THIN FLOW HEADER TO DISTRIBUTE FEED WATER FOR COMPACT HEAT EXCHANGER

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ABSTRACT

Flow header to distribute a fluid to small multiple pipes is commonly used in boilers and heat exchangers. The system contributes to raise the heat transfer efficiency in the components. The flow distribution mechanism of the header has been studied and the calculation procedure for the design has also been recommended for a single-phase condition. The most parts of these studies have been focused on the header of round pipes. The thin rectangular flow header is preferable for the compact design of heat exchanger. However the flow behavior and distribution mechanism in the thin header is not well understood. The experimental study was conducted with several kinds of thin rectangular and small square headers, and the conventional prediction method with a simple iteration procedure to obtain the distribution behavior was modified to take account of the frictional pressure loss in the header.

INTRODUCTION

In boilers and heat exchangers, a horizontal header to distribute a fluid to multiple branch pipes is often used. The multiple branch pipes contribute to raise the heat transfer and thermal efficiency of plants.

Recently, the more compactness and higher efficiency are required on the industrial equipments and the facilities such as the heat exchangers. Thin rectangular flow header is preferable for compact design of heat exchanger. The distribution mechanism in the horizontal thin rectangular and small square header is not well understood.

Kubo et al. [1] used 4 kind of round pipes as horizontal header to measure the distributed water flow to each pipe and pressure difference in header. The headers inner diameter were ϕ20, 25, 30 and 35 mm. The headers had 10 branch pipes whose inner diameter was ϕ10 mm. Approximately a uniform distribution was obtained in the largest header of ϕ35 mm, and a non-uniform distribution was obtained in other headers. Generally the larger flow rate was obtained in the further branch pipe from the header inlet and the stronger non-uniformity of flow distribution was observed in the smaller header. They also indicated that the smaller ratio of header to branch pipe cross-sectional area, m, resulted as the smaller pressure recovery coefficient, η, in header.

Osakabe et al. [2] proposed the prediction method for water distribution behavior in horizontal header. The simple iteration procedure was used and the calculation results agreed well with the experimental water distribution except the very low water flow rate at header inlet. In the conventional prediction methods established by Kubo et al. [1] and Osakabe et al. [2], a frictional pressure loss in the header has been neglected. In a small header, it is pointed out that the frictional pressure loss has to be considered [3]. However the calculation procedure to obtain the distribution behavior has not been well described.

In this study, experimental study was conducted with several kind of horizontal thin rectangular and small square header, and prediction method with the simple iteration procedure for distribution behavior was modified to take account of the frictional pressure loss in the header.

NOMENCLATURE

A	: header cross-sectional area (m^2)
A_s	: branch pipe cross-sectional area (m^2)
D	: equivalent diameter of header (m^2)
d	: branch pipe diameter (m^2)
g	: acceleration due to gravity (m/s^2)
h	: length of branch pipe (m)
L	: interval length between branch pipes (m)
u	: water velocity (m/s)
m	: ratio of cross-sectional area ($=A/A_s$) (-)
p	: pressure (Pa)
q	: distribution flow rate of branch pipe (-)
Q	: total water flow rate at header inlet (m^3/s)
R	: pressure loss coefficient (-)
Re	: Reynolds number of header (-)
Re_s	: Reynolds number of branch pipe (-)
η	: pressure recovery coefficient (-)
λ	: friction loss coefficient (-)
ξ	: inlet distribution loss coefficient (-)
ρ	: density (kg/m^3)
ν	: kinematic viscosity coefficient (m^2/s)

Subscript

i	: number of branch pipe

s : branch pipe
a : atmosphere

EXPERIMENTAL APPARATUS

The experimental apparatus consisted of a horizontal thin header, four vertical branch pipes and upper plenum made of transparent acrylic resin for the observation of the flow pattern. The branch pipes were connected to the header at an interval of 130 mm. The entrance length between the header inlet and the first branch pipe was 600 mm to ensure a fully developed flow in the header. The several kinds of thin header were used for the parametric study. The cross sections of the thin header were 5×10, 5×13, 5×17, 5×20, 5×30, 5×40, 10×10, 10×40, 20×20 and 20×40 mm in height×width. So the maximum height of the thin header was 20mm. The branch pipes were 1000 mm in length and 10 mm in inner diameter.

