PERFORATOIN OF OIL WELL TUBING WITH MULTI-NOZZLE SUBMERGED ABRASIVE WATERJETS

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1. INTRODUCTION

In recent years, natural gas attracts much attention as a clean energy source because the discharge of CO_2 by the combustion of natural gas is less than that of oil and coal. In Japan, natural gas is produced as petroleum gas in Hokkaido, Akita, Niigata and Fukushima, and natural gas dissolved in water is produced in the area from Boso Peninsula to Tokyo Bay. If production of natural gas from a production well lasts for a long term, it becomes necessary to take measures against decrease of production. Therefore, improvement of productivity of existing wells is required by additional perforation of casing pipes as measures against decrease of volume of production by long usage of production wells. In addition, perforation may also be necessary in cases of workover and well abandonment.

There are methods using shaped explosive charges and coiled tubing for perforation. However, these methods require response to regulation or large equipments. Thus, an easier and simpler perforation system must be considered. Perforation technology with waterjets for polyvinyl chloride casing pipe has been developed and put in practical use. Since pure waterjets cannot perforate steel tubing, study about abrasive waterjets (AWJ) which added abrasives to pure waterjets has been carried out (Shimo (2002) and Nakane (2003)). Thus, it has been shown that AWJ can perforate steel tubing under high ambient pressure up to 7 MPa (Takahashi (2004)). However, in the previous studies the system is a single-nozzle system that can perforate only one hole at once. In practical application, since a lot of holes are required to be perforated quickly, a single-nozzle system is insufficient. For that reason, the development of an AWJ system which can perforate multiple holes at once is required now.

In this study, I designed and developed a multi-nozzle submerged abrasive waterjets system, and clarified the perforation performances of the system. Firstly, I derived empirical formulas from the results of laboratory experiment obtained by Takahashi (2004). Secondly, I confirmed availability of the empirical formulas by field experiments using an actual well. Finally, I developed a multi-nozzle system and carried out laboratory experiments to clarify the perforation performance.

2. DERIVATION OF EMPIRICAL FORMULAS FROM EXPERIMENTAL RESULTS BY SINGLE-NOZZLE SYSTEM AND APPLICATION TO A FIELD

Empirical formulas for a single-nozzle system are derived from the results obtained by laboratory experiments carried out by Takahashi (2004).

2.1 EXPERIMENTAL SYSTEM AND EXPERIMENTAL PROCEDURE

Oil well tubing (API J-55) was used as specimen. Its average thickness was 4.15 mm. Garnet of #60 was mainly used as abrasive. To measure the impinging time required for perforation (t_p), a strain gauge was glued on the outer surface of the specimen, which was opposite to the impinging point of waterjets. The impinging time required for perforation (t_p) is determined by the time of breakage of the strain gauge.

2.2 DERIVATION OF EMPIRICAL FORMULAS

The empirical formula for abrasive mass flow rate (m_A) is obtained as

$$m_A = 0.434\sqrt{p_a + 0.03}\ . \qquad (1)$$

Abrasives mass flow rate (m_A) depends on ambient pressure but does not depend on driving pressure (p).

The empirical formula for mass of abrasives required for perforation (M_p) is obtained as

$$M_p = \frac{11.4 + 11000\sigma^2}{(p - p_a)}\rho_w\ . \qquad (2)$$

Mass of abrasives required for perforation (M_p) is governed mainly by two factors: cavitation number (σ) and differential pressure between the driving pressure (p) and the ambient pressure (p_a). Accordingly, the following formula is obtained as an empirical formula for the impinging time required for perforation (t_p) by dividing Eq. (2) by Eq. (1).

$$t_p = \frac{M_p}{m_A} = \frac{11.4 + 11000\sigma^2}{0.434\sqrt{p_a + 0.03}(p - p_a)}\rho_w\ . \qquad (3)$$

2.3 FIELD EXPERIMENTS

Availability of the empirical formulas described above was confirmed by field experiments. Impinging time was set to sufficiently be long for perforation because there were no methods for detecting when perforation is complete during the experiments. However, it was confirmed that AWJ can perforate casing pipes for an actual well and that empirical formulas are available.

