Flow characteristics of water delivery piping system and its effective flow area at discharge branches

Fumio Shimizu, Masatoshi Akinaga, Yuya Matsuyoshi, Kazuhiro Tanaka
680-4, Kawazu, Iizuka, Fukuoka 820-8502, Japan

shimizu@mse.kyutech.ac.jp

Abstract. When we scatter water uniformly over a wide area, we often make a large number of branches and discharge outlets in a main pipe and let water be discharged from each outlet. In order to achieve uniform sprinkling, it is necessary to understand the state of the water flowing out from each outlet properly. In the present paper, the flow field inside a water delivery pipe with multiple short branch pipes was investigated using numerical calculation and experimental measurement. As a result, computational results and experimental results showed good agreement, and the validity of the computational method was confirmed. At the discharge outlet, flow surface in which air and water were mixed was formed. It was confirmed that the water area was smaller on the upstream side and became larger as going downstream. It was clarified that the discharge flow rate and the water flow area changed greatly due to the change in the discharge outlet diameter and the terminal outlet diameter.

1. Introduction
A water delivery piping equipment is used for the purpose of water scattering, snow disappearance, prevention of dust scattering and so on. In the construction of piping system aiming at uniform water scattering over a wide area, we often make a large number of branch pipes and discharge outlets in the main pipe and let water be discharged from each outlet. Generally, short length branch pipes and outlets are often installed on the main pipe in the water delivery equipment. In the present study, a dispersed water piping facility with multiple short length branches is called "water delivery piping system".

Piping system with bifurcations and long length branches to the main pipe is generally called "dividing pipe system", and a large number of studies have been carried out [1-2]. In these researches, branch losses with respect to the flow ratio of the branch pipe and main pipe have been investigated in detail for many connecting angles. In the dividing pipe, consideration has been given to a case where the branch length before and after the dividing part is sufficiently long, and researches has been conducted with the influence of the separation and the backflow occurring near the branch part. In addition, researches on "uniform-flow manifold" system for dividing equal flow rates to a plurality of branch pipes have also been conducted [3-4]. The simplest case is supplying water at high pressure, and this piping system is called "header pipe" [5].

In a general piping system, design using the flow characteristics of the header pipe is often performed. However, when the pipe length is extremely long or the flow resistance is large, it is difficult to realize the water supply system as the header pipe conception. Maintaining a piping system in a high pressure state is wasteful equipment design, and it is a contrary system to the idea of energy
saving. Therefore, there is great significance in investigating flow characteristics in a water delivery piping system. Since there is an outer boundary immediately after branching and water is released into the atmosphere, it is susceptible to the influence of the outlet boundary in the water delivery pipe. It is difficult to apply the research results of the dividing flow system in the case of piping system with short branches.

There are many parameters when we design a system of a water delivery pipe. Regarding the main parameters, cross-sectional shape, inner diameter, total length, inlet pressure, and inlet flow velocity can be mentioned for the main pipe. For the branch pipe, branch location, cross-sectional shape, inner diameter, branch length, number of branches, outlet pressure, outlet flow rate, and outlet flow velocity can be mentioned. Depending on the selection of parameters, there is a possibility that a complicated three-dimensional gas-liquid two-phase flow state in which air and water coexist inside the main pipe appears, so it is difficult to understand the phenomenon and grasp flow characteristics. In the present paper, we will proceed with research under the following constraints to clarify the content of research.

1. We install multiple discharge branches and one terminal in one main pipe.
2. All pipes have round cross section.
3. The interior of the main pipe is filled with water and air is not mixed in.
4. The piping system is installed horizontally.

The purpose of the present study is to investigate the flow characteristics of the water delivery piping system using numerical analysis and experimental measurement after confirming the validity of computational method for the delivery piping system. We also investigate the influence of terminal pipe diameter and discharge branch diameter on the internal flow characteristics.

2. Computational method and experimental equipment

2.1. Configuration of water delivery pipe

Figure 1 shows the schematic figure of a water delivery pipe. The main pipe had six branch pipes and one terminal pipe. In the present study, the diameter of the main pipe was represented by $D$, the diameter of discharge outlets by $d$, the length of branch pipes by $l$. The terminal pipe diameter was represented by $D'$, the terminal pipe length was represented by $L'$. Both discharge and terminal outlets were numbered from the upstream side, such as Out1, Out2 and so on. The main pipe length $L/D$ was 78, the discharge branch length $l/D$ was 0.4, the number of branch pipe was 6, and the terminal pipe length $L'/D$ was 1.0. The influence on the flow characteristics were investigated when the discharge outlet diameter $d/D$ and the terminal outlet diameter $D'/D$ were varied.

![Figure 1. Schematic figure of water delivery pipe.](image-url)
2.2. Computational method

As governing equations, we used a continuity and the Navier-Stokes equations for three-dimensional incompressible viscous fluid. We used ANSYS CFX for commercial software, which was based on the finite volume method for discretization method. Although the inside of the main pipe was filled with water, there was a possibility that both air and water were mixed in the discharge branches and the terminal pipe. In the present study, we analyzed the entire flow field as gas-liquid two-phase flow which simultaneously handles gas and liquid phases. As a method of tracking the gas-liquid interface, we used the Volume of Fluid method to solve the advection equation on the volume fraction of water.

