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Numerical Analysis on Pressure Oscillation and Attenuation Process inside Pipelines to Achieve Early Gas Supply Recovery

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ABSTRACT

Numerical simulation was conducted to understand the behavior of pressure oscillations inside pipelines. The pipeline network where Tokyo Gas supplies natural gas is divided into about 1100 independent small blocks. Pressure inside each block is constantly monitored and kept below 2.5 kPaG by pressure governors. When a major earthquake occurs, gas meters and pressure governors are designed to interrupt the natural gas supply automatically in order to prevent secondary disasters. Gas leaks can be identified by checking the existence of decrease in this monitored pressure. However, when the pressure governors and the gas meters at the end of the pipelines shut off suddenly, pressure oscillations occur because of the compressibility and the inertia of the flow. This makes it difficult to check the behavior of the monitored pressure, and the judgment of the gas supply recovery is suspended until the oscillation attenuates sufficiently. To understand the pressure oscillation behavior, one-dimensional numerical simulation for the flow in the pipeline network with different geometries was conducted. The analysis was carried out in two phases, which are the simulation for the simple straight tube to confirm the availability of simulation technique and the simulation to investigate the pressure oscillation behavior for the actual complex network.

In the first phase, experiments with a long straight tube with valves at both ends representing a pressure governor and a gas meter were performed. These two valves were closed suddenly to create a pressure oscillation. Simulations were conducted under the same conditions as experiments. Repetitive reflections of expansion and compression waves at the end of the tube were observed, which developed into pressure oscillations. The pressure amplitude, the overall waveform, and the duration time of oscillation from the simulation results gave close agreement with those of the experiments. This implies that the behavior of the pressure oscillation inside the large pipeline network can be reproduced by the numerical simulation.

In the second phase, simulation models including branches and gas meters composed of 149 actual pipeline networks were constructed. The steady state flow was calculated based on the real gas consumption data. After the steady state was calculated, all the gas meters and the pressure governors were shut off at the same time. The results showed that, in most cases, the duration time of the pressure oscillation after the interruption of natural gas supply was less than 600 seconds, which indicates the monitored pressure decrease after 600 seconds may be due to gas leaks. They also showed that, although the obtained pressure oscillation curve was similar to that for the straight tube, the duration time revealed a positive correlation with the average diameter of the pipes in the network. This could lead to the prediction of the duration time of the network without conducting numerical simulations and the earlier gas recovery than 600 seconds.

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2.BODY OF PAPER

2.1. INTRODUCTION

Supplying pressure of gas pipelines in Tokyo Gas areas is kept below 2.5 kPaG by pressure governors. The pipelines are made up of 179 “L-blocks”, and supply and shut off of gas in each L-block can be controlled individually. Each L-block holds about 80,000 consumers, and the block spreads around 5 to 10 km toward each direction [1]. These L-blocks are further divided into smaller individual “S-blocks”, and there are about 1,100 S-blocks in Tokyo Gas areas.

In the case when an earthquake with its Japanese seismic intensity value exceeds a lower 6 occurred, pressure governors are designed to interrupt the gas supply in each block automatically. At the same time, gas meters placed at the end of gas consumption points also automatically interrupt the gas supply in order to prevent secondary disasters.

Pressure inside the gas supply blocks is measured by sensors placed just after the pressure governors. Collected pressure data are transferred to the central server, and the pressure is constantly monitored to achieve stable supply. Tokyo Gas presently estimates the damage of earthquake based on large earthquakes that occurred in the past [2]. It is possible to improve the damage estimation of earthquakes by using the monitored pressure of supply blocks which directly reflects the state of gas supply. This will lead to the optimization of pressure governor performance, and the earlier gas supply recovery can be achieved. In order to use this monitored pressure to estimate the damage of earthquakes, the decrease of pressure inside the pipeline, more specifically the existence of gas leaks, must be determined in about 10 minutes after the earthquake occurs. This is because after 10 minutes, gas meters at the consumption points will be recovered, and the pressure decrease due to the gas consumption will start.

However, when pressure governors and gas meters shut off at the same time, pressure oscillation occurs due to the inertia and compressibility of the gas inside the supply block. This pressure oscillation makes it difficult to check the behavior of the monitored pressure, and the judgment of the gas supply recovery has to be suspended until the oscillation attenuates sufficiently.