3. DEVELOPMENT OF MULTI-NOZZLE SYSTEM AND ESTIMATION OF ITS PERFORATION PERFORMANCES

A multi-nozzle system was developed based on the empirical formulas obtained in chapter 2 and perforation experiments with the multi-nozzle system were carried out.

3.1 DESIGNING OF MULTI-NOZZLE SYSTEM

The maximum ambient pressure (p_a) for the experiments with a multi-nozzle system is determined to be 3 MPa based on the frequency distribution of the depth of the lower end of casing pipes (inner diameter 103.9 mm, outer diameter 114.3 mm, thickness 5.2 mm) required for perforation. The outer diameter of a nozzle holder is determined to be 93.9 mm because it is necessary that clearance between the nozzle holder and a casing pipe is at least 5 mm. Considering a pressure loss, driving pressure is determined to be 63.7 MPa. Then, number of nozzles is determined based on the design that a multi-nozzle system consists of independent single-nozzle systems. Firstly, the maximum impinging time (t_{max}) is calculated for cases that the number of nozzles is from one to five when the capacity of a tank for abrasives is 7.5 kg that is equal to that for field experiments. Next, the time required to impinge for 60 seconds after perforation (t_p+60) to get sufficient hole diameter is calculated. Fig. 1 shows the relations among ambient pressure (p_a), t_{max} and (t_p+60). The ambient pressure at the intersection point of t_{max} and (t_p+60) in Fig. 1 means the maximum ambient pressure at which AWJ can be impinged for 60 seconds after perforation when the capacity of a tank for abrasives is 7.5 kg. The largest number of nozzles for the ambient pressure at the intersection point to be more than 3 MPa is four when driving pressure (p) is 63.7 MPa (Fig. 1). Therefore, the number of nozzles for a multi-nozzle system is determined to be four in this study. I also consider that a pump for fields is small (driving pressure: 44.3 MPa).

3.2 MULTI-NOZZLE SYSTEM

Fig. 2 shows the multi-nozzle system developed in this study and Fig. 3 shows the schematic diagram of the nozzle holder. High pressure water is supplied to the nozzle holder through high pressure rods. High pressure water line is divided into four directions in the nozzle holder, and waterjets are injected from four waterjets nozzles to inner wall of the specimen. Abrasives are supplied from four individual tanks for abrasives to the nozzle holder through four abrasive supply lines with ball valves and abrasive flow rate control valves. Washer type constant flow rate valves (KEIHIN CO., Ltd, RSSP-10) were used as abrasive flow rate control valves. Refer to Takahashi's graduation thesis (Takahashi (2004)) for details. The combination of waterjets nozzles, abrasive nozzles and abrasive flow rate control valves is unique through whole experiments.

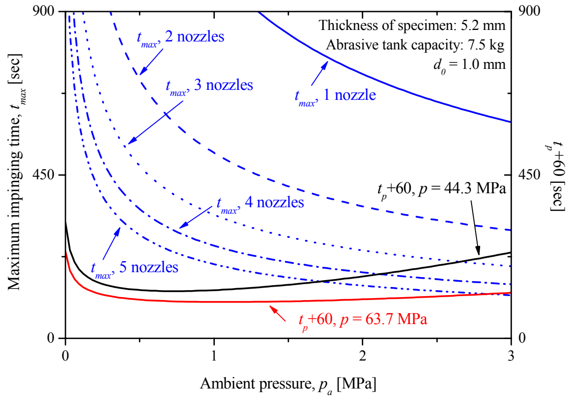


Fig. 1 Effects of ambient pressure (p_a) on mass of abrasives required for perforation (M_p) and impinging time required for perforation (t_p).

