THIN FLOW HEADER TO DISTRIBUTE FEED WATER FOR COMPACT HEAT EXCHANGER

Tomoshige NAKAMURA, Sachiyo HORIKI and Masahiro OSAKABE

Tokyo University of Mercantile Marine, Koutou-ku, Tokyo 135-8533, Japan
Phone & FAX +81-3-5245-7404
E-Mail osakabe@ipc.tosho-u.ac.jp

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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. However the thin rectangular flow header is preferable for the compact design of heat exchanger. 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 headers.

The experimental apparatus consisted of thin header, four vertical branch pipes and separators made of transparent acrylic resin for the observation of the flow pattern. The several kinds of thin header were used for the parametric study. The cross sections of the thin header were 40×20, 40×10, 40×5, 30×5, 20×5 and 10×5 mm. 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. The water was collected in the separators at the end of branch pipes. The water flow rate was obtained by noting the time interval to accumulate a known level of water in the separator. The flow pattern in the header was visualized by injecting aluminum particles of about 2μm in size at the header inlet.

The conventional prediction method generally indicates the higher distribution rate at the farther branch pipe from the header inlets due to the pressure recovery in the present thin header. However in the most experiments except the smallest thin header of 10 × 5 mm , the distribution rate was approximately constant at the 1st , 2nd and 3rd branch pipe, and slightly decreased at the 4th pipe. It was considered that the strong vortex generated at the inlet of the 4th pipe decreased the distributed flow rate. In the smallest thin header of 10×5 mm, the distribution rate increased in the flow direction of header as predicted by the conventional prediction method taking account of the pressure recovery in the header. The conservative evaluation method for the thin header was also proposed.

NOMENCLATURE

A: flow area of header
A_S: flow area of branch pipe
d: inner diameter of branch pipe
g: acceleration due to gravity
h: length of branch pipe
m: ratio of flow area of header to that of branch pipe(=A/A_S)
p: pressure
q: distribution water flow rate to branch pipe
Q: total water flow rate to header
R: pressure loss coefficient
Re_S: Reynolds number in branch pipe
u: velocity
η: pressure recovery coefficient
λ: friction loss coefficient
ν: kinematic viscosity
ρ: density
ξ: distribution loss coefficient

subscript
i: branch pipe number, s: branch pipe

INTRODUCTION

In boiler and heat exchangers, a horizontal header to distribute a fluid into multiple branch pipes is often used. The multiple branch pipes contribute to raise the heat transfer and thermal efficiency of plants. Recently, a condensation-type economizer of small boiler has been planned and developed to the raise the thermal efficiency and decrease the emission of CO_2 (Osakabe, 1999b, 2000). When the additional economizer for the ultimate heat recovery was considered, the compact design was very important. For the purpose, the bare tube of small diameter and the thin flow header was proposed. The knowledge of the flow distribution behavior for the thin flow header was considered to be the most important for the performance of the compact heat exchanger.

The distribution mechanism is well understood and guidelines for the circular header design have been established for single-phase flow (Kubo and Ueda, 1968). For the horizontal header for heat exchanger, Esaki et al. (1990) also has examined about several kinds of experimental parameters such as the length of branch pipe or the length of header etc. On the other hand, fundamental study of the T-junction for the rectangle cross-section is also carried out with a numerical simulation by some researchers. For example, Neary and Sotiropoulos (1996) have reported on laminar flow through 90-degree diversions of rectangular cross-section by numerical method. However, an experimental research on a thin rectangular header is very limited.

This paper has made clear the water distribution behavior of thin rectangular header by measuring the distribution rate to each branch pipe and visualization by aluminum particles. The empirical correlation for the pressure recovery coefficient was proposed.

