

Article

# Heat Transfer Enhancement of Circular- and Petal-Shaped Double-Tube-Type Heat Exchangers by Triple Ones

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Received: 16 November 2020; Accepted: 12 December 2020; Published: 14 December 2020



**Abstract:** Conventional circular double or triple tube type heat exchanger, DHE or THE, is one of the compact heat exchangers; a large number of studies have been performed to improve their heat transfer performance. The authors demonstrated that a petal-shaped special DHE with a large wet perimeter yields a high heat transfer efficiency,  $\eta$ . In this study, the DHE with six or five petals-, five shallow petals-, and circular-inner tubes were used. To further improve the  $\eta$  of the DHE, a THE with a petal-shaped inner tube along with the middle and outer circular tubes were used. Hot water flowed through the inner tube and cold water flowed through the middle and outer tubes as a counter current flow. The heat transfer was approximately equal; however, the flow resistance (pressure loss) of the outer tube of the DHE could be decreased using the middle and outer tubes under the same amount of cold water as the DHE; consequently, the  $\eta$  could be improved. In addition, the effect of changing the flow path of the hot- and cold-water flows on the  $\eta$  was examined.

**Keywords:** double and triple tube heat exchangers; petal-shaped tube; large wet perimeter; heat transfer enhancement; heat transfer efficiency

## 1. Introduction

From the viewpoint of energy and resource reductions improvement in the heat transfer performance, h.t.p., of heat exchangers is required. A heat exchanger is generally a device to transfer thermal energy from hot fluid to cold fluid and many types exist for different practical applications. A large number of studies on their h.t.p. and enhancement have been carried out from a fundamental and applied perspective in the last half century. As a result, many things have become clear, and recently, there have been few studies on them except for special ones.

General circular double and triple tube heat exchangers, CP-tube and CP-tri-tube, are widely used as a condenser, vaporizer, sub-cooler, heat recovery exchanger, crystallizer, etc. in industry [1,2]. Many studies to improve the h.t.p. of double tube heat exchangers have been performed; for example, by using a non-circular tube instead of circular inner tube or by inserting a twisted tape in the tube [3–6]. Promvong, et al. [4] demonstrated heat transfer enhancement using a helical-ribbed tube with double twisted-tape inserted. A triple tube heat exchanger consisting of concentric tubes has also been examined [1,7,8]. Rădulescu, et al. [1] presented a theoretical analysis of h.f.t. of double concentric tube heat exchanger, or triple one.

The authors studied the improvement of the h.t.p. of the CP-tube using a petal-shaped special double tube with a large wet perimeter [9–11]. The flow and h.t.p. of a petal-shaped double tube with six or five petals, 6P- or 5P-tube, and their h.t.p. were studied [11]. The wet perimeters of the

6P- and 5P-tubes were 2.44 and 1.80 times of the CP-tube, respectively. A test tube was fabricated using copper, and the outer diameter, length and wall thickness are 22.0 mm, 2400 mm and 1.0 mm, respectively. It had a petal-shaped special inner tube and outer tubes which are pressed against each other. Hot water of about 60 °C flowed through the inner tube at the Reynolds number scaled by a circle equivalent diameter  $Re_e = (0.4 - 2.5) \times 10^4$ ; cold water of about 20 °C flowed as a counter current flow through the outer tube at the flow rate of  $V_{out} = 8.0$  (L/min), and the outside was insulated. The heat transfer of the 6P-tube with the largest wet perimeter reached the maximum; however, the flow resistance was the largest because of the largest wet perimeter. Subsequently, the h.t.p. of the 5P-tube became the maximum, i.e., about 1.5 times of the general CP-tube at a mean velocity of hot water,  $w \approx 0.4 - 1.0$  m/s. Next, the effects of void fraction of air-water, two-phase, bubble flow through the inner tube of the petal-shaped double tube on the flow and heat transfer characteristics were investigated [10]; subsequently, to further enhance the h.t.p. of the 5P-tube, the optimal shape of cross section of the double tube was studied. A 5P'-tube with a five-shallow-petal-shaped inner tube with a smaller wet perimeter than the 5P-tube was proposed. This presented a much smaller pressure loss than the 5P-tube; consequently, the h.t.p. was improved.