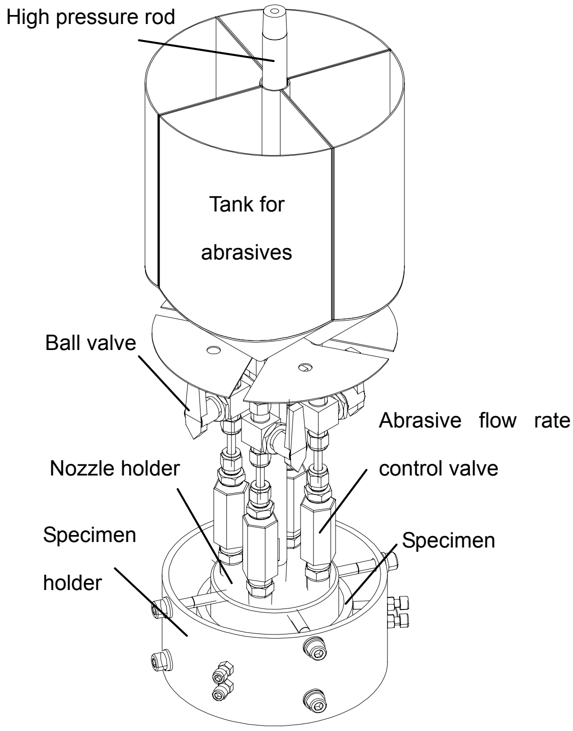


Fig.2 Schematic diagram of multi-nozzle system.

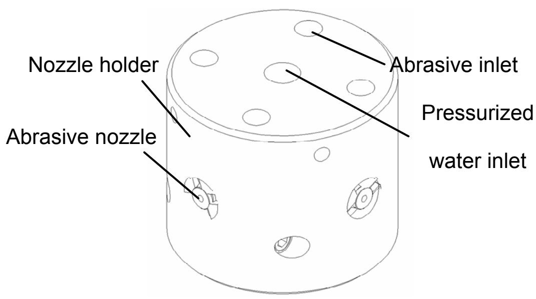


Fig.3 Schematic diagram of nozzle holder.

3.3 EXPERIMENTAL SYSTEM AND EXPERIMENTAL PROCEDURE

Fig. 4 shows the schematic diagram of the experimental system. The experimental system consists of water tank 1, high pressure water pumps 2, 3, a switching valve unit 4, a pressure vessel for perforation test 5, a pressure vessel for cyclone separator 6, high pressure hoses 7, an ambient pressure control valve 8 and a system for measurement. Firstly, high pressure water was supplied to the pressure vessel for cyclone separator 6 through the switching valve unit 4, and ambient pressure was kept constant by the ambient pressure control valve 8. Then, high pressure water was supplied to the multi-nozzle system in the pressure vessel for perforation test 5 by switching flow path, and perforation test started. In this study, strain gauges were glued on the outer surface of the specimen, on the side opposite to the impinging point of waterjets, to measure impinging time required for perforation (t_p).

Table 1 shows experimental conditions mainly used in this study. Because target specimens were not available, specimens that have the same outer diameter as the target specimens but larger thickness than that of the target specimens are used. Average thickness of the specimens was 6.54 mm. Standoff distance (x) used in this study was set to be about 4 mm so that that for target specimens may be 5 mm.

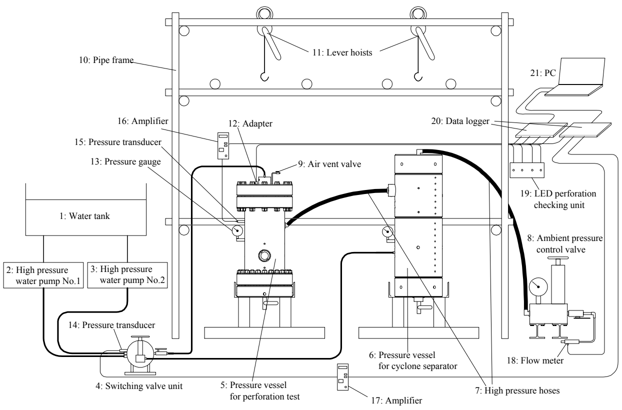


Fig. 4 Schematic diagram of experimental system.

3. EXPERIMENTAL RESULTS

Fig. 5 shows an example of experimental results obtained by the multi-nozzle system developed in this study. This figure shows that the multi-nozzle system can perforate four holes at the same time when driving pressure (p) is 63.7 MPa and ambient pressure (p_a) is 3.0 MPa. When driving pressure (p) was 44.3 MPa, perforation tests were carried out up to 2.0 MPa of ambient pressure (p_a). In case of 2.0 MPa of ambient pressure, only one hole could be perforated. If sufficient amount of abrasives and accordingly sufficient injection time (t) of AWJ are available, the multi-nozzle system can perforate four holes at the same time.

