Self-excited Pressure Vibration in the Low-Pressure Pipeline
Using an Automatic Pressure-reducing Valve (I)
-Growth mechanism of self-excited vibrations in the case of installing a pressure-reducing valve at the middle of the pipeline-

Kazuma Akiyoshi¹, Yuki Suzuki², Hideya Ito³ and Hitone Inagaki⁴

Abstract: There is a case where a self-excited pressure variation is generated in low-pressure pipeline systems using an automatic pressure-reducing valve. For example, the pressure acting on the tube and valve is higher than the expected pressure and results in damage to the equipment. This study aims to explain the upstream and downstream pressure variations of the valve by carrying out pressure measurements in an actual pipe, in order to identify the mechanism of the self-excited variations and take effective countermeasures. For a reducing valve set up in the middle of the pipeline, the results indicated that the pressure variations that occur soon after opening the valve propagate upstream and downstream without attenuation, maintaining a constant amplitude, and generate continuing pressure variations that resemble self-excited oscillations. In addition, numerical simulations based on the wave model are conducted to evaluate the relationship between the response of an automatic pressure-reducing valve and the hydraulic transient phenomena in a pipeline system. If the pressure-reducing valve is adjusted for high-sensitivity, pressure variation due to external disturbances in the terminal region (downstream of the valve) may increase because of the period of pressure oscillation in the conduit of the upstream and downstream parts of a control valve.

Keywords: Automatic pressure-reducing valve; Self-excited pressure; Pressure variation; Wave model; Period of pressure oscillation

1 Introduction
In gravity-flow pipeline systems used in farm irrigation districts, the size of the facilities has been minimized by distributing designed pressures optimally while ensuring necessary pressures to users. In the actual channel design, the design considers vertical alignment of descending slope in which the pressure on duct lines is higher toward the downstream side, because of the terrain condition. PVC (polyvinyl chloride) pipes are often used in residential areas, from downstream to the end of the pipeline, where the pressure is high. PVC pipes are cost-effective, but the compressive strength is less than that of ductile iron and steel, despite having the same diameter.

Hence, pipeline accidents, such as rupture of pipes and valves, often occur. To prevent the accidents, the low-pressure pipeline system was developed, which can reduce the pressure in the upstream side (primary side) and control the pressure in the downstream side (secondary side) constantly by using an automatic pressure-reducing valve, for areas where installing a semi-closed system using a pressure-reducing water tank is difficult.

Originally, conventional automatic pressure-reducing valves were installed in waterworks, and the objective was to reduce the pressure during water transportation. Hence, the shutoff function for the required hydrostatic pressure in farm irrigation fell short. Consequently, the pressure-reducing valves showed response lags for changes in the downstream pressure at all times. It caused gradual pressure oscillations in the pipeline (Cho et al., 1987; 1988).

Saito and Inagaki (1996; 1997) solved the issues of the actuating mechanism in conventional pressure-reducing valves via a field test and suggested the low-pressure system, wherein airbags and safety valves were installed to avoid the pressure oscillation.

Moreover, Inagaki and Kunitake (1996) and Inagaki et al. (1998) improved the actuating mechanism of conventional pressure-reducing valves and developed the automatic pressure-reducing valves, which force the pressure from upstream and downstream to the main valve pistons by switching the pilot valves. Such improved pressure-reducing valves respond instantaneously and appropriately to downstream pressure variations. Hence, they show advanced controlled performances for the pressure on the downstream side (secondary side), and necessary water-stop function is ensured. In addition, the verification of stability in the case where multiple pressure-reducing valves are placed in series and methods to suppress water hammer pressure using safety valves were studied experimentally, and some precautionary countermeasures are proposed (Inagaki et al., 1999; 2010, Takahashi et al., 2009a; 2009b; 2010).