In this study, to further improve the h.t.p. of the 5P-tube, the reduction of a large flow resistance (pressure loss) of the outer tube is studied using a triple tube, 5P-tri-tube, and others; a good h.t.p. is shown. In this case, hot water of 60 °C flowed through the inner tube and cold water of 20 °C flowed through the middle and outer tubes as a counter current flow. The heat transfer was approximately equal; however, the flow resistance (pressure loss) of the outer tube of the double-tube-type heat exchanger (DHE) could be decreased using the middle and outer tubes of the triple-tube-type heat exchanger (THE) under an equal flow rate of cold water because the velocities of the cold water are smaller than that of the DHE; consequently, the  $\eta$  could be improved considerably. For example, the  $\eta$  of the 5P'-tri-tube to the 5P-tube was  $\eta = 10.5 - 2.0$  in the range of  $Re_e = 0.4 \times 10^4$  to  $1.3 \times 10^4$  under the flow condition of flowing hot water through the center tube and cold water of 4.0 (L/min) through the middle and outer tubes. The effect of changing the flow paths of the hot- and cold-water flows on the h.f.p. is examined. The results obtained will be very useful for enhancing the h.f.p. of the actual devices mentioned before

## 2. Experimental Apparatus and Procedure

### 2.1. Petal-Shaped Triple Tube and Cross Section

Figure 1 shows an outline of the triple tube-type heat exchanger (THE). The total length of the tube fabricated using copper is 2.4 m and the outside is covered by an insulator. The THE consisted of a petal-shaped special inner tube (inner), middle tube (middle) and outer circular tube (outer), and the outer diameter and thickness of the middle tube are 22.0 and 1.0 mm, respectively; the inner diameter and thickness of the outer tube are 25.6 and 1.5 mm, respectively. The inner tube is crimp-connected to the outer tube and is supported by connectors at both ends.

Figure 2 shows the cross section of the triple tubes used and the size is shown in Table 1. Three kinds of triple tubes were used. The first and second triple tubes, 6P- and 5P-tri-tubes, consist of the six- and five-petal-shaped inner tubes, middle tube and circular outer tubes. The petal shaped inner tube was made by drawing, and the inner tube and middle tube of 6P- and 5P-tubes were pressed against each other. The third triple tube was a 5P'-tri-tube that consisted of a five shallow-petal-shaped inner tube as well as middle and circular outer tubes. The CP-tri-tube and CP-tube (CP-double-tube) were used for comparison with the petal-shaped triple tube. The CP-tube [11] is the result of removing the outer tube from the CP-tri-tube. The inner diameter of the CP-inner tube was equal to the equi-area diameter of the 6P-inner tube. As will be described later, since the wet perimeter  $p_{6P}$  of the inner tube of the 6P-tube is very large and consequently the hydraulic diameter  $d_h$  becomes very small. For example, the  $d_h$  corresponding to the  $p_{6P}$  of the inner tube is  $d_{h6P} = 5.1$  mm though the equivalent diameter is  $d_e = 12.2$  mm. This seems too small and consequently we used the CP-tube with the equivalent

diameter. Each tube has been fabricated such that the area of the cross sectional is almost equal and the difference is within  $\pm 7\%$ . Meanwhile, the wet perimeter  $p$  of the inner tube is very different and the  $p$  of the 6P-, 5P-, 5P'-, and 5P'- tri-tubes are 2.44, 1.80, and 1.11 times of the CP-tube, respectively.

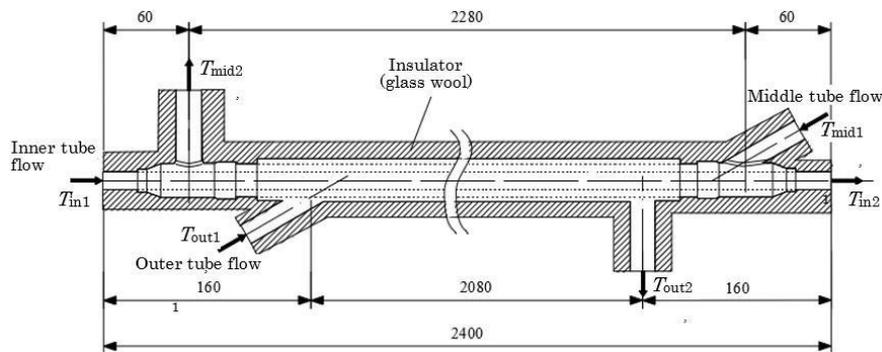


Figure 1. Outline of petal shaped triple-tube.