In this report, one-dimensional numerical simulation is conducted to reproduce and understand the behavior of pressure oscillation and attenuation process inside the gas supply blocks.

2.2. Validation of simulation method

2.2.1. Experiment

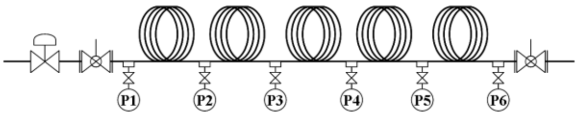

Fig. 1 Schematic view of an experimental setup.

To confirm the availability of simulation method, an experiment using a simple long straight tube was conducted. Figure 1 shows the schematic view of the experimental setup. The straight tube was made up of 5 coiled polyethylene tubes with inner diameter of 52.9 mm. Each tube was 40 m long, therefore in total the length of straight tube was 200 m. The gas inside the tube was 13A city gas (CH_4:89.6%, C_2H_6:5.62%, C_3H_8:3.43%, C_4H_{10}:1.35%). Pressure inside the tube was controlled by the pressure regulator placed at the beginning of the tube. Ball valves were used to represent the shutting structure of pressure governor and gas meter, and they were placed just after the pressure regulator and at the end of the tube. These valves were also used to control the flow rate. Pressure sensors were placed at P1 ~ P5 in Fig. 1 so that the pressure is constantly monitored at intervals of 40 m. Supply pressure was 2.2 kPaG, and the flow rate was 20 Nm^3/h. The situation which describes the sudden shut off of gas supply by pressure governors and gas meters at the occasion of earthquake was represented by the sudden closure of ball valves while the gas inside the tube was still moving.

2.2.2. Simulation

Numerical simulation focusing on pressure oscillation and attenuation process inside the straight tube under the same condition with the experiment described in 2.2.1 was conducted using one-dimensional unsteady flow analysis solver, Advance/FrontNet/Γ. In the simulation model, the straight tube was composed of several pipe elements. Each pipe element was one-dimensionally divided into cells in the direction of axis. Flow inside the tube was numerically analyzed by solving the one-dimensional unsteady Navier-Stokes equations based on the information of flow in each cell. The gas inside the tube was CH_4, and the pressure loss through the tube was adjusted by changing the frictional loss of the inner wall so that the pressure observed just after the sudden shut off at P1 and P6 in Fig. 1 equal to the experimental results. Valve elements were placed at the both ends of the tube to represent the pressure governor and the gas meter, and the time it takes for the valves to close was 0.1 second.

2.2.3. Reproducibility of simulation

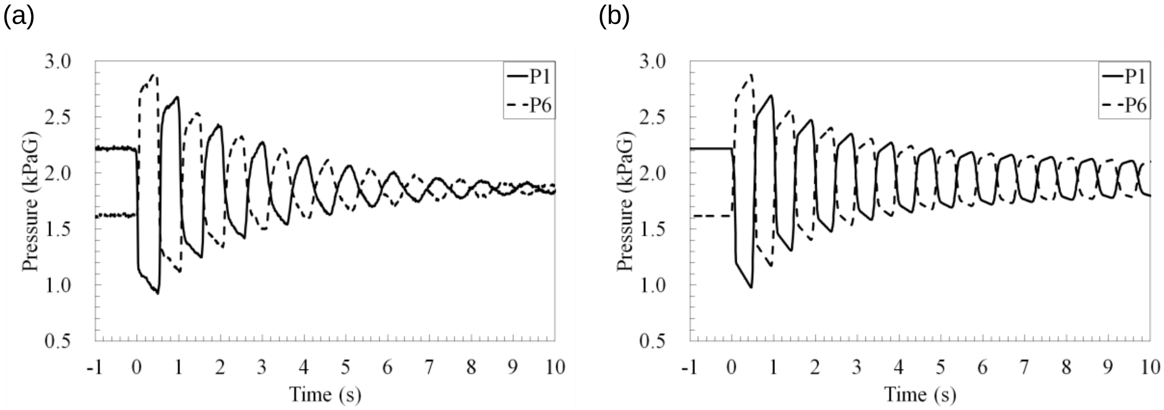

Fig. 2 (a) Experimental and (b) numerical results of pressure oscillation in a straight tube.