Water was supplied to the header and distributed into branch pipes, by a constant static head of water tank placed higher than the apparatus. The water was collected in the upper plenums at the end of branch pipes. The ends of branch pipes were released to atmosphere at the upper plenums. The water flow rate was obtained by noting the time interval to accumulate a known level of water in the upper plenums. The flow pattern in the header was visualized by injecting aluminum particles of about 2μm in size at the header inlet.

EXPERIMENTAL RESULTS AND DISCUSSION

Maximum water flow rate of each thin header

Shown in Fig.2 is the relation of maximum flow rate and header cross-sectional area A. The maximum flow rate becomes smaller with reducing the cross-sectional area of header. Water was provided to the header test section by a constant static head of water tank. The decreasing header cross section increases the frictional and other pressure loss in the header and results in a reduction of the maximum water flow rate. When the compactness is needed on the design of header, not only the water distribution behavior but also the total pressure loss in the whole header system has to be considered.

Conventional prediction method for distribution behavior

Conventional prediction method for water flow distribution behavior [2] to each branch pipes only takes account of pressure recovery behavior that occurs due to the decreasing water flow rate in the header with the distributed water flow into the branch pipes. The conventional predictions agree well with the experimental results at the larger cross-sectional area ratio of header to branch pipe except very low water flow rate. The conventional prediction method can give the relation of the flow distribution rates into the branch pipes and the total flow rate at header cross-section of 5×10 and 10×40 mm as shown in Fig.3.

The non-uniform distribution behavior can be observed in the prediction of 5×10 mm header. The higher flow rate in the last pipe is due to the increasing pressure towards the header end with the pressure recovery. By increasing the total water flow rate to the header, the flow rate to the first branch pipe near the header inlet decreases and that to the far end pipe increases.