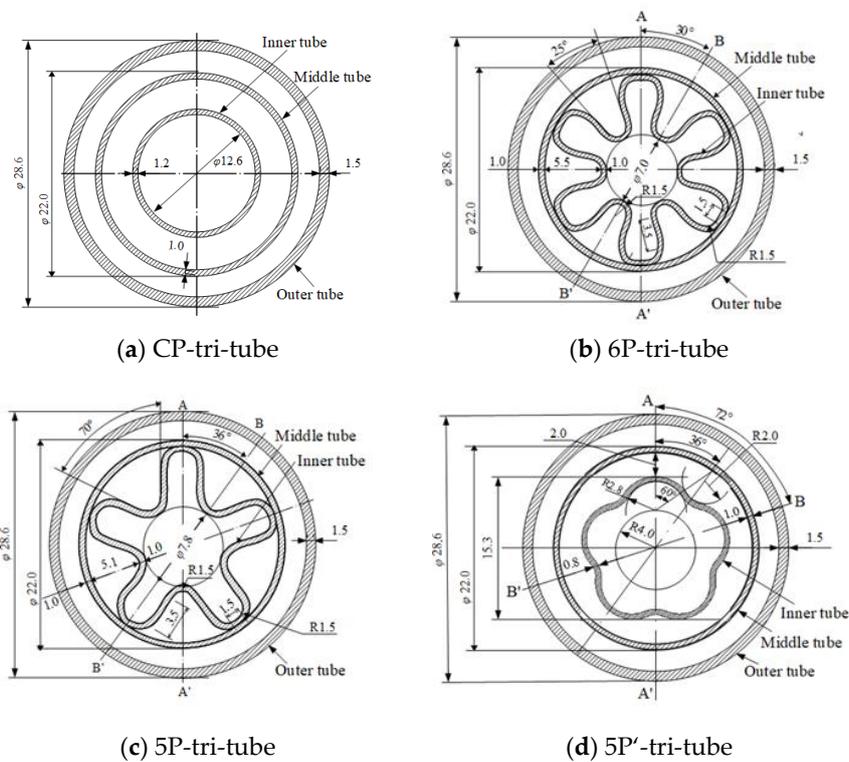


Figure 2. Triple tube heat exchanger (Cross section).

Table 1. Dimensions of cross section of triple-tube type heat exchanger.

	6P-tri-tube			5P-tri-tube			5P'-tri-tube			CP-tri-tube		
	Inner	Middle	Outer	Inner	Middle	Outer	Inner	Middle	Outer	Inner	Middle	Outer
*Area of cross section: $A$ [mm <sup>2</sup> ]	124.0	108.0	130.6	131.0	130.0	130.6	132.2	134.7	130.6	124.7	137.5	130.6
*Wet perimeter: $p$ [mm]	96.5	120.0	149.2	71.2	121.4	149.2	44.0	113.1	149.2	39.6	110.0	149.2
Ratio to CP-tri-tube	2.44	1.009	—	1.30	1.10	—	1.11	1.03	—	—	—	—
*Equivalent diameter: $d_e$ [mm]	12.6	11.7	12.9	12.9	12.9	12.9	13.0	13.1	12.9	12.6	13.2	12.9
*Hydraulic diameter: $d_H$ [mm]	5.1	3.6	3.5	7.3	4.3	3.5	12.0	4.8	3.5	—	5.0	3.5

Table 1 shows the area of the cross section  $A$ , wet perimeter  $p$ , equivalent diameter  $d_e$ , and hydraulic diameter  $d_h$  for each test tube.

## 2.2. Experimental Procedure

### 2.2.1. Measurements of Flow Rate and Pressure Loss

The flow resistance, or pressure loss,  $\Delta P$  of each tube of the inner-, middle- and outer-tubes were measured in the fully developed flow region of 1.4 m interval by static pressure hole with diameter 0.8 mm and an inverted U-shaped pipe manometer.

### 2.2.2. Measurement of Heat Transfer Performance

Hot water of approximately 60 °C flowed through the inner tube and cold water of approximately 20 °C flowed through the middle and outer tubes as a counter current flow. At that time, the temperature difference was set as 40 °C = const. The total flow rate  $V_c$  of the cold water was  $V_c = 8.0$  (L/min) = const. For example, when the cold water flows through the inner tube of the CP-tube the mean velocity is  $w \approx 1.07$  (m/s). Heat transfer  $Q$  was obtained by measuring the temperature difference between the inlet and exit of each tube and the flow rate,  $m$ .

$$Q = mC_p(T_{h1} - T_{h2}) \left[ = mC_p(T_{c1} - T_{c2}) \right] \quad (1)$$

where,  $m$ : mass flow rate;  $C_p$ : the specific heat;  $T_{h1}$  and  $T_{h2}$ : the inlet and exit bulk temperatures, respectively, of the hot water;  $T_{c1}$  and  $T_{c2}$  are those of the cold water, respectively.

