axis to reduce the effect of the thickness of the test piece. The distributions of the measurements ranged over the values as shown in Fig. 10 which is for the case of \( P = 10 \) MPa and \( d = 0.5 \) mm as examples of them.

![Fig. 5 The part for fixing a measuring piece.](image)

\[ x = 55 \text{ mm} \]
\[ T = 0.8 \text{ s} \]

\[ x = 115 \text{ mm} \]
\[ T = 1.0 \text{ s} \]

\[ x = 400 \text{ mm} \]
\[ T = 1.7 \text{ s} \]

\[ x = 705 \text{ mm} \]
\[ T = 6.0 \text{ s} \]

Fig. 6 The photographs of measuring pieces of the skins of oxen which were taken just after tested jets passed through them.

(\( d = 2 \) mm, \( P = 15 \) MPa)
The following conclusions may be drawn from the above experimental results. In case of a high-speed liquid jet such as the tested jet discharged from a bigger hole the higher the pressure in the upper reaches of it, the higher the pressure \( P \), the larger the diameter \( d \) or the shorter the distance between the skin and the hole, the more quickly the jet can pass through the human skin the toughness of which is similar to that of the measuring piece. In case of a high-speed liquid jet such as the tested jet discharged from a smaller hole the lower the pressure in the upper reaches of it, the jet may pass through the human skin the more quickly when the skin is at a smaller but finite distance from the hole than when the skin is at the other distances; the distance \( r \) was around \( r=10 \text{cm} \) in this study. When the pressure \( P \) is around \( P=20 \text{MPa} \), the jet discharged from the hole of \( d=2 \text{mm} \) in diameter piercing a wall of \( 5 \text{mm} \) in thickness, such as the wall of carbon-steel pipe of \#80 and of \( 40 \text{mm} \) in nominal diameter for a pressurized pipeline meeting the standard JIS G 3456, may pass through the human skin within 10s even if the skin is at \( 1 \text{m} \) distance from the hole, and the jet discharged from the hole of \( d=0.5 \text{mm} \) in diameter may pass through the human skin within 10s when the skin is at about 10cm distance from the hole. When the pressure \( P \) is \( 5 \text{MPa} \) or lower, the jet of hydraulic fluid discharged from the hole of \( 2 \text{mm} \) round in diameter onto the wall of \( 5 \text{mm} \) in thickness may take roughly 10s or more to pass through the human skin the toughness of which is similar to that of the measuring piece.

The fact that the jet tested in this research passed through the measuring piece in the region 2 mentioned in Section 4, in which the jet changes from continuous flow to droplet flow, or around it most quickly was confirmed by watching. The reason is thought to be that in the region 2 or around it the effects of the repetition of droplet hitting and the effects of the total pressure of the jet are superposed on each other.

Fig. 7 The lengths of time tested jets took to pass through the skins of oxen as measuring pieces. No. 1.

Fig. 8 The lengths of time tested jets took to pass through the skins of oxen as measuring pieces. No. 2.

Fig. 9 The lengths of time tested jets took to pass through the skin of oxen as measuring pieces. No. 3.

Fig. 10 An example of distribution of the piercing times \( T \) measured.
6. Effectiveness of a Transparent Resin Board of Polyvinyl Chloride as a Protector against the Jet

From the studies mentioned above, a very big danger was confirmed to exist in the case that hydraulic equipment of very high pressure is broken down or mis-operated and a high-speed jet discharged from it hits a human body. The authors studied the effectiveness of the protector set between the hydraulic equipment and a worker around it and to develop a protector available when the hydraulic equipment of very high pressure has to be used.

As the first step to the studies on the effectiveness of protectors of various kinds, the effectiveness of a transparent resin board of polyvinyl chloride of 1cm in thickness, which is relatively easy to produce and process and convenient for the maintenance of the hydraulic equipment because of its transparency, is to be studied. And how the jet is passes through a test piece, which could not be studied with the skin of an ox, is to be made clear using the board.

6.1 Method of experiment

This experiment was done as follows. A test piece of 5cm×5cm of square shape was cut out from a transparent resin board of polyvinyl chloride of 1cm in thickness. The test piece was set at a plane where the central axis of the jet passed through approximately the center of the upper surface of the test piece perpendicularly using the part for fixing a test piece shown in Fig. 11. The mass drop in the test piece, m, and the change of its shape in the experiment were measured in various cases of distance between the hole the jet is discharged from and the test piece, s; the diameter of the hole, d; the pressure in the upper reaches of the hole, p; and the length of time the jet was kept discharging, t.