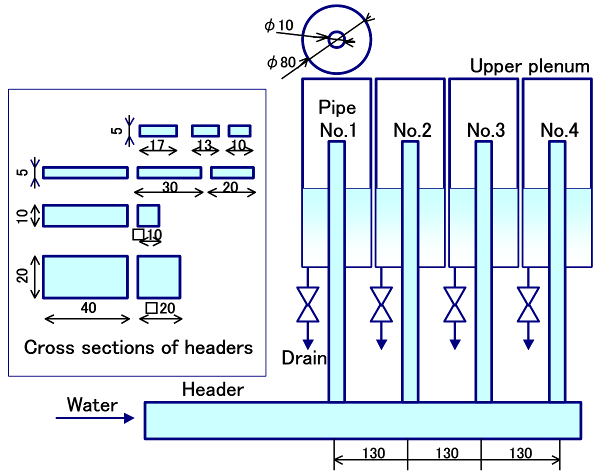

Fig. 1 Schematic of experimental apparatus

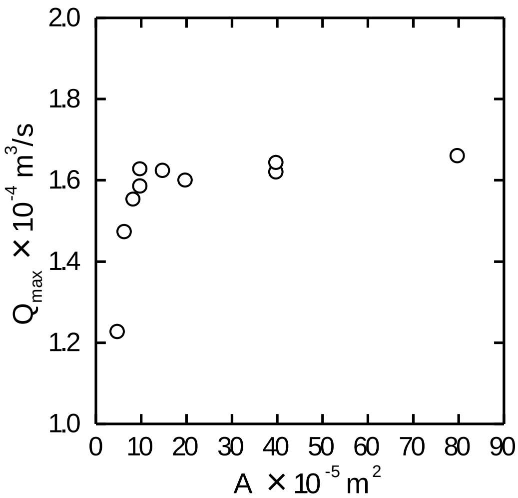

Fig. 2 Relation of header cross-section and maximum flow rate

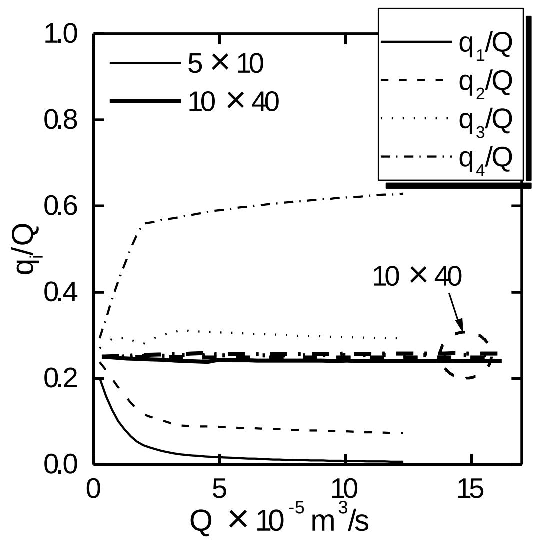

Fig. 3 Conventional predictions

Approximately a uniform distribution is obtained in 10×40 mm header. The water velocity of 10×40 mm header was lower than that of 5×10 mm header. The pressure recovery behavior is larger at the smaller cross-sectional area ratio of header to branch pipe and the larger fluid velocity.

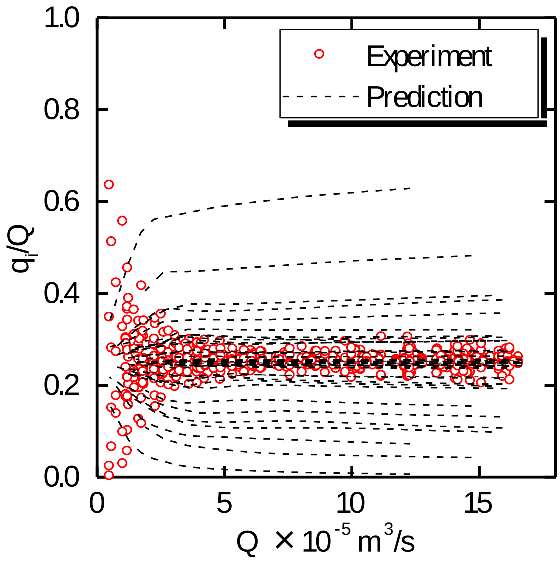

Fig. 4 Comparison of experimental data and conventional predictions

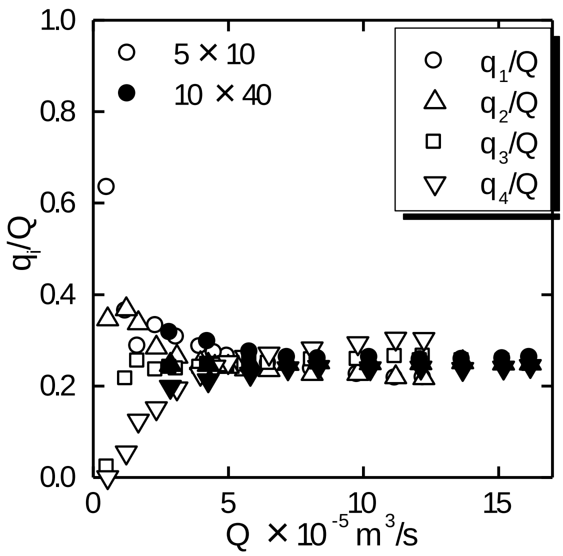

Fig. 5 Experimental water flow distribution

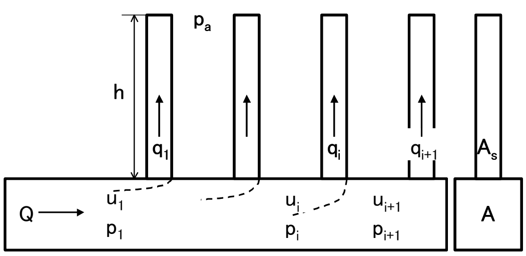

Fig. 6 Schematic of definition in calculation for distribution rate

Thin and small header experiment

Shown in Fig.4 is the comparison of water flow distribution rate, q_i/Q, for present experiment and calculation results by the conventional prediction method in all the 10 headers. The experimental distribution flow rate was 0.2~0.3 when the header inlet flow rate, Q, is larger than 4×10^{-5} m^3/s. When Q is relatively small, non-uniform distributions were observed. In all the non-uniform distributions, the lower flow rate was obtained at the last pipe and the higher flow rate was obtained at the first pipe. Experimental distribution flow rate indicated the different behavior from the conventional prediction result. These results suggest the existence of the other factor for the header pressure calculation except the pressure recovery mechanism.

Shown in Fig.5 is the relation of the experimental water distribution rate to each pipe and header inlet water flow rate in 5×10 and 10×40 mm headers. Experimental results indicate the different behavior in water distribution from the conventional prediction already shown in Fig.3.