Figure 2 (a) shows the experimental results of pressure observed at P1 and P6. After the sudden shut off of gas supply by closing the valves at t = 0, expansion wave and compressive wave was observed at P1 and P6 respectively. These expansion and compressive waves travel back and forth through the straight tube, which evolved into pressure oscillation. The maximum and minimum value of pressure oscillation was 2.9 kPaG and 0.9 kPaG respectively. The pressure oscillation attenuated gradually as time goes on, and after about 10 seconds, it converged into a value around the supply pressure which is 2.2 kPaG.

Figure 2 (b) shows the numerical simulation results. The maximum and the minimum pressure gave close agreement with the experimental results. The overall wave form of expansion and compressive wave also agreed well. A degree of frictional loss of the wall should give a dominant effect on the attenuation of the pressure oscillation. Numerical results, however, gave more gradual attenuation than that of the experimental results. This is the effect of neglecting the elasticity of the tube itself and the pressure loss of branch structure at the position of pressure sensors. These elements have a slight effect on the attenuation process of pressure oscillation. The frequency of the pressure oscillation in simulation result was higher than that of the experimental results. This is the result of the difference in acoustic velocity between 13A city gas and CH_4 and the error in measuring the total length of the tube.

Despite the small difference, such as the attenuation time and the frequency of oscillation, results in experiment and simulation gave overall agreement in the pressure oscillation process. This implies that the one-dimensional unsteady flow analysis can be used to evaluate the pressure oscillation and attenuation process inside the supply blocks.

2.3. Pressure analysis on supply blocks

2.3.1. Simulation conditions

The actual supply block is different from the straight tube in that although most of the blocks have only one pressure governor, they have several branches and consumption points. In conducting the numerical simulation on these supply blocks, supply pressure was set to be 2.3 kPaG, and the gas inside was assumed to be CH_4. Valve elements representing the pressure governor and gas meters were set to close in 1 second simultaneously. Frictional loss was the only pressure loss mechanism to be considered, and the pressure loss at branch points was neglected.

2.3.2. Evaluation based on characteristic values

Configuration of supply blocks changes frequently due to the extension and removal of the pipes. For example, several individual supply blocks can be connected and end up with one large supply block. This prevents us from estimating the attenuation time of the pressure oscillation in all the supply blocks beforehand, since the frequency of the change in configuration is unknown and conducting numerical simulations takes long time. One possible solution is to find a characteristic value representing the configuration of supply blocks which has a positive correlation with the attenuation time of pressure oscillation. For example, a degree of frictional loss of the wall was considered to have an effect on the attenuation process, so that a characteristic value regarding with this frictional loss might show a good correlation. Once the relationship between the characteristic value and attenuation time is found, it can be applied to the estimation of the attenuation time in newly formed supply blocks without conducting cumbersome numerical simulations.

The characteristic values considered in this report are as follows: (1) average diameter [m], (2) average volume [m^3], (3) average length [m], (4) average residence time [hour], (5) distance between pressure governor and the center of consumption [m], (6) area [km^2], (7) number of branches, and (8) number of loops. In simulation models, branch points and gas consumption points were connected by pipe elements. These pipe elements were counted up, and the number of pipe elements was used to calculate the average values. Average residence time of gas was calculated by dividing the total volume of the supply block [m^3] by the amount of consumption [Nm^3/h]. Branch points were defined to be points where 2 pipe elements were branched off from 1 pipe element. Loops were defined to be a shortest path starting from a pipe element and coming back to the same element, and the loops that contain other loops were neglected.

Typical 149 of 1,100 supply blocks were chosen to be analyzed. Characteristic values of these blocks were calculated, and the relationship with the attenuation time was evaluated.