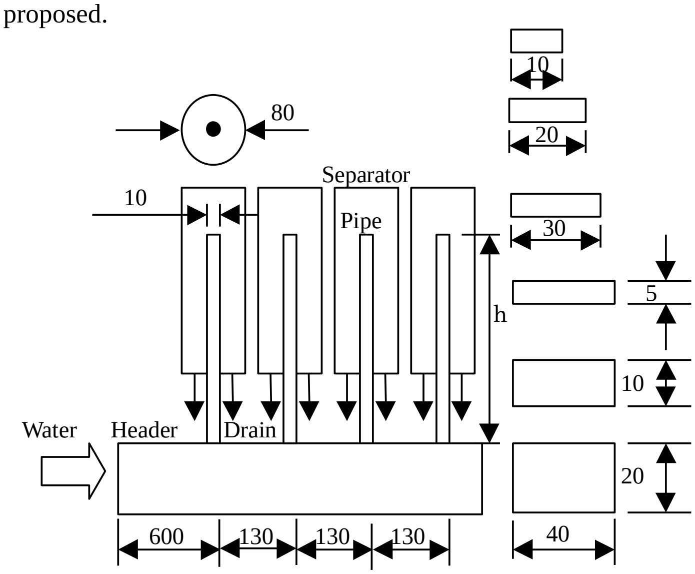

Fig. 1 Schematic of experimental apparatus

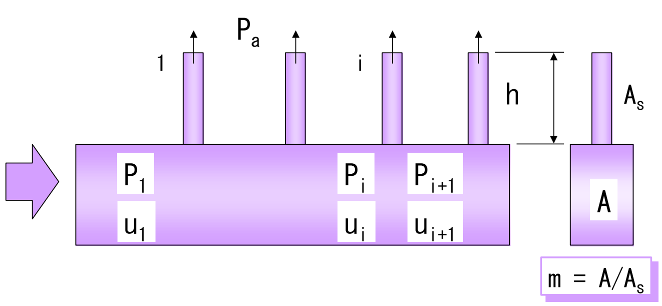

Fig. 2 Notation for calculation procedure

EXPERIMENTAL APPARATUS AND METHOD

Shown in Fg.1 is a schematic diagram of the experimental apparatus. The experimental apparatus consisted of thin header, four vertical branch pipes and separators 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 40×20, 40×10, 40×5, 30×5, 20×5 and 10×5 mm. The branch pipes were 1000 mm in length and 10 mm in inner diameter.

The water flow rate to the header was maintained at 8.5～15.8m^3/s. Water was supplied to the header and distributed into branch pipes. The water was collected in the separators at the end of branch pipes. The water flow rate was obtained by noting the time interval to accumulate a known level of water in the separator. The flow pattern in the header was visualized by injecting aluminum particles of about 2μm in size at the header inlet. The visualized flow pattern was recorded by the video camera.

PREDICTION METHOD OF WATER DISTRIBUTION

The header pressures before and after the branch pipe, i, counted from the header inlet are define as P_i and P_{i+1}, respectively, as shown in Fig.2. The ratio of the header flow area, A, to the branch pipe flow area, A_S, is defined as $m(=A/A_S)$. By using the pressure recovery coefficient, η, the pressure difference, P_i - P_{i+1}, is expressed as follows;

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

where u is velocity, ρ is density. It is reported that η is approximately 1 for the flow area ratio, m, is enough the large and gradually decreases with a decrease in m(Kubo & Ueda, 1968). The estimation method of η is discussed in the below.

The pressure difference between the inlet and outlet of the branch pipe is,

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

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,

$$R = \xi + 4\lambda \frac{h}{d} \qquad (3)$$

where d is the inner diameter of branch pipe. The inlet distribution loss coefficient, ξ, was assumed as 0.5 in the present calculation. As a uniform distribution can be obtained with a larger value of R, 0.5 is used as a conservative value. The friction loss coefficient, λ, is defined as,

$$\lambda = 16/Re_S \quad \text{for laminar flow,} \qquad (4)$$

$$\lambda = 0.079\,Re_S^{-0.25} \text{ for turbulent flow,} \quad (5)$$

where Re_S is the Reynolds number in a branch pipe($=u_S d/\nu_L$), u_S is water velocity in branch pipe. The non-dimensional pressure and velocity are defined as,

$$p_i^* = \frac{p_i - p_a - \rho gh}{\rho u_1^2/2} \quad (6)$$

$$j_i^* = \frac{j_i}{j_1} \quad (7)$$

By using Eqs.(6) and (7), Eqs.(1) and (2) become;

$$p_{i+1}^* - p_i^* = \eta\left(u_i^{*2} - u_{i+1}^{*\,2}\right) \quad (8)$$

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

The above Eqs.(8) and (9) are the basic equations to give a flow distribution in the header(Osakabe et al., 1999a). The important parameters in the equations are the flow area ratio, m, pressure recovery coefficient, η, and the pressure loss coefficient, R.