The pressure loss in the small header is considered to be large as shown in Fig.2. The header pressures before and after the branch pipe, i, counted from the header inlet are defined as p_i and p_{i+1}, respectively, as shown in Fig.6. The branch pipe flow rate, q_i, is determined with the pressure difference between the inlet and outlet of the branch pipe.

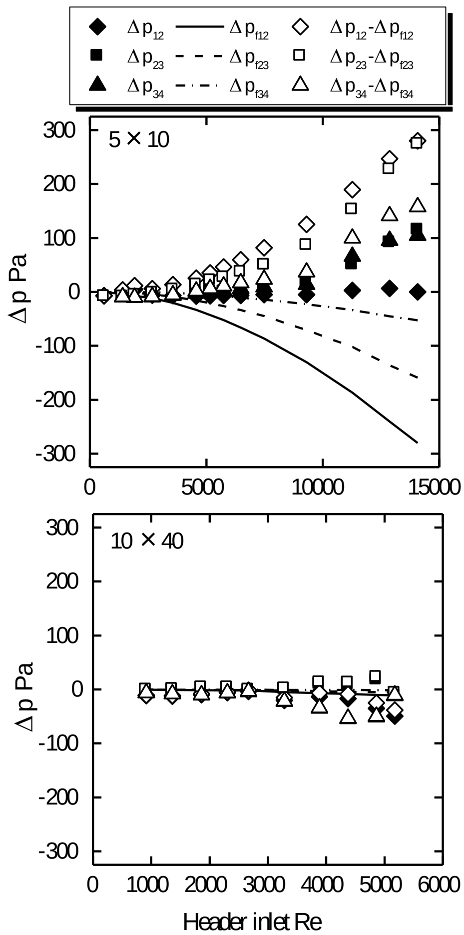

Fig. 7 Comparison of total and frictional pressure loss between branch pipes

For the better understanding of the experimental results, the header pressure, p_i, was calculated from the branch pipe water flow rate, q_i, that is experimentally measured. And the header pressure difference, $\Delta p_{i,i+1}$, was also calculated from the obtained p_i. The header water velocity, u_i, was calculated from the measured water flow rate into each branch pipe and the header frictional pressure loss, $\Delta p_{fi,i+1}$, was calculated by using u_i. These calculation gave the header pressure difference, $\Delta p_{i,i+1}$, header frictional pressure loss, $\Delta p_{fi,i+1}$, and the difference of $\Delta p_{i,i+1}$-$\Delta p_{fi,i+1}$ as shown in Fig.7.

The positive pressure difference means that the pressure is increasing forward the header end. The header pressure difference, $\Delta p_{i,i+1}$, and the header frictional pressure loss, $\Delta p_{fi,i+1}$, at 5×10 mm header that is the largest in the present 10 headers. The existence of large frictional pressure loss declares can not neglect frictional pressure loss in the prediction. The difference, $\Delta p_{i,i+1}$-$\Delta p_{fi,i+1}$, indicates the pressure difference in header except the frictional pressure loss, which consists of the pressure recovery and the pressure losses due to the flow separation and the vortex. The strong pressure recovery is considered to exist in the smallest header of 5×10 mm.

Shown in Fig.8 is schematic of the flow separation and the vortex observed in 5×10 mm header at the header inlet water Re of 5000. The flow separations in the header occurred just after the branch pipe due to the water absorbed into the branch pipe. The largest flow separation was observed at the No. 3 branch pipe. At the far location from header inlet, the header water velocity decreased due to the distributed water to branch pipe and the separation took place in the reverse pressure gradient field. The secondary flow behavior including the separation was observed at the inlet of the furthest branch pipe of No. 4.

The vortexes were also observed at the inside of branch pipe inlet. The largest vortex observed at the inlet side branch pipe. It is considered that the vortexes absorbs the horizontal momentum in the header and contributes to mitigate the pressure recovery in the header.