With the increase in the application of low-pressure pipelines, the problem of self-excited vibration of valves has...
surfaced. This vibration was not predicted in the design stage, and high-pressure oscillations exceeding the designed pressure are developed upstream of the valves. Moreover, the variations do not decay. Hence, fractures occur in the low-pressure systems when pressure-reducing valves are used, which are responsible for the pipeline accidents. Therefore, some effective countermeasures need to be established.

Hence, as described above, several problems that confuse on-site engineers occur in the low-pressure systems when pressure-reducing valves are used, which are responsible for the pipeline accidents. Therefore, some effective countermeasures need to be established.

2 Field measurement example of self-excited pressure vibration

2.1 Outline of the pipeline

The authors investigated an example of a large pressure variation continuing for a long time, which was linked with an opening and shutting operation of division works in the low-pressure system. In this system, improved pressure-reducing valves and direct acting constant flow valves are used, which are shown in Figure 1 (Inagaki et al., 2007).

The field test was conducted in a gravity-flow pipeline, which obtains water from a water reservoir, and the total length of the pipeline is approximately 1.7 km. It diverges to branch lines 1 and 2 at distances of 1.1 km and 1.3 km from the reservoir, respectively. The high and low water levels in the reservoir are 170.6 m (HWL) and 161.6 m (LWL), respectively, and the normal management water level is 167.4 m (NWL). In addition, the test adopts a single-stage type decompression method, which reduces the static water level by approximately 28 m from NWL 167.4 m via the automatic pressure-reducing valve and decreases the control water level on the downstream side of the pressure-reducing valve to WL 139.0 m.

2.2 Results of pressure vibration measurement

The field measurement data were collected for 9 h in total in four days while changing the conditions of the pressure-reducing valve and division works. An operation, which fully opens the end valve S1 on the branch line 1 and activates the direct acting constant flow valve Q1, was carried out after the flow of water stops. Figure 2 shows the pressure in the primary and secondary sides of the pressure-reducing valve and that of the upstream side of the direct acting constant flow valve Q1.

2.3 Probability of self-excited pressure vibration

The result of the field test shows that the pipeline has no vibrational inputs from outside, and the pressure oscillation occurs because of mere initial agitations arising from water, which starts flowing to the pipeline. This indicates that the pipeline has mechanisms and properties that convert the input flow into a vibrational force (vibration phenomenon). Furthermore, this phenomenon appears to have a feature of self-excited vibrations, because the pressure oscillation continues once it is initiated.

Therefore, it is appropriate to estimate that the self-excited pressure vibration occurred.

Figure 1: Pressure altitude vertical section of the pipeline
2.4 Criteria of self-excited pressure vibration

Minute pressure variation (agitation) in the secondary side of the pressure-reducing valve can amplify and continue the pressure oscillation in the primary side of the valve. Hence, the possible existence of the source of the self-excited vibration in the pipeline should be considered, rather than response conditions of the pressure-reducing valve itself.

The occurrences of the self-excited vibration derived from the pipeline or the controlled equipment such as valves are deduced when the following vibration phenomena occur.

1. The pressure on the secondary side of the pressure-reducing valve is controlled; however, the pressure oscillation in the primary side develops or continues and shows no signs of decay.
2. The pressure variation in the primary side of the pressure-reducing valve is larger than that of the secondary side.
3. No striking suppressing effects are obtained, even though the response sensitivity of the pressure-reducing valve is adjusted.
4. The pressure oscillation occurs only for a specific pressure-reducing valve.
5. Equipment that may produce agitations is connected at the end of the pipeline.

From the viewpoint that the causes of the self-excited pressure oscillation exist in the pipeline, the authors analyzed a growth mechanism of the self-excited vibrations based on the field measurement data. Consequently, the analysis strongly suggests that the occurrence of the self-excited pressure oscillation is because of the installation positions of the pressure-reducing valves and the occurrence of agitations in the rear side of the pipeline. The results are presented in section 3 to 6.