6.2 Experimental results and discussions

Fig. 12 shows results of the experimental studies on the relation between the mass drop m and the distance s in case that the length of time the jet was kept discharged, t, was t=1min, and Fig. 13 shows results of the experimental studies on the relation between the depth of the damage done by an attack of the jet in the upper surface of a testing piece, L, and the distance s in the same case. From these results, a big damage may be confirmed to be made in the test piece around a place where the jet passes through the skin of an ox most quickly in case that the diameter of the hole, d, is relatively small and the pressure p is relatively low. Fig. 14 shows results of the experimental studies on the relation between the area of upper surface of a test piece destroyed by an attack of the jet, S, and the distance s in the same case. Peaks such as those in the rela-
tions mentioned above were not recognized in this relation.

Fig. 15 and Fig. 16 show results of the experimental studies on the relation between the length of time the jet was kept discharged, \( t \), and the mass drop in the test piece in this period, \( m \). From these figures, the rate of the mass drop due to the tested jet \( m \) is confirmed to increase with an increasing pressure \( P \) monotonously and to reach a peak near \( r=10\text{cm} \) with the change in the distance \( r \).

Fig. 17 and Fig. 18 show results of the experimental studies on the relation between the length of time, \( t \), and the depth of a damage to the test piece done by an attack of the jet, \( L \), in this period. From Fig. 17, the rate of increase of the depth of the damage, \( dL/dt \), may be confirmed to increase with an increasing pressure \( P \) monotonously. From Fig. 18, the rate of increase may be confirmed to be nearly constant under changing of the distance \( r \) in case that the distance \( r \) is relatively small. From Fig. 17 and Fig. 18, the rate may be confirmed to decrease with an elapse of time \( t \) monotonously.

Fig. 19 and Fig. 20 show results of the experimental studies on the relation between the area of upper surface of a test piece destroyed by the jet, \( S \), and the length of time, \( t \). The area \( S \) may be confirmed to reach a constant with an elapse of the time \( t \) asymptotically and quickly.

From the results of these experimental studies mentioned above, a transparent resin board of polyvinyl chloride of 1cm in thickness may be confirmed to be useful as a protector for hydraulic equipment when the pressure in the equipment, \( P \), is kept below 100MPa or the protector is set in a place at sufficient distance, which is related with the pressure \( P \), from the wall of the equipment.

7. Conclusions

In this research, a danger of a high-speed liquid jet discharged from a small circular hole when hydraulic equipment is broken down or mis-operated and the way to avoid the danger were studied experimentally using the raw skin of an ox and a...
transparent resin board of polyvinyl chloride as test pieces. The following are some of the results of this research.

(1) When a high-speed liquid jet such as the tested jet is discharged from a hole, usually the bigger the hole is, the higher the pressure in the upper reaches of it or the shorter the distance between the skin and the hole is, the more quickly the jet can pass through the human skin the toughness of which is similar to that of the test piece.

(2) In case of a high-speed liquid jet such as the tested jet discharged from a smaller hole in the upper reaches of which the pressure is lower, the jet can pass through the human skin the more quickly when the skin is at a small distance from the hole than when the skin is at the other distances.

(3) In case of the tested jet discharged from the hole of 2mm in diameter the pressure in the upper reaches of which is around 20MPa on the wall of 5mm in thickness, the jet can pass through the human skin which is at 1m distance from the hole within 10s. And even when the jet is discharged from the hole of 0.5mm in diameter on the wall, the jet can pass through the human skin which is at 10cm distance from the hole within the same time laps.

(4) In case that the pressure in hydraulic equipment is less than 5MPa, the jet discharged from the hole of 2mm round in diameter may take roughly 10s or more to pass through the human skin.

(5) Transparent resin board of polyvinyl chloride of 1cm in thickness may be useful as a protector against a jet from the hydraulic equipment if the board is set at a suitable distance from the equipment depending on the pressure of the jet.

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8. References


Fig. 19 Relation between the area of upper surface of a test piece destroyed by the jet, S, and the length of time a tested jet was kept discharged, t. No. 1.

Fig. 20 Relation between the area of upper surface of a test piece destroyed by the jet, S, and the period of time a tested jet was kept to be discharged, t. No. 2.