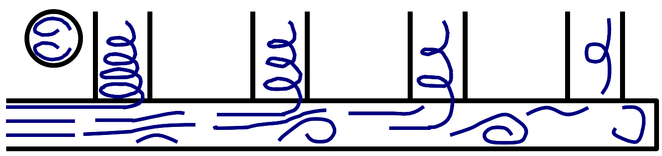

Fig. 8 Schematic of separation and vortex

Modified prediction method of water distribution

The conventional prediction method modified on header frictional loss. By using the pressure recovery coefficient, η, the pressure difference, p_{i+1}-p_i, is expressed as follows:

$$p_{i+1} - p_i = \eta \frac{\rho}{2}\left(u_i^2 - u_{i+1}^2\right) - 4\lambda \frac{L}{D}\frac{\rho u_{i+1}^2}{2} \qquad (1)$$

where ρ is density, λ is friction loss coefficient, L is interval length between branch pipes and D is an equivalent diameter of header. The first term on the right-hand side is the pressure recovery and the second one is the frictional pressure loss. The friction loss coefficient, λ, is defined as,

$$\lambda = 16/\mathrm{Re} \quad \text{for laminar flow} \qquad (2)$$

$$\lambda = 0.079\mathrm{Re}^{-0.25} \quad \text{for turbulent flow} \qquad (3)$$

where Re is the Reynolds number in header(=$u_i D/\nu$), ν is the kinematic viscosity coefficient of water.

It is reported that η is approximately 1 for the flow area ratio, m, of the present apparatus and gradually decreases with a decrease in m [1]. In the present calculation, η was fixed as 1. The pressure difference between the inlet and outlet of the branch pipe is,

$$p_i - p_a = R\frac{\rho}{2}\left(u_i - u_{i+1}\right)^2 m^2 + \rho g h \qquad (4)$$

where g is acceleration due to gravity, h is branch pipe length and suffix "a" indicates atmosphere. The first term on the right-hand side is the pressure loss and the second one is the static pressure difference. The parameter, R, is a pressure loss coefficient defined as,

$$R = \xi + 4\lambda_s \frac{h}{d} \qquad (5)$$

where d is the inner diameter of branch pipe. The inlet distribution loss coefficient, ξ, was assumed to be 0.5 in the present calculation. The frictional loss coefficient, λ_s, is defined as same as λ. The non-dimensional pressure and velocity are defined as:

$$p_i^* = \frac{p_i - p_a - \rho g h}{\rho u_1^2 / 2} \qquad (6)$$

$$u_i^* = \frac{u_i}{u_1} \qquad (7)$$

By using Equations (6) and (7), Equations (1) and (2) become:

$$p_{i+1}^* - p_i^* = \eta\left(u_i^{*2} - u_{i+1}^{*\,2}\right) - 4\lambda \frac{L}{D} u_{i+1}^{*\,2} \qquad (8)$$

$$p_i^* = Rm^2(u_i^* - u_{i+1}^*)^2 \qquad (9)$$

The above Equations (8) and (9) are the basic equations to give a flow distribution in the header.

Shown in Fig.9 is an iteration procedure to obtain the distributions of velocity and pressure in the header. The calculation starts at the velocity condition, $u_1^* = 1$ and an assumed pressure, p_1^*, at the header inlet. Equations (8) and (9) give the next non-dimensional velocity in the header. This procedure yields the whole distribution of pressure and velocity in the header. After that, the assumed initial pressure is modified to give zero velocity in the header just after the last branch pipe. The iteration is continued until zero velocity at the end of header is obtained.