3 Water hammer due to pressure-reducing valve

3.1 Fundamental equation of water hammer

Considering an unsteady phenomenon in the pipeline that has a considerable change in water pressure, such as the presence of water hammer, Eq. (1) is the continuity equation, and Eq. (2) is the equation of motion when the friction loss and the pipe slope terms are omitted.

\[
\frac{\partial v}{\partial t} + \frac{v^2}{g} \frac{\partial v}{\partial x} = 0 
\]  
\[
\frac{\partial v}{\partial t} + g \frac{\partial y}{\partial x} = 0
\]

where \( x \) is the distance from a reservoir, \( t \) is the time, \( g \) is gravitational acceleration, \( y \) is the piezometric head in the pipe, \( v \) is the flow velocity, and \( c \) is the propagation speed of pressure.

By eliminating \( v \) from Eq. (1) and Eq. (2), Eq. (3) is obtained, which relates to propagation of the piezometric head \( y \). By eliminating \( y \), Eq. (4) is obtained as the one-dimensional wave equation, which considers \( v \).

\[
\frac{\partial^2 y}{\partial t^2} - c^2 \frac{\partial^2 y}{\partial x^2} = 0
\]
\[
\frac{\partial^2 v}{\partial t^2} - c^2 \frac{\partial^2 v}{\partial x^2} = 0
\]

Eq. (3) and Eq. (4) are the general solution of Eq. (5) and Eq. (6).

\[
y - y_0 = F \left( t + \frac{x}{c} \right) + f \left( t - \frac{x}{c} \right) 
\]
\[
v - v_0 = -\frac{g}{c} \left\{ F \left( t + \frac{x}{c} \right) - f \left( t - \frac{x}{c} \right) \right\}
\]

where \( y_0 \) is the piezometric head in the pipe when the time \( t=0 \) and the distance \( x=0 \), and \( v_0 \) is the flow velocity when the time \( t=0 \) and the distance \( x=0 \).

\( F \left( t + x/c \right) \) indicates an advancing wave, which occurs due to the shutting operation of the end valve of the pipeline, proceeding toward the negative direction of \( x \) (toward the upstream reservoir) with a velocity \( c \). \( f \left( t - x/c \right) \) indicates a reflective wave, which occurs when a direct wave reflects at the starting point of the pipeline (or on the pressure-reducing valve) and proceeds toward the positive direction of \( x \) (toward the end valve) with a velocity \( c \).

3.2 Propagation of water hammer wave occurred in the end of low-pressure system

This study considered the low-pressure system, which constantly controls the pressure in the downstream side (primary side) by using the pressure-reducing valve as shown in Figure 3. This system is modeled based on the pipeline on which the field measurement is conducted, as shown in Figure 1. The authors considered the diameter of the pipe as \( D=250 \) mm, the propagation rate of the pressure wave as \( c=316 \) m/s, the total length of the pipeline as \( 2L=2\times1346 \) m,
the water level of the upstream tank as HWL 167.4 m, the control pressure altitude as EL 139.0 m, and the flow rate as 0.01 m³/s. In Figure 3, the pressure heads of the upstream and downstream sides of the pressure-reducing valve are \(H_{10}\) and \(H_{20}\), and the flow velocities are \(V_{10}\) and \(V_{20}\), respectively, before the pressure wave \(F_1\) reaches the valve.

The authors generate a rectangular pressure wave \(F_1\) by closing the valve present at the end of the pipeline momentarily. From \(t=0-L/c\), the pressure wave proceeds from the end of the pipeline toward the water tank, and the flow velocity at the section where the advancing wave passed becomes 0 m/s. The pressure heads and flow velocities of the pipeline, shown in Figure 3 to Figure 10, are calculated by using a characteristic curve method (Wylie B.E. et al., 1993). The thin slant lines drawn in Figure 3 to Figure 7 indicates the location of the initial point of the pressure wave at every 0.4 s.