The inlet and exit temperatures were measured by a thermocouple of Cu-Co that were set on the center of the tube were verified and confirmed in advance whether they equal the bulk temperature [11]. A flow condition is the case where the flow rate of cold water of the middle- and outer-tubes is 4.0 (L/min). This is shown as (h-c-c, x-4.0-4.0) or (x-4.0-4.0). Another case is when the flow rates of the middle- and outer-tubes are 6.0 and 2.0 (L/min), respectively, and it is shown represented as (h-c-c, x-6.0-2.0) or (x-6.0-2.0). The mean velocity will be used as a reference length and a quantity to organize the pressure loss, heat transfer, and h.t.p. The effect of changing the flow path of the hot- and cold-water flows on the h.t.p. is examined.

### 2.2.3. Reference Length, $L_c$

In general, the hydraulic diameter  $d_h$  is used as a reference length of a noncircular tube, and to organize the pressure loss  $\Delta P$  of the tube, heat transfer  $Q$ , and heat exchange efficiency  $\eta$ , and so-called dimensionless parameters, such as the Reynolds number, are used.

$$d_h = 4A/p \quad (2)$$

where,  $A$ : area of cross section;  $p$ : wet perimeter.

However, in this case, the  $d_h$  of the petal-shaped inner tube becomes extremely small because the wet perimeter is extremely large. For example, the  $d_h$  of the inner tube of the 6P-tube is  $d_{h6p} = 5.1$  mm though the equi-area diameter is  $d_e = 12.2$  mm. In addition, the  $d_h$  is different considerably for the 6P-, 5P-, 5P'-tubes compared with the CP-tube. Furthermore, the velocity distribution at the cross section is largely different between the circular, petal shaped inner and outer tubes [11,12]. For example, the velocity at the petal shaped narrow region of the 6P- and 5P-inner tubes is approximately 60% and 70% of the maximum velocity at the tube center, respectively, and the velocity distribution on the tube wall of the petal shaped tubes will also be different. Moreover, in the petal shaped narrow area longitudinal vortices (Prandtl's secondary flow of second kind) will be generated [12,13].

Since the hydraulic diameter is derived based on the wall friction, and consequently these difference has a decisive influence on it. These imply that in this case,  $d_h$  is not a reasonable parameter as a reference length, diameter.

The pressure loss  $\Delta P$  of the tube, heat transfer  $Q$ , and heat transfer efficiency  $\eta$  should be organized in dimensionless numbers, but in this study no suitable ones are not found and consequently the Reynolds number  $Re_e$  with the equivalent diameter  $d_e$  as the reference length  $d_e$  was used.

### 3. Estimation of Overall Heat Transfer Coefficient, $k$

Here, the overall heat transfer coefficient  $k$  for the (c-h-c) of the CP- and 5P-tri-tube will be examined to reveal the heat transfer more generally from the middle tube to inner or outer tube.

Figure 3 shows the outline diagram of the CP-tri-tube with the symbol used. In addition, Reynolds, Prandtl and Nusselt numbers were calculated by the following formulas, respectively:

$$Re = \frac{w \cdot \rho \cdot L_c}{\mu} \quad (3)$$

$$Pr = \frac{C_p \cdot \mu}{\lambda} \quad (4)$$

$$Nu = \frac{a \cdot L_c}{\lambda} \quad (5)$$

where,  $w$ : mean velocity,  $\rho$ : density,  $L_c$ : reference length,  $\mu$ : viscosity,  $C_p$ : specific heat,

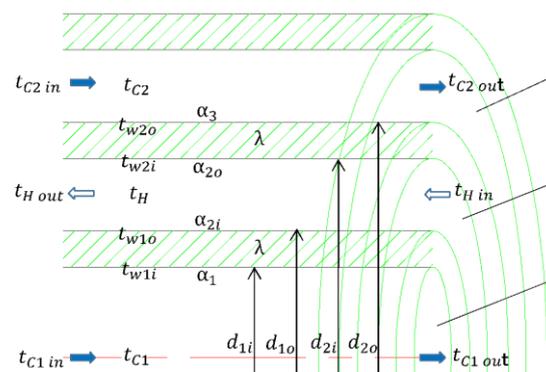


Figure 3. Notations for calculation of overall heat transfer coefficient,  $k$ .