For the multi-nozzle system, empirical formulas for abrasives mass flow rate (m_A), mass of abrasives required for perforation (M_p) and impinging time required for perforation (t_p) are obtained as follows:

$$m_A = 0.37\sqrt{p_a + 0.09}\ , \tag{4}$$

$$M_p = \frac{6.9 + 1730\sigma^{1.05}}{(p - p_a)}\rho_w\ , \tag{5}$$

$$t_p = \frac{M_p}{m_A} = \frac{6.9 + 1730\sigma^{1.05}}{0.37\sqrt{p_a + 0.09}(p - p_a)}\rho_w\ . \tag{6}$$

Based on these formulas, the perforation performance of the multi-nozzle system was estimated. Fig. 6 shows the relation between impinging time after perforation ($t - t_p$) and hole diameter (d_p), and Fig. 7 shows the effects of ambient pressure (p_a) on hole diameter at 60 seconds after perforation ($d_{p\text{-}60}$). As shown in Fig. 6, the hole diameter increases and the increasing rate of the hole diameter decreases as the impinging time increases. Thus, the hole diameter may not keep on increasing, but may converge. As shown in Fig. 7, the hole diameter increases and the increasing rate of the hole diameter decreases as the ambient pressure increases up to 3.0 MPa. The hole diameter can be assumed to finally converge or decrease if the ambient pressure increases further. The following empirical formula for the relation between ambient pressure (p_a) and hole diameter at 60 seconds after perforation ($d_{p\text{-}60}$) is obtained:

$$d_{p-60} = 4.49 p_a^{0.18}\ . \tag{7}$$

The results shown in Fig. 6 are normalized by the results shown in Fig. 7. As a result, the relation between the normalized hole diameter ($d_p' = d_p / (4.49p_a^{0.18})$) and the impinging time after perforation is obtained, which is shown in Fig. 8. As shown in Fig. 8, the normalized hole diameter lie on one straight line up to about 60 seconds. Therefore, the empirical formula for the normalized hole diameter (d_p') is obtained for impinging time after perforation of less than 65 seconds.

$$d_p' = 0.22(t - t_p)^{0.37}\ . \tag{8}$$

Accordingly, the empirical formula for the hole diameter is obtained from both Eq. (7) and Eq. (8).

$$d_p = 0.22(t - t_p)^{0.37} \cdot 4.49 p_a^{0.18}\ . \tag{9}$$

As shown in Eq. (9), the hole diameter (d_p) does not depend on driving pressure (p), but is governed by the impinging time after perforation ($t - t_p$) and ambient pressure (p_a). It is noted that Eq. (9) is available up to about 65 seconds of impinging time after perforation.

4. CONCLUSIONS

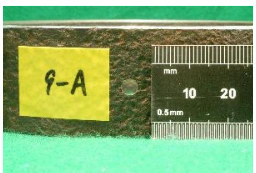
In this study, I developed a multi-nozzle system based on empirical formulas for a single-nozzle system. Main results obtained in this study are summarized as follows:

1) The multi-nozzle system with four waterjets nozzles and four abrasive nozzles can perforate four holes at the same time for ambient pressure of less than 3 MPa.
2) The empirical formulas for abrasives mass flow rate (m_A), mass of abrasives required for perforation (M_p) and impinging time required for perforation (t_p) for both the single-nozzle system and multi-nozzle system are established.
3) The empirical formula for hole diameter (d_p) was obtained.
4) The hole diameter increases and the increasing rate of the hole diameter decreases with the impinging time of AWJ.
5) The hole diameter increases and the increasing rate of the hole diameter decreases as the ambient pressure increases up to 3.0 MPa.

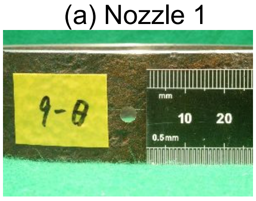
Table 1 Experimental conditions.