**3.3 Relationship between operation of pressure-reducing valve and upstream pressure**

**3.3.1 When pressure control of pressure-reducing valve is imperfect**

As shown in Figure 4, the flow velocity in the upstream of the pressure-reducing valve is \(V_{10}\), and the flow velocity and the pressure head in the downstream side are \(V_{20}\) and \(H_{20}\), respectively, after the progressive wave \(F_1\) passed the valve. The rectangular wave produced by the reflection is \(f_1\), and the rectangular wave generated in the upstream side via the pressure-reducing valve is \(F_2\), after the rectangular progressive wave \(F_1\) reached the valve. The negative regressive wave \(f_1\) counteracts the water hammering positive pressure wave of the advancing wave, and then the flow velocity of the section where the regressive wave passed changes to \(V_{20}\). The positive advancing wave \(F_2\) proceeds toward a water outlet of the water tank flow, and the flow velocity of the section where the progressive wave passed changes to \(V_{10}\).

The pressure head and the flow velocity in the upstream and downstream sides of the pressure-reducing valve after the passage of progressive wave \(F_1\) can be expressed as Eq. (7) and Eq. (8) using Eq. (6).

\[
V_{20} - V_{10} = -\frac{g}{c}(F_1 - f_1) \tag{7}
\]

\[
V_{1t} - V_{10} = -\frac{g}{c}F_2 \tag{8}
\]

Moreover, when the flow rate is continuing in the upstream and downstream sides of the valve, Eq. (9) is established.

\[
V_{10} = V_{20} \quad V_{1t} = V_{2t} \tag{9}
\]

The relationship between the pressure wave \(f_1\), which is reflected at the valve, and the pressure wave \(F_2\), which is propagated toward upstream, is expressed as Eq. (10) by solving Eq. (7), Eq. (8), and Eq. (9).

\[
F_2 = F_1 - f_1 \tag{10}
\]

Figure 4 shows the calculated result of pressure heads and flow velocities assuming that the pressure control error of the pressure-reducing valve is 50% between the control pressure (EL 139.0 m) and the attained wave \(F_1\). The displacement of the pressure wave \(f_1\) becomes -3.3 m when the attained wave \(F_1\) whose displacement is 6.6 m reaches the downstream side of the pressure-reducing valve, because of the imperfect pressure control of the pressure-reducing valve. Hence, the pressure-reducing valve cannot decrease the pressure head to the target value (EL 139.0 m). The displacement of the pressure wave \(F_2\), which propagates toward the upstream side because of the operation of the pressure-reducing valve, becomes 9.9 m as shown in Eq. (10). The pressure head of the initial point of the progressive wave on the upstream side of the pressure-reducing valve is smaller than \(H_{10}\) by 3.3 m, since the pressure head on the downstream side of the pressure-reducing valve increases by 3.3 m because of the attained wave.
The flow velocity $V_2$ of the reflected wave $f_1$ decreases to 0.1 m/s from 0.2 m/s at the initial point, since the pressure-reducing valve reflects a part of the attained wave $F_1$, on the downstream side. On the other hand, the flow velocity $V_{10}$ of the advancing wave $F_2$ increases to 0.3 m/s from 0.2 m/s at the initial point, since the pressure-reducing valve allows passage of a part of the attained wave $F_1$, on the upstream side.

### 3.3.2 When secondary pressure control of pressure-reducing valves responds appropriately

Cho (1989) assumed that a main piston of the pressure-reducing valve descends instantaneously to an extent so as to maintain the pressure head in the downstream side of the valve as $H_{20}=H_{30}$, when the valve responds to the pressure variation in the downstream side of the valve. The reflective wave $f_1$ of the progressive wave $F_1$ was then introduced, as seen Eq. (11).

$$H_{2t} - f_1 = H_{20} + F_1$$
$$f_1 = -F_1$$  \hfill (11)

The pressure-reducing valve responds instantaneously so that the reflective wave $f_1$ of the progressive wave $F_1$ satisfies Eq. (11), and controls pressure fluctuations in the downstream side of the valve. On the other hand, the transmitted wave $F_2$, which proceeds toward the primary side of the valve because of the response of the valve, is expressed as Eq. (12) by solving Eq. (10) and Eq. (11).

$$F_2 = F_1 - f_1 = 2F_1$$  \hfill (12)

Therefore, the pressure wave, which occurred instantaneously at the end of the pipeline, is amplified two-fold by instantaneous shuttling operation of the pressure-reducing valve, and is propagated toward the upstream side as the advancing wave after arrival to the pressure-reducing valve, as shown in the Figure 5.