$\alpha$ : heat transfer coefficient,  $\lambda$ : thermal conductivity

Since  $\alpha$  in Equation (5) is unknown, Nu was obtained by Gnielinski modified formula of empirical formula of Petukhov-Popov.

$$Nu = \frac{\left(\frac{f}{8}\right)(Re - 1000) \cdot Pr}{1 + 12.7 \sqrt{\frac{f}{8}} (Pr^{\frac{2}{3}} - 1)} \quad (6)$$

where,

$$f = 3.03 \times 10^{-12} \cdot Re^3 - 3.67 \times 10^{-8} \cdot Re^2 + 1.46 \times 10^{-4} \cdot Re - 0.151 \quad (7)$$

$2300 < Re < 4500$

$$f = (0.782 \ln Re - 1.51)^{-2} \quad (8)$$

$4500 < Re < 10^6$

The heat transfer coefficient  $\alpha_1$  between the cold water flowing through the inner tube and the inner wall of inner tube and  $\alpha_3$  between the outer wall of middle tube and the cold water flowing through the outer tube can be obtained from the above equations as follows.

$$\alpha_{1,3} = \frac{\left(\frac{f}{8}\right)(Re-1000) \cdot Pr \cdot \lambda}{1 + 12.7 \sqrt{\frac{f}{8}} (Pr^{\frac{2}{3}} - 1) \cdot L_c} \quad (9)$$

The heat transfer coefficients  $\alpha_{2i}$  and  $\alpha_{2o}$  in the middle tube can be expressed by Newton's law of cooling as follows.

$$Q_{C1} = \alpha_1 \cdot A_{1i} \cdot (t_{w1i} - t_{C1}) = \alpha_{2i} \cdot A_{1o} \cdot (t_H - t_{w1o}) \quad (10)$$

$$Q_{C2} = \alpha_3 \cdot A_{2o} \cdot (t_{w2o} - t_{C2}) = \alpha_{2o} \cdot A_{2i} \cdot (t_H - t_{w2i}) \quad (11)$$

where,  $A_{1i}$ ,  $A_{1o}$ : heat transfer areas of the inside and outside of inner tube,  $A_{2i}$ ,  $A_{2o}$ : heat transfer areas of the inside and outside of middle tube,  $t_{C1}$ ,  $t_H$ ,  $t_{C2}$ : arithmetic mean temperature of fluid passing through inner, middle, and outer tubes,  $t_{w1i}$ ,  $t_{w1o}$ : temperatures on inner and outer wall surfaces of inner tube,  $t_{w2i}$ ,  $t_{w2o}$ : temperatures on inner and outer wall surfaces of middle tube.

Equations (10) and (11) show the heat transfer relationships between the inner and outer tubes and between the middle and outer tubes, respectively.  $t_{w1i}$  and  $\alpha_{2i}$  can be obtained from Equation (10), and  $t_{w2o}$  and  $\alpha_{2o}$  can be obtained from Equation (11). Furthermore,  $\alpha_{2i}$  and  $\alpha_{2o}$

$$\alpha_{2i} = \frac{Q_{C1}}{A_{1o} \cdot (t_H - t_{w1o} - \frac{Q_{C1}}{2\pi L \lambda} \ln \frac{d_{1o}}{d_{1i}})} \quad (12)$$

$$\alpha_{2o} = \frac{Q_{C2}}{A_{2i} \cdot (t_H - t_{w2o} - \frac{Q_{C2}}{2\pi L \lambda} \ln \frac{d_{2o}}{d_{2i}})} \quad (13)$$

where,  $\lambda_{Cu}$ : thermal conductivity of the tube (phosphorus deoxidized copper)

Now, if  $k_1$  and  $k_2$  are the overall heat transfer coefficients from the middle tube to inner tube and from the middle tube to outer tube, respectively, they can be expressed as follows.

$$k_1 = \frac{1}{\frac{1}{\alpha_1} \cdot \frac{d_{1o}}{d_{1i}} + \frac{d_{1o}}{2\lambda} \ln \frac{d_{1o}}{d_{1i}} + \frac{1}{\alpha_{2i}}} \quad (14)$$

$$k_2 = \frac{1}{\frac{1}{\alpha_{2o}} + \frac{d_{2i}}{2\lambda} \ln \frac{d_{2o}}{d_{2i}} + \frac{1}{\alpha_3} \cdot \frac{d_{2i}}{d_{2o}}} \quad (15)$$