PRESSURE RECOVERY COEFFICIENT

A momentum balance in a horizontal header with a mass effluent rate of m_S into the vertical branch pipe as shown in Fig.4 gives,

$$dp = \rho u^2 - (\rho u - m_S)(u + du) - m_S u \quad (10)$$

The third term on the right hand side of Eq.(10) takes account of the effluent rate of the horizontal momentum into the branch pipes. When only the vertical flow is allowed in the branch pipes, the effluent momentum term in the horizontal header should be zero. However, it is possible that the horizontal momentum can be carried into the branch pipe with a secondary flow in the pipe. By using $m_s = -\rho du$ and neglecting the higher-order small term, Eq.(10) becomes,

$$dp = -\rho u du \quad (11)$$

By integrating Eq.(11),

$$p_{i+1} - p_i = \frac{\rho}{2}\left(u_i^2 - u_{i+1}^2\right) \quad (12)$$

Equation (12) is equal to Eq.(1) with the pressure recovery coefficient η= 1. When the effluent momentum is $m_S u$, the coefficient η becomes 1.

Shown in Fig.5 is the relation of water distribution rate to each pipe at the water velocity u_1=2.42, 2.04 and 1.70m/s for the smallest header of 5×10mm in this study. The nonuniform distribution behavior can be observed. The higher flow rate in the last pipe is due to the higher pressure in the header generated with the pressure recovery. The predictions were conducted at the different pressure recovery coefficients. As the result, the prediction using η =0.24 agreed well with the experimental result.

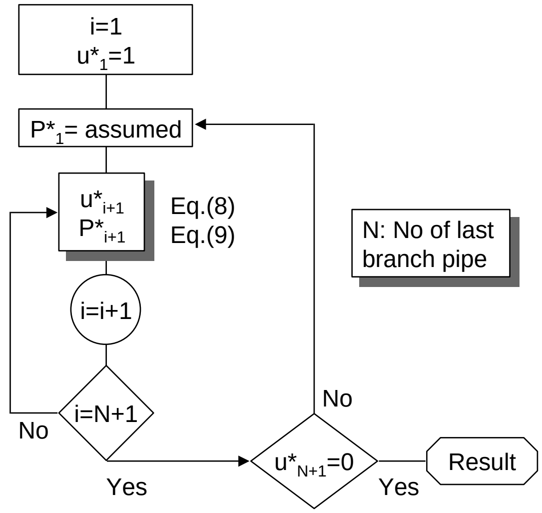

Fig. 3 Iteration procedure

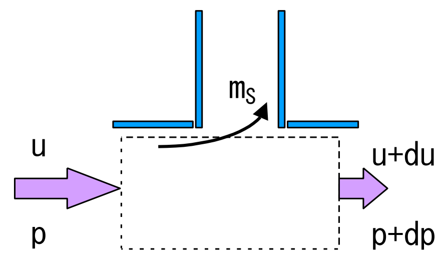

Fig. 4 Momentum balance in horizontal header

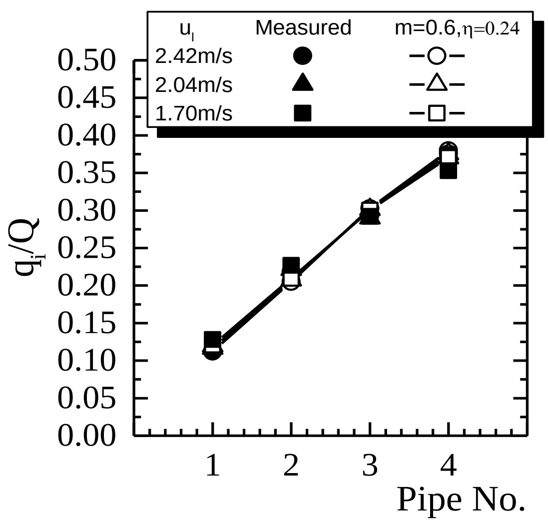

Fig. 5 Water distribution flow rate to each pipes on the smallest test header of 5×10mm.