### 4 Growth mechanism of self-excited pressure vibration

#### 4.1 Formation of self-excited pressure vibration

Cho (1988) explains the possibility that the pressure wave due to water hammer is amplified because of the elastic behavior of the pressure-reducing valve, and then induces a steady pressure oscillation.

As the flow rate frequently changes, such as during the start or end of the flow, and flow rate or water head control via valves is often conducted when minute pressure changes (oscillation) occur in the pipe due to some type of transitional agitation, the pressure-reducing valve can react against such a change in water pressure by increasing it.

When the operating mechanism of the pressure-reducing valve was improved and the response speed increased like the present situation, the self-excited pressure vibration can occur; since the pressure variation amplifies (grows) increasingly with time during shuttling of the pipeline.

In pressure-reducing valves, the progress of responsiveness and the generation of the self-excited vibration are related to interactions. For the agricultural pipelines, control of hydrostatic pressures is imperative. Therefore, it is necessary to develop methods to avoid or minimize the generation of self-excited vibrations.

As shown in Figure 3, to simplify the generation and growth mechanisms, this study assumes that the pressure-reducing valve, which is installed at the halfway point of the pipeline considering no pressure loss, responds to external disturbance instantaneously, and that the valve closes instantaneously at the end of the pipeline.

#### 4.2 Propagation of water hammer pressure at $t=L/c–2L/c$

A positive advancing wave $F_1$, which occurred instantaneously at the end of the pipeline, increases two-folds because of the instantaneous closing of the pressure-reducing valve, and is transmitted toward the upstream side as a positive advancing wave $2F_1$ after reaching the valve at $t=2L/c$, as shown in Figure 5. The pressure wave, which was reflected at the valve after arriving from the end, proceeds toward the end as a negative regressive wave $-F_1$.

#### 4.3 Propagation of water hammer pressure at $t=2L/c–3L/c$

As shown in Figure 6, the positive advancing wave $2F_1$ in the upstream side reflects in antiphase at an open type of reservoir at $t=2L/c$ and becomes a negative regressive wave $-2F_1$. It then proceeds toward the valve negating a positive water hammer wave of the advancing wave, and reaches the valve at $t=3L/c$. In addition, in the downstream side of the pressure-reducing valve, a negative regressive wave $-F_1$ reflects at the end valve and becomes a negative progressive wave $-F_1$. It then reaches the pressure-reducing valve along with the negative regressive wave on the upstream side ($t=3L/c$).

#### 4.4 Propagation of water hammer pressure at $t=3L/c–4L/c$

When a negative regressive wave $-2F_1$ from the upstream
side arrives at the pressure-reducing valve, it becomes a negative progressive wave \(-2F_1\), maintaining the same pressure, as shown in Figure 7, and converges with a negative progressive wave \(-2F_1\), which was increased two-folds by a negative progressive wave \(-F_1\) in the downstream side of the valve. It then transmits as a negative progressive wave \(-4F_1\), which is quadruple times the size of the pressure wave \(F_1\) that first occurred in the upstream end.

The phenomenon, wherein the pressure-reducing valve responds to the minimum pressure variation that occurred in the pipe as seen previously, is repeated during shuttling of the pipe, which then increases the self-excited pressure vibration.

4.5 Excitation of water hammer pressure due to pressure-reducing valve

Figure 8 shows the relationship between the pressure head (i.e., pressure altitude and steady water head of the pipeline; water head difference between upstream HWL 167.4 m and downstream EL 139.0 m) and the flow velocity when the pressure-reducing valve responded instantaneously and appropriately to the pressure variation in the downstream side.