2.4. Results and Discussion

2.4.1. Results of pressure analysis

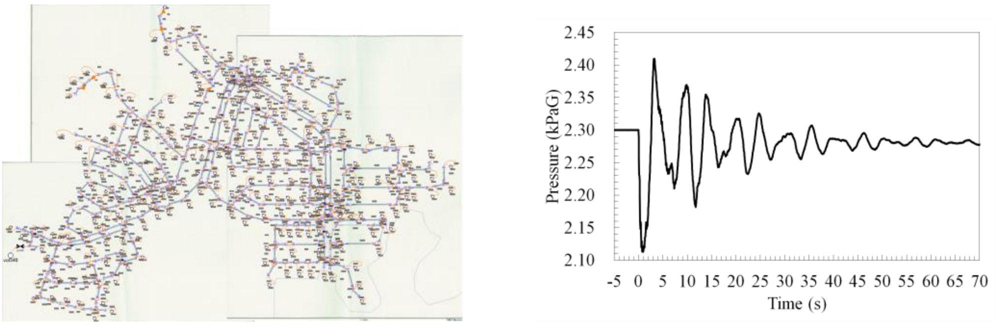

Fig. 3 Overview and an example of pressure oscillation in a supply block.

Figure 3 shows an overview and an example of pressure oscillation and attenuation process in a supply block. The time of sudden shut off of the valves was $t = 0$. An intense oscillation was seen just after the shut off, but due to the frictional loss of the pipe wall, the pressure gradually attenuated until it converged into a stable value.

Figure 4 shows the calculated attenuation time of the supply blocks. Attenuation time was defined as a time it takes for the amplitude of pressure oscillation to converge into less than 0.01 kPa. The result showed that 600 seconds (10 min) after the shut off, pressure oscillations in supply blocks converged almost completely. This indicates that the attenuation time in most of the supply blocks is smaller than the time it takes for the gas meters at the consumption points to recover from shut off. This result also implies the availability of using the monitored pressure to evaluate the decrease in pressure inside supply blocks and gas leaks caused by the damage of earthquake can be detected. The difference in attenuation time among the simulation models, however, gives a possibility of setting a threshold value less than 600 seconds for each block, which leads to an earlier gas supply recovery. To find out this threshold value, organization of the attenuation time based on characteristic values of supply blocks was carried out.

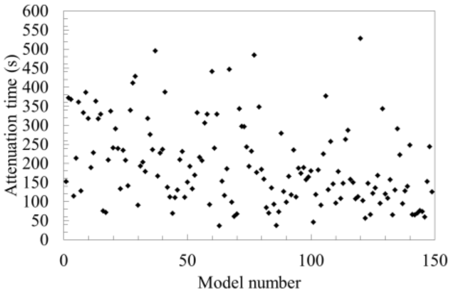

Fig. 4 Attenuation time distribution of supply blocks.

2.4.2. Correlation with characteristic values

Figure 5 shows the relationship between each characteristic value and the attenuation time. Average diameter and average volume showed a positive correlation. The others, however, showed random distributions which implies there are low or no correlation. The correlation was evaluated by simple linear regression analysis. In this method, the relationship between two elements was expressed in linear function based on the result of fitting by least square method. Coefficient of determination, which indicates the degree of correlation, was calculated from the covariance value in the linear function. The coefficient of determination greater than 0.5 is considered to have a “good” correlation. Table 1 shows the coefficient of determination for each characteristic value. The average diameter showed the best value of 0.566, which agrees with the qualitative result from Fig. 5.

As discussed above, the average diameter of the supply block showed the best correlation with attenuation time, however, the reason remained uncertain. In the advocated method, each characteristic value was evaluated individually. There is still a possibility that by combining several characteristic values, better correlation can be found. Further evaluation using multiple classification analysis should be done in finding effective characteristic values to understand and estimate the attenuation time of pressure oscillation.

Table 1 Coefficient of determination for each characteristic value.

Characteristic value	Coefficient of determination
Average diameter	0.566
Average volume	0.459
Average length	0.030
Average residence time	0.003
Distance from governor	0.063
Area	4.00E-05
Number of branches	0.023
Number of loops	0.069