It is reported that η is approximately 1 for the flow area ratio, m, is enough large and gradually decreases with a decrease of the ratio m (Kubo & Ueda, 1968). When the header becomes smaller, the frictional loss increases and the pressure recovery behavior might be depressed. Shown in Fig.6 is the relation between η and m. By using the data by Kubo & Ueda and the present smallest header of 5×10mm, the following relation can be obtained.

$$\eta = 1 - e^{-0.4m} \tag{13}$$

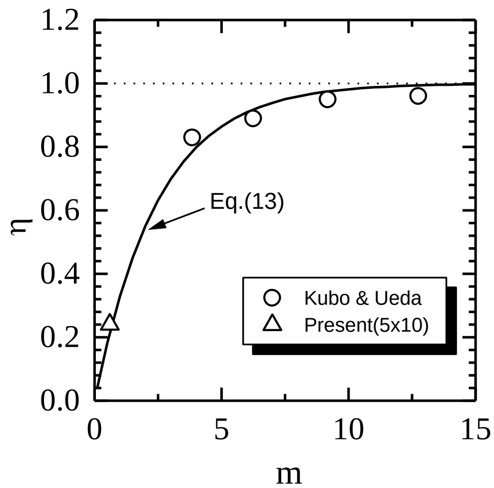

Fig. 6 Pressure recovery coefficient

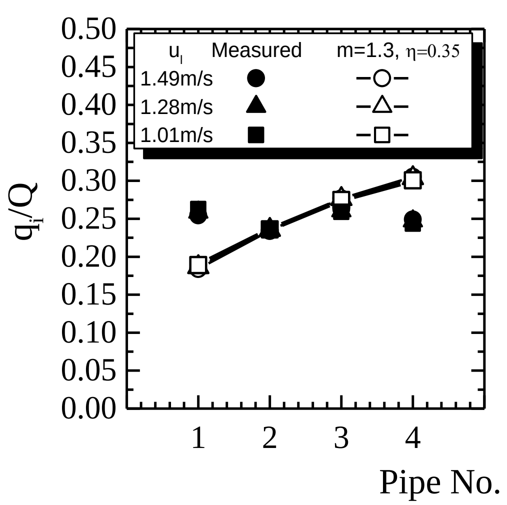

Fig. 7 Water distribution flow rate to each pipes on the test header of 5×20mm.

EFFECT OF HEADER WIDTH

Shown in Fig.7 is the relation of water distribution rate to each pipe at the water velocity u_1=1.49, 1.28 and 1.01m/s for the test header of 5×20mm which width is larger than that in the smallest header by 10mm. The flow distribution behavior is completely different from that in the smallest header of 5×10mm. The pressure recovery behavior disappeared by increasing the width only by 10mm. The prediction indicates the larger distribution rate at the farther pipe due to the pressure recovery. In the calculation, the pressure recovery coefficient η was 0.35 with Eq.(13) using the flow area ratio m of 1.3 for this header size. It is considered that the side flow appeared due to the widening of width as shown in Fig.8. The side flow mitigated the pressure recovery behavior in the header. It should be noted that the prediction with Eq.(13) gives a conservative evaluation for the thin header.

Shown in Fig.9 is the relation of water distribution rate to each pipe at the water velocity u_1=1.04,0.86 and 0.66m/s on the header of 5×30mm farther increasing the width by 20mm.

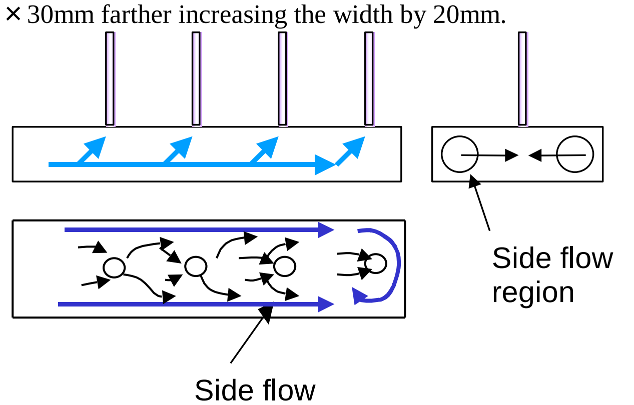

Fig. 8 Side flow region generated in the thin header

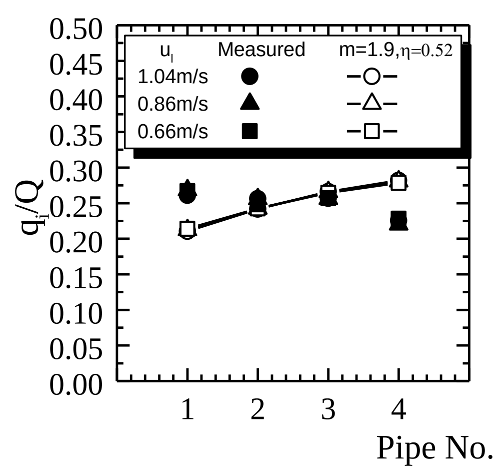

Fig. 9 Water distribution flow rate to each pipes on the test header of 5×30mm.