The relationship between the pressure head and the flow velocity, shown in Figure 8, is obtained by drawing a trace, which makes a round trip to the slightly left-leaning line group in the upstream side of the pressure-reducing valve. This is a trace of when a pressure wave propagating toward the upstream side due to actuation of the valve is formed, and it indicates that the period of the pressure and the variations in the flow velocity are approximately the same, but the signs of both are different. Moreover, the phase is out of alignment for a half period (180°).

Furthermore, Figure 9 shows a temporal change in the pressure head of the pipeline and the flow velocity. In Figure 9, the flow velocities in the upstream and downstream side of the pressure-reducing valve are drawn in the same line since there are equal as shown in Eq. (9). The pressure heads of the pipeline increase to an even multiple while reversing the phase with respect to each half period (8.5 s = \(2 \times 1346 \text{ m/s}\)). This result shows a phenomenon wherein the pressure wave develops while the change in pressure due to the actuation of the pressure-reducing valve shuttles in the pipe of the upstream section.

In addition, this phenomenon is comprehensible due to the increase in the size of the spiral while the pressure head and the flow velocity downstream of the reservoir (upstream end of the pipeline) are centered at the zero point and draw a spiral rectilinear trace, as seen in Figure 8.
draw a small and roughly rhombic trace centering at the zero point. Hence, indicating that the agitation given from the end is insignificant.

**5 Phenomenon in practical pipeline**

5.1 Factor actualized pressure oscillation phenomenon

With regard to the generating mechanism of the self-excited pressure oscillation, a simple model neglecting friction losses is used to clearly obtain a relationship between the cause of pressure oscillation and the oscillation phenomenon. However, the occurrence of pressure oscillation is complicated in actual stream as the downstream pressure passes the pressure-reducing valve toward upstream because of the response lag of the valve or because of the energy loss due to friction of the pipe.

When using a conventional pressure-reducing valve, it is inferable that the occurrence of the pressure oscillation of pipeline in the upstream side due to the action of the conventional valve is controlled consequently, as the valve does not operate instantaneously and the response lag to the secondary pressure control occurs. Moreover, the valve can control the pressure with conforming to the downstream pressure variation by adjusting the sensitivity of the pilot valve (Cho et al., 1988).

On the other hand, as the pressure-reducing valve improved the operative mechanisms that came into usage, the decompression process operates instantaneously and appropriately. Subsequently, the vibration phenomenon in the upstream side (primary side) is assumed to become clear corresponding to improvement in the control functions of the pressure in the downstream side of the pressure-reducing valve.

5.2 Pressure oscillation considering friction loss in pipeline

 Considering friction loss in the pipeline, the authors reproduced the occurrence of the pressure oscillation by using a characteristic curve method (Wylie B.E. et al., 1993) with an investigation model of the pressure oscillation mechanism. This study assumed the friction loss factor as \( f = 0.036 \) and the closing time of the end valve as 4 s. The temporal change in the pressure head and the flow velocity is shown in Figure 10. In Figure 10, the flow velocities in the upstream and downstream of the pressure-reducing valve are drawn in the same line since there are equal as shown in Eq. (9).

In Figure 10, the upstream pressure oscillation continues with a period of approximately 17 s. However, the amplitude of the oscillation does not increase in contrast to the case where friction losses are not considered (Figure 8 and Figure 9). This is because the upstream pressures amplified by the pressure-reducing valve lose their energy owing to friction while propagating in the upstream pipeline.

The relativeness between the pressure heads and the flow velocities, shown in Figure 11, indicates a linear trace shutting in the upstream side of the pressure-reducing valve. Both the pressure head and the flow velocity are out of phase for half period (180°), similar to the case where friction is neglected, as shown in Figure 8, and both the periods are nearly the same.