In the numerical calculation of the present study, steady flow analysis was performed. Hexagonal type structured grid was used and it was the number of about 1.2 million grid points. In the vertical direction, gravity acceleration which was set at 9.81 [m/s²] was considered. The SST k-ω model was used for the turbulence model. The delivery pipe shape with the discharge outlet diameter \( d/D = 0.6 \), and the terminal outlet diameter \( D'/D = 0.25 \) was taken as the standard model. For the boundary condition of the inlet, it was given Re=36,000 based on the diameter of the main pipe and inflow velocity. Pressure was fixed at atmospheric pressure on the outlet boundaries.

2.3. Experimental equipment

We made experimental equipment of the standard model configuration. We carried out the measurement of pressure distribution along the main pipe and discharge flow rate from each outlet. A schematic figure of the experimental equipment was shown in figure 2. A water tank, a pump, a valve, a flowmeter, a main pipe, reservoirs and manometer were composed for the experimental equipment. The measurement procedure was shown, as follows.

1. We store much water in the large tank. Water was carried from the tank to the main pipe using a pump. Air was removed from the main pipe, the main pipe was filled with water.
2. We set the inlet flow rate using a flow valve and float type of a flowmeter.
3. We confirmed that the state of water flow was converged on the steady state. After that we measured the discharge flow rate from each branch outlet using reservoir tanks.
4. On the wall of the main pipe, pressure measurement holes were installed at 25 locations on the opposite side of the branch outlet. A measurement hole was connected to a manometer and static pressure measurement was performed.

![Figure 2. Schematic figure of experimental equipment.](image-url)
3. Comparison between computational and experimental results

Numerical analysis and experimental measurements were performed on the flow channel of the standard model. The shape of the branch pipe was the diameter \( d/D = 0.6 \), the length \( l/D = 0.4 \), and the number of branch was 6. The shape of the terminal pipe was set to the diameter \( D'/D = 0.25 \) and the length \( L'/D = 1.0 \). In order to confirm the validity of the computational method, both numerical calculation and experimental measurement were carried out for the same configuration of a water delivery pipe, and the results were compared.

3.1. Pressure distribution inside main pipe

Figure 3 shows the pressure distribution in the main pipe obtained from both computational and experimental results. The horizontal axis indicated the distance from the inlet which was normalized by the main pipe diameter \( D \). The vertical axis indicated the static pressure measured at each position. The computational results were indicated by solid line and the experimental results were indicated by triangle marks. In the computational results, the average static pressure within the vertical cross section of the main pipe was plotted. The experimental results plotted the values measured by the manometer.

It was observed that both results showed pressure fluctuations with undulations. In the pipe region without branches, the pressure inside the main pipe decreased linearly as going downstream. This phenomenon is a pressure drop due to friction loss of the pipe wall. At the branch pipe positions, pressure rose discontinuously. This cause was that the flow rate in the main pipe decreased due to branching of the pipeline, and the flow velocity in the main pipe decelerated. For this reason, zigzag shaped pressure distribution was formed. Computational results captured the state of this fluctuation. The rising tendency of the average pressure as going downstream was captured both results. Although there were slight differences quantitatively, computational results and experimental results were good agreement qualitatively.

![Figure 3. Comparison between computational and experimental results (Pressure distributions inside main pipe).](image-url)
3.2. Basic flow characteristic in main pipe
In order to understand the basic flow characteristic in the main pipe, the average velocity and the total pressure distribution obtained from computational results are shown in figure 4. The dashed line indicated the average velocity and the solid line indicated the total pressure. An average value within a cross section perpendicular to the main pipe axis was calculated.

The average flow velocity was constant in the straight section without branch. In the branch section, the flow velocity sharply dropped, and once it passed through the branch section, the flow velocity became constant again. This reason was that the upstream water flow of the main pipe was divided to the downstream and the branch pipe region. As the amount of water in the main pipe decreased due to the branching, it can be seen that the flow velocity also decreased so as to satisfy the law of conservation of mass. Looking at the result of the total pressure, it can be seen that the total pressure gradually decreased as it went to the downstream of the main pipe. The total pressure drop in the straight section was a linear variation and was considered to be caused by the friction loss of pipe wall. In addition, slight fluctuations were observed in the branch part, which was considered to be the influence of the branch loss. Compared with the pipe friction loss, the influence of branch loss was very small.