The measurement indicates that the distribution rate slightly decreases in the flow direction. Especially, the distribution rate of the 4th pipe is small compared to those of the other pipe. However, the prediction indicates the gradual increase in the flow direction.

Shown in Fig.10 is the flow pattern just under the 4th branch pipe in the 5×30 header. The photograph was taken from the bottom of header. The twin large vortex can be seen around the branch pipe. It is considered that the strong vortex decreased the flow rate to the branch pipe. On the other hand, the clear vortex could not be observed in the smallest header of 5×20mm.

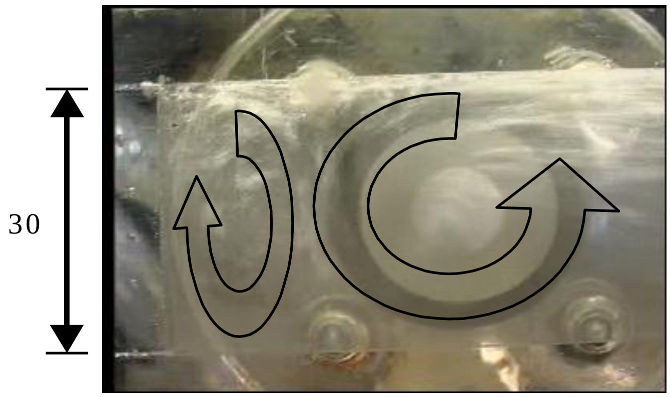

Fig. 10 Flow pattern just under the 4th branch pipe on the test header of 5×30mm

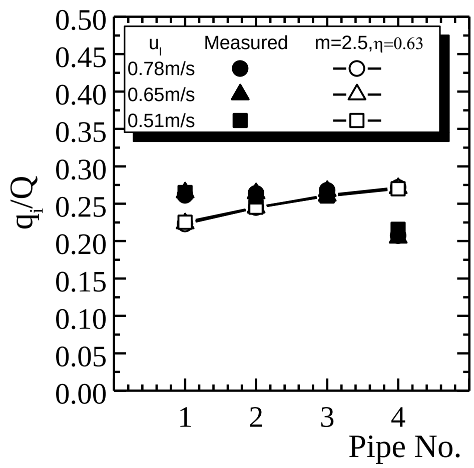

Fig. 11 Water distribution flow rate to each pipes on the test header of 5×40mm.

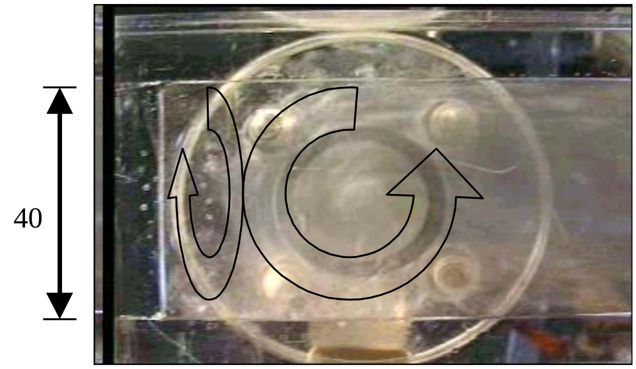

Fig. 12 Flow pattern just under the 4th branch pipe on the test header of 5×40mm

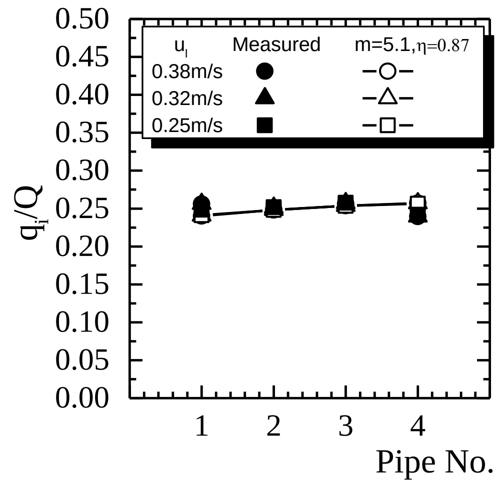

Fig. 13 Water distribution flow rate to each pipes on the test header of 10×40mm.