In addition, in the downstream side of the valve, the relativeness shows a small and roughly elliptical trace in the flow velocity ranging from −0.3 m/s to +0.3 m/s near the pressure head EL 140 m, and indicates that the agitation given at the end is small.

On the other hand, in the downstream side of the reservoir (upstream end of the pipeline), a horizontal and roughly elliptical trace is drawn in the range of pressure head from EL 150 m to EL 180 m and flow velocity from −1.2 m/s to +1.2 m/s. This derives from the declination between pressure heads and flow velocities for quarter period (90°), similar to the case where friction is neglected.

The pressure is at maximum or minimum, as seen in Figure 8, when the flow velocity is zero; however, the peak is concave in Figure 11, and a similar tendency is shown in
6 Generating mechanism of agitation due to control by division works

The generating mechanism of pressure oscillation in the conventional low-pressure systems is that the pressure wave, which is generated due to rapid closing of the valve at the end of the pipeline, is amplified and continued because of the pressure-reducing valve installed at the middle of the pipeline.

Therefore, considering the generation of the self-excited pressure vibration in the low-pressure system, generating a pressure wave at the end of the pipeline as an agitation and entering it into the system are the origination processes.

When a direct acting constant flow valve was installed at the end of the system, the pressure oscillation occurs because of an initial agitation, such as during the opening of the end valve and the beginning of the flow from the state where the operation of the low-pressure system had stopped, as shown in Figure 2.

By setting the opening rate of the valve or using a direct acting constant flow valve as a control method of division works, this study replicates the pressure variation at the beginning of the flow and reviews the generating mechanism of the agitation due to the control of division works.

6.1 Pressure oscillation due to opening rate of the valve

The method, which involves installing a control valve in division works and controlling the division duty by setting the opening rate of the valve according to the required amount, is common. In this method, the division duty changes corresponding to the variation in pipeline pressures while the convergence of the stream range is fast with respect to the transitional stream range variation such as when the flow has begun or when the division duty changes.

The modeling, as shown in Figure 12, was applied in the downstream section for the pressure-reducing valves of the low-pressure system (Figure 3). This study assumed the control pressure head of the pressure-reducing valve EL 139.0 m as a starting water head; the length of pipeline is \( L = 1000 \text{ m} \), the diameter of the pipes \( D = 150 \text{ mm} \), the propagation velocity of the pressure wave \( c = 308 \text{ m/s} \) and the division duty is set (target) as 0.02 m³/s.

\[
Q = A \sqrt{2gh} \quad (13)
\]

\[
A = 0.0009
\]

The relativity between the flow rate and the pressure head at the division works at the end of the pipeline is shown in the left side of Figure 13, and the temporal change in the pressure head at the division works is shown in right side of Figure 13.

Figure 13 and Figure 15 are calculated by using a characteristic method (Wylie B.E. et al., 1993).

In the case of the water level border, which sets the opening rate of the valve, the downstream pressure varia-
tion and the division duty change linearly and arrive a characteristic curve of the valve in a short time, and then converge with a steady state. When such a valve control, which can be treated as a water level border, is conducted, the control is assumed not to provide the agitation, which generates the pressure variation at the end of the pipeline.

6.2 Operative mechanism of direct acting constant flow valve

In a direct acting constant flow valve, a piston placed to stop the flow is supported by a spring, and the spring expands and contracts because of the pipeline pressure acting on the piston, and then the piston acts elastically as shown in Figure 14. Some interspaces arise between the piston and the inside wall, and then the flow occurs owing to the pressure difference because of the to-and-fro motion of the piston.

In this type of constant flow valve, a water hammer wave in the upstream of the valve is expected to amplify and reflect as the water pressure in the upstream of the valve acts as a working pressure for the piston, and closes the piston because of the opening and closing property of the valve.

To replace the pressure variation when the end valve is opened from the state that the operation of the low-pressure system stops, this study targeted the downstream section of the low-pressure system, from downstream of the pressure-reducing valve to the end of the pipeline, as shown in Figure 14, and simulated division works including the direct acting flow valve at the end.