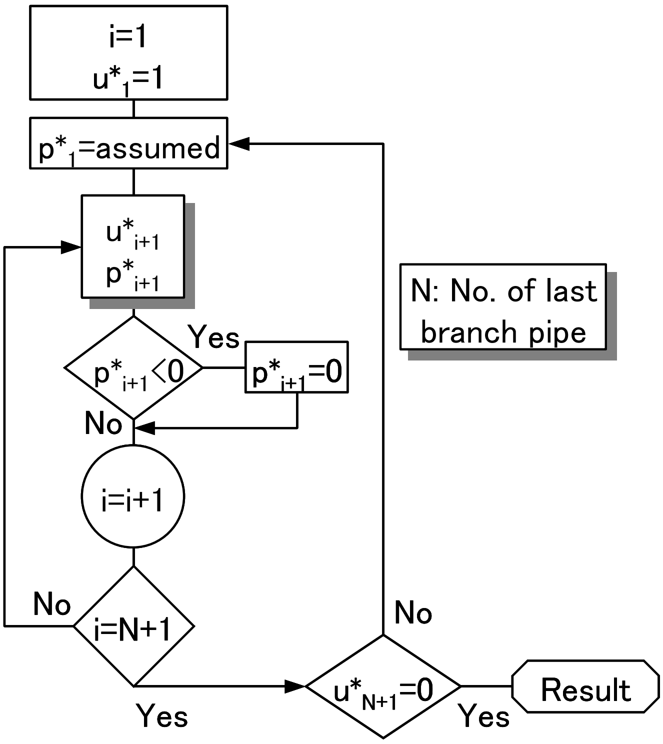

Fig. 9 Iteration procedure

In the conventional calculation procedure [2], it was difficult to take account of the frictional pressure loss in the header due to the instability of the iteration calculation. The calculated pressure in the header sometimes became less than zero and it was impossible to continue the iteration. In the present iteration procedure, the calculated pressures less than zero were automatically presumed to be zero. This new simple procedure successfully ensured the stable iteration procedure.

The above modified calculation procedure gives the flow distribution rate into the branch pipes at 5×10 and 10×40 mm headers, as shown in Fig.10. In the calculation for the header pressure difference, the pressure recovery behavior and the frictional pressure loss are considered.

When Re is relatively large in 5×10 header, the water distribution rate to the last branch pipe is large and the rate to the first pipe is small. By decreasing Re, the flow rate to the last branch pipe is decreasing and that to the first branch is increasing. In the large Re region, the header pressure difference is strongly affected by the pressure recovery behavior and calculation results as the higher flow rate into the end side branch pipe. In small Re region, the pressure difference was strongly affected by frictional pressure loss and calculation results as the higher flow rate into the inlet side branch pipe, that observed in Fig.7. The calculation results give better agreement with the experimental data than the conventional calculation results.

The calculated modified prediction method agrees well with the experiment results in 10×40 header in the large Re region. However the prediction can not calculate the large deviation of distribution rate at the small Re region. The larger water distribution rate to the first pipe was observed in the experiment in spite of the relatively uniform distribution of the prediction. These differences between the experimental and calculated results would be improved with the new prediction method that take account of the flow separation, the vortex and the other pressure loss mechanism in header.