Shown in Fig.11 is the relation of water distribution rate to each pipe at the water velocity u_1=0.78,0.65 and 0.51m/s in the header of 5×40mm increasing the width by 30mm. The prediction indicates the slight increase of distribution rate in the flow direction of header. However, the experimental distribution rate was approximately constant at the 1st, 2nd and 3rd branch pipe. The distribution ratio of 4th pipe is smaller than the others.

Shown in Fig.12 is the flow pattern just under the 4th branch pipe in the 5×40 header. The photograph was taken from the bottom of header. The large vortex can be seen around the branch pipe. It is considered that the strong vortex decreased the flow rate to the branch pipe. The existence of the side flow mitigates the pressure recovery behavior but generates the vortex at the end of thin header.

EFFECT OF HEIGHT

Shown in Fig.13 is the relation of water distribution rate to each pipe at the water velocity u_1=0.38, 0.32 and 0.25m/s in the header of 10×40 mm which height is larger that of 5×40 by 5mm The prediction indicates the slight increase of distribution rate in the flow direction of header. However, the experimental distribution rate was approximately constant. In the comparison of Figs. 11 and 13, it should be noted that the distribution rate to the 4th pipe increased with the increase of header height. This behavior is corresponding to the attenuation of vortex at the header end.

Shown in Fig.14 is the relation of water distribution rate to each pipe at the water velocity u_1=0.20, 0.16 and 0.13m/s in the header of 20×40 mm. In this case, the prediction and the experimental flow rate agree well. The vortex at the 4th pipe was completely attenuated and could not be observed.

By increasing the height in the thin header, the vortex at the header end could be eliminated and the uniform distribution could be obtained.

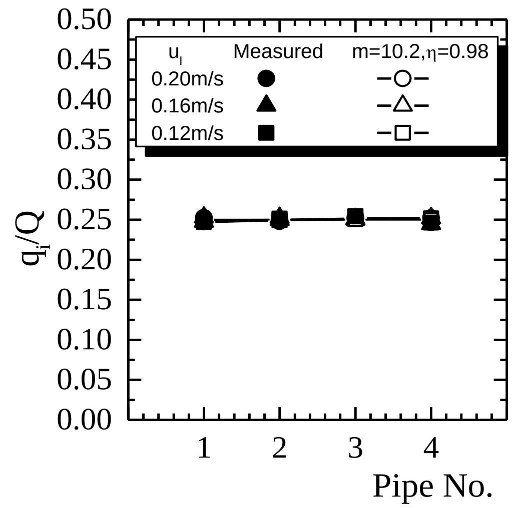

Fig. 14 Water distribution flow rate to each pipes on the test header of 20×40mm.

CONCLUSION

Distribution behavior of single-phase flow was experimentally studied in several kinds of thin-type header with four vertical branch pipes of 10mm in inner diameter. The following major results were obtained:

(1) In the smallest thin header of 10×5 mm, the distribution rate increased in the flow direction of header as predicted by the conventional prediction method taking account of the pressure recovery in the header. By using the previous data for round pipe header and the present smallest header, the empirical correlation for the pressure recovery coefficient was proposed. The pressure recovery coefficient decreased with a decrease of the flow area ratio of header to branch pipe.

(2) The pressure recovery behavior disappeared by increasing the width only by 10mm from the smallest header of 5×10mm. The side flow appeared due to the widening of width and mitigated the pressure recovery behavior in the header.

(3) The existence of the side flow successfully mitigated the pressure recovery behavior but generates the vortex at the end of thin header. It was considered that the strong vortex generated at the end decreased the distributed flow rate to the 4th pipe.

(4) By increasing the height in the thin header, the vortex at the header end could be eliminated and the uniform distribution could be assured.

(5) The conventional prediction method using the proposed pressure recovery coefficient generally indicated the higher distribution rate at the farther branch pipe from the header inlets. The method is useful for the conservative evaluation of thin header.

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