![Figure 4. Average velocity and total pressure inside main pipe.](image)

3.3. Discharge flow rate from outlets
Figure 5 shows the results of the flow rate of discharging water from each outlet obtained from numerical calculations and experimental measurements. The horizontal axis indicated the normalized distance from the main pipe inlet and the vertical axis indicated the water flow rate of each outlet which is normalized by the inlet flow rate. Circle marks indicated computational results and triangle marks indicated experimental results. Since water flowed out from a total of seven places, six discharge outlets and one terminal outlet, seven marks were plotted. Since the terminal at the most downstream side had a small diameter, the outflow flow rate was smallest compared to other discharge outlets. The amount of discharge water from the six outlets increased as it went to the downstream of the main pipe. Both computational and experimental results showed quantitatively good agreement. This feature was in agreement with the content that "branch flow rate increased as approaching the end of the main pipe" reported in reference [6].
The water behavior from discharge outlets was observed. The computational results are shown in figure 6. This figure showed the water velocity distribution from the six outlets. Outward velocity of water was shown in color. The arrow mark in the upper part of figure showed the flow direction of the main pipe. The discharge water from the branch outlet had a bow shape distribution with a high speed area on the downstream side. On the upstream side, there was a white blank area, which was filled with air. Since air flowed from the outlet into the discharge branches, water did not flow through the entire branch pipe. In the present paper, the water area at the discharge outlet was called “effective flow area”. The effective flow area was smaller on the upstream side and larger on the downstream side.

![Figure 5](image)

**Figure 5.** Comparison between computational and experimental results (Discharge flow rate from outlets).

![Figure 6](image)

**Figure 6.** Velocity distribution on the cross section of discharge outlets (Computational results).
Figure 7 shows photographs of water flow from the branch outlet at Out2 and Out4. The arrow mark in the upper part showed the flow direction of the main pipe. It can also be confirmed from experimental photographs that a lot of water flowed on the downstream side, and water did not flow out from the upstream side of the outlet surface. It is observed in the experiment that the effective flow area of water increase on the downstream side.

The validity of the computational method using in the present study was confirmed, since the computational and the experimental results showed good agreement based on the above comparison.

![Figure 7. Behaviour of outflow water at discharge outlets (Experimental results).](image)

4. Influence of terminal and discharge outlets for the flow characteristics of water delivery pipe

Numerical analysis of various conditions was carried out in order to investigate the influence of the terminal outlet and the branch outlet on the flow characteristics of the water delivery pipe.

4.1. Influence of terminal pipe diameter

Numerical calculation was performed by changing the terminal outlet diameter $D'/D$ from 0.1 to 0.7 while fixing the discharge outlet diameter at $d/D=0.6$. The computational results are shown in figure 8. Figure 8(a) shows the discharge flow rate from the branch and the terminal outlets, and figure 8(b) shows the effective flow area of each outlet. The flow rate from the branch outlets was small at the upstream and the flow rate increased as it went to downstream. The effective flow area was also small at the upstream and increased at the downstream. The variation tendency in the discharge flow rate and the effective flow area with respect to the distance from the inlet did not change even if the terminal pipe diameter was changed. A slight change of the terminal size caused a change in the outflow of all discharge outlets and the effective flow area. The terminal pipe diameter was considered to be one of the factors that greatly influenced the flow of the water delivery pipe.
Numerical calculation was performed by changing discharge outlet diameter $d/D$ from 0.2 to 0.8 while fixing the terminal pipe diameter at $D'/D=0.25$. The results are shown in figure 9. Figure 9(a) shows the discharge flow rate from outlets, and figure 9(b) shows the effective flow area. It can be seen that when the size of the outlet diameter changed, the tendency of the discharge water changed greatly. In the case of $d/D=0.2$, the flow rate was almost constant for all the outlets, and the effective flow area was almost 1.0. This indicated that water flowed out from the whole outlet area without inflowing air into the branch pipe. When $d/D=0.2$, it can be seen that the equal flow rate was achieved. When $d/D$ was larger than 0.4, the flow rate increased on the downstream side. As the $d/D$ increased, the difference of the flow rate between the upstream side and the downstream side gradually increased. A similar trend was also seen in the change in effective flow area. As the $d/D$ increased, the difference of the effective flow area between the upstream side and the downstream side changed greatly. It was also found that the outlet diameter $d/D$ greatly influences the flow characteristics of the water delivery pipe.
5. Conclusion
We carried out the numerical calculation and the experimental measurements on a water delivery pipe with six branch pipes and one terminal pipe. As a result of investigating the water discharge characteristics from the outlets, the following conclusions were obtained.

(1) Numerical calculation method using commercial software was established. Since computational results and experimental results showed good agreement, the validity of the numerical calculation method was confirmed.

(2) At the discharge outlet, the flow mixed in air and water was formed and the effective flow area of water was observed. The effective flow area increased as it went downstream. In the flow of the water delivery pipe, it was a major feature that there was an effective flow area of water. The discharge flow rate also increased as going downstream.

(3) The outflow characteristics greatly changed depending on the size of the terminal pipe. It is considered that the terminal pipe was one of the main factors determining the outflow characteristic of the water delivery pipe.

(4) When the discharge outlet diameter was small, the discharge flow rate from each outlet became equal. However, as the outlet diameter became larger, the flow rate decreased on the upstream side, and the flow rate increased as it goes to the downstream side. The outlet diameter greatly influenced the flow of the water delivery pipe.

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