In addition, in the results of the field measurement, as shown in Figure 15, there was a pressure variation at the end of the pipeline, which can be treated as a water level border, as shown in Figure 15. When a direct acting constant flow valve is installed at the end of the downstream pipeline of the pressure-reducing valve, the effect of the pressure variation sustains longer than that of the water level border.

Therefore, a relationship between the pressures and the flow rates was expressed by curves, and the valve property was treated as a flow rate border, as shown in Figure 15.

6.3 Pressure oscillation due to direct acting constant flow valve

The relationship between the flow rates and the pressure heads of the pipeline in the division works at the end of the pipeline is indicated in the left side of Figure 15.

When the flow rate border assumes the use of the direct acting flow valve, pressure heads and flow rates reach a characteristic curve of the valve linearly after beginning the flow, and then trace the valve property in response to a pressure variation. The pressure heads and flow rates exhibit roughly elliptical traces eventually, and a self-excited vibration occurs (Chaudhry, 1979).

In addition, the temporal change in the pressure head and the flow rate after the beginning of the flow is shown in the right side of Figure 15. When a direct acting constant flow valve is installed at the end of the downstream pipeline of the pressure-reducing valve, the effect of the pressure variation sustains longer than that of the water level border.

The valve property of the constant flow valve is assumed as an ideal characteristic curve for the model calculation, while the self-excited vibration occurs transiently. On a practical device, an accurate valve property which is used in model calculation cannot be obtained; hence, the case where the relationship between the acting pressures and flow rates does not adapt adequately to the local condition is also simulated. The results of the reproduction calculation show that continuous self-excited pressure vibration occurs. Moreover, at the actual operation, the situation is assumed to be worse than the calculated result, shown in Figure 15, as an elastic action of the spring is added to the piston of the constant flow valve.

In addition, in the results of the field measurement, as
shown in Figure 2, the pressure on the upstream of the direct acting constant flow valve Q1, which is present at the end of pipeline continues and oscillates. This phenomenon is observed because of the self-excited vibration due to the constant flow valve, by considering past results of verification.

Therefore, the result shows that when the end valve of the division work has the property \((\text{d}A/\text{d}H<0)\) and the water hammer wave shuttles in the pipe, the water hammer wave does not decay due to friction, as the valve acts as a source of the pressure fluctuation and new energies are provided when water pressure fluctuations occur in the pipeline because of the initiation of flow. Hence, the self-excited oscillation continues.

7 Conclusions
This study considered the case where the pressure-reducing valve is placed at the middle of the pipeline, and natural oscillating periods of the pipeline on the upstream and downstream side of the pressure-reducing valve harmonize. If a minimum pressure change (oscillation) occurs in the pipeline due to the transitional agitation at the downstream end, the valve can react to that water pressure variation and cause a self-excited vibration, and then provide the pressure oscillation on upstream of the valve.

When valves that have the property of generating pressure oscillation, such as a direct acting constant flow valve, is installed, the pressure oscillation relating with the water hammer wave is assumed to occur in the entire pipeline.

In particular, in the pipeline system for farm irrigation, contrary to the system for paddy irrigation, the system is directly linked to the constant flow valve and the sprinkler equipment, such as solenoid valves and sprinklers of the greenhouse, and forms the closed pipeline system. Therefore, in the low-pressure systems, the system often comprises of a combination of pressure-reducing valves and end instruments, and in such cases, pressure oscillation is easily caused.

However, the low-pressure system has a mechanism in which agitations, such as start and stop of the flow, are converted to a pressure oscillation, amplified, and then maintained, but when the system is in the condition where such mechanisms do not act, the fatal self-excited vibration can be avoided.

In the future, the authors will conduct the analysis of the pressure waveform based on the field test data, and reveal the factors that cause the self-excited pressure vibration phenomenon in low-pressure systems, particularly the relationship with the natural oscillating period of the pipeline, which is determined by installation position of the pressure-reducing valve.

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