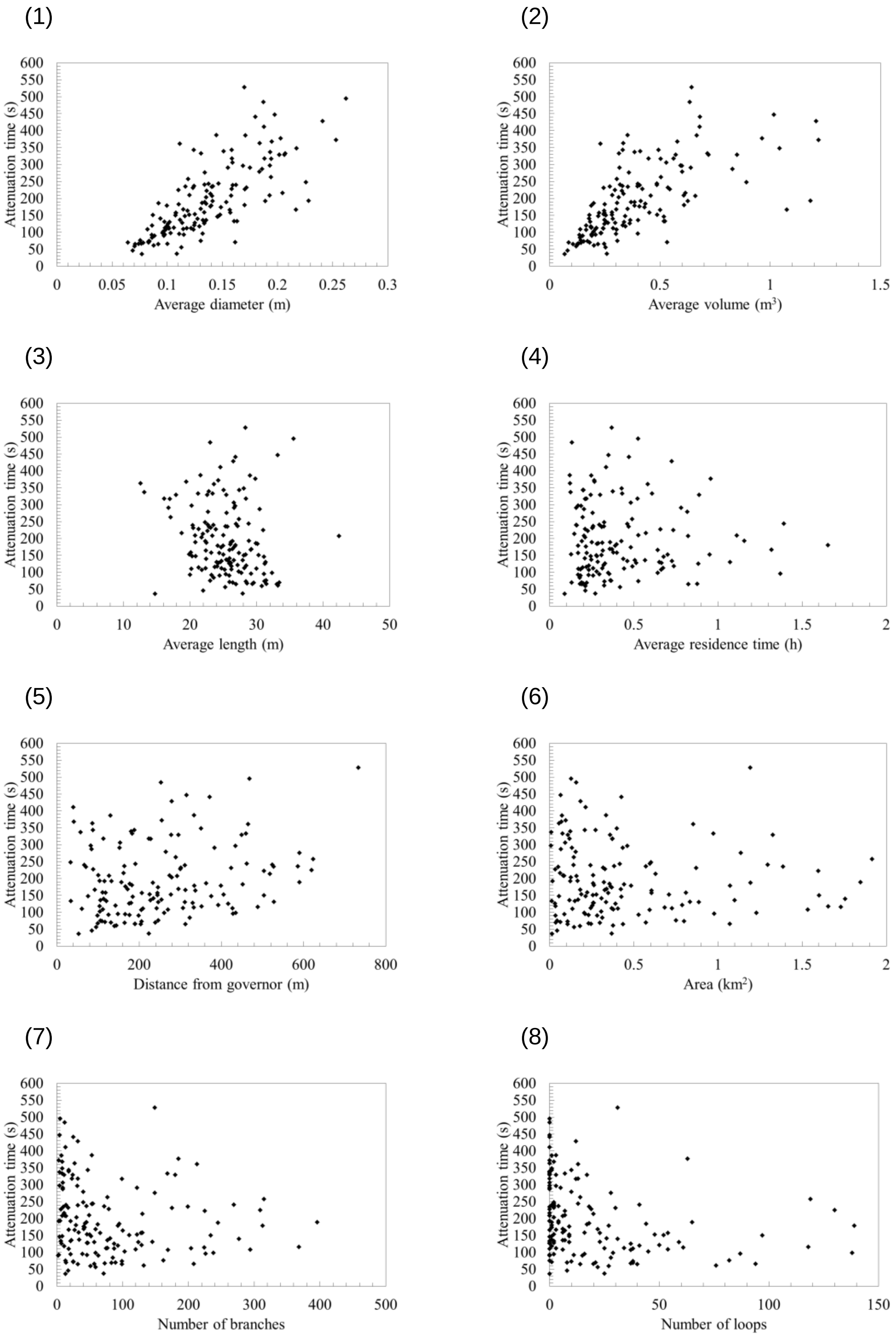

Fig. 5 Relations between attenuation time and (1) average diameter, (2) average volume, (3) average length, (4) average residence time, (5) distance between pressure governor and the center of consumption, (6) area, (7) number of branches, and (8) number of loops.

2.5. Conclusion

We have conducted a one-dimensional unsteady flow analysis on pressure oscillation and attenuation process inside supply blocks caused by the sudden shut off of pressure governors and gas meters at the incidence of earthquakes. We found through the comparison of experiment and simulation result on simple straight tube that the numerical analysis can be used to evaluate the overall behavior of pressure oscillation process. Applying the simulation method into actual supply block models, attenuation time of pressure oscillation was less than 600 seconds, which implies the availability of using the monitored pressure just after the pressure governors to detect gas leaks caused by the damage of earthquakes. We also evaluated the correlation between characteristic values and attenuation time, and the average diameter showed the best correlation. We will keep on improving the accuracy of simulation and introducing the multiple classification analysis to look for the better characteristic values, and thus leading to the early gas supply recovery.

3. Acknowledgement

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4. Reference

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