Water jet nozzle diameter, d_o [mm]	1.0	
Driving pressure, p [MPa]	44.3	63.7
Ambient pressure, p_a [MPa]	0.2, 0.5, 1.0, 2.0	0.2, 0.3, 0.5, 1.0, 2.0, 3.0
Standoff distance, x [MPa]	3.4 ~ 4.5	3.4 ~ 4.5
Abrasive nozzle diameter, d_F [mm]	3	
Abrasive nozzle length, l_F [mm]	12	
Abrasive	Garnet # 60	
Nominal volume flow rate of flow washer, f_w [l/min]	5.0	

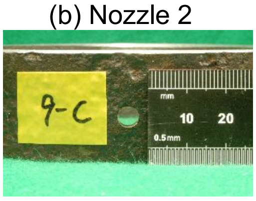
(a) Nozzle 1



(b) Nozzle 2



(c) Nozzle 3



(d) Nozzle 4

Fig. 5 Photos of perforated specimen (p = 68.7 MPa, p_a = 3.0 MPa, t = 157 sec).

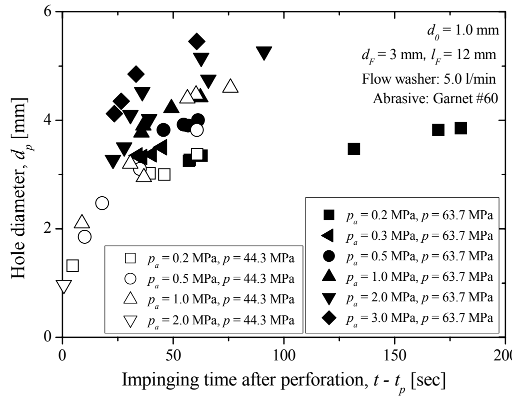


Fig. 6 Relation between impinging time after perforation ($t - t_p$) and hole diameter (d_p).

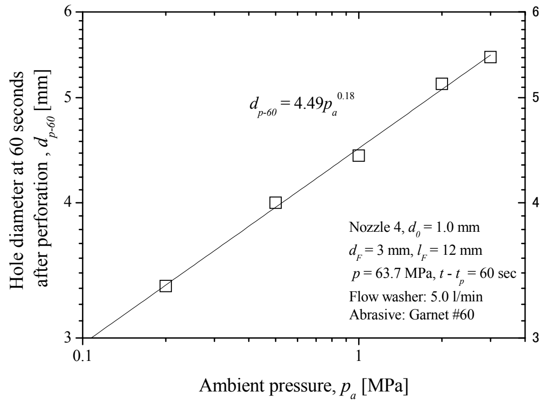


Fig. 7 Effect of ambient pressure (p_a) on hole diameter at 60 seconds after perforation ($d_{p\text{-}60}$).

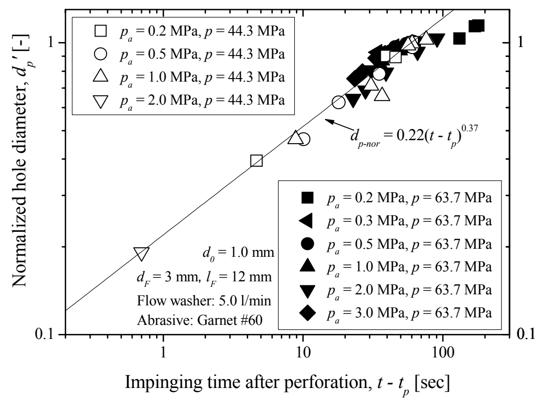


Fig. 8 Relation between impinging time after perforation ($t - t_p$) and normalized hole diameter (d_p').

REFERENCES

[1] Shimo, 2002, Fundamental investigation about perforation of steel tubing with submerged abrasive waterjets, Tohoku Univ. Graduation Thesis.

[2] Nakane, 2003, Fundamental investigation about perforation of steel tubing with submerged abrasive waterjets under high pressure water, Tohoku Univ. Graduation Thesis.

[3] Takahashi, 2004, Development of submerged abrasive waterjets system for perforation of oil well tubing, Tohoku Univ. Graduation Thesis.