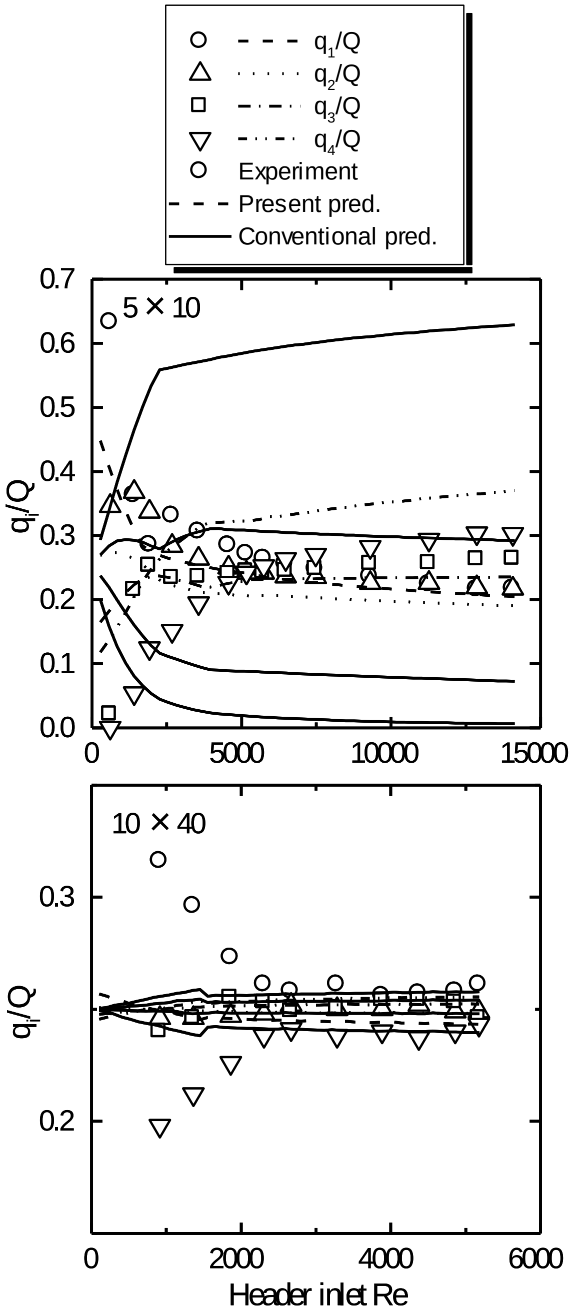

Fig. 10 Effect of frictional pressure loss in predictions

Comparison of thin and square cross-section of header

Shown in Fig.11 is the comparison of water flow distribution rate into the branch pipes between the thin rectangular header and the square header of the same cross-sectional area of A=1.0 $\times 10^{-4}$ and 4.0×10^{-4} m^2. By decreasing the header inlet water flow, the non-uniform distribution appeared at the larger flow rate in thin rectangular header compared to the square header. The header pressure losses that consist of the friction, the flow separation and the vortex, is considered to be larger in the thin header than the square header due to the secondary flow.

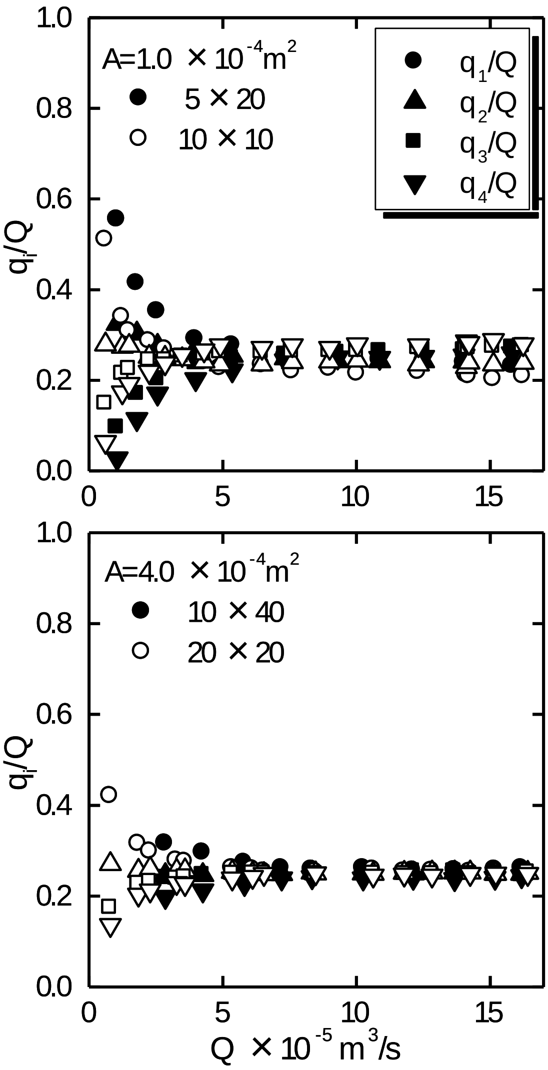

Fig. 11 Comparison of thin rectangular and square section of header

CONCLUSIONS

Distribution behavior of water was experimentally studied in the horizontal thin rectangular headers and the square headers with four vertical branch pipes. The following major results were obtained:

1. The maximum total water flow rate to the header system under a constant water head condition became smaller with decreasing the cross-sectional area of header. This behavior is considered to be due to the increased pressure loss in the smaller header system.
2. When the water flow rate in the header inlet was small, the non-uniform distribution to the branch pipes were observed. This behavior was considered to be due to the large effect of pressure loss in the header more than the pressure recovery effect. The pressure losses were considered to be due to the friction, the flow separation, the vortex and the secondary flow.
3. When the header inlet flow rate was large, approximately a uniform distribution rate of 0.2~0.3 to 4 branch pipes was observed. This behavior at the large flow rate more than 4 $\times 10^{-5}$ m^3/s is considered to be due to the weak pressure recovery behavior suppressed by the pressure losses in the header.
4. The prediction method was modified to take account of the frictional pressure loss. In the conventional calculation procedure, it was difficult to take account of the frictional pressure loss in the header due to the instability of the calculation. In the present iteration procedure, the calculated pressures less than zero were automatically presumed to be zero. This new simple procedure successfully ensured the stable iteration. The modified prediction results agreed well with the experiment results.
5. The water distribution behaviors were compared between the thin rectangular headers and the square headers of a same cross-sectional area. By decreasing the header inlet water flow rate, a non-uniform distribution appeared at the larger flow rate in thin rectangular header compared to the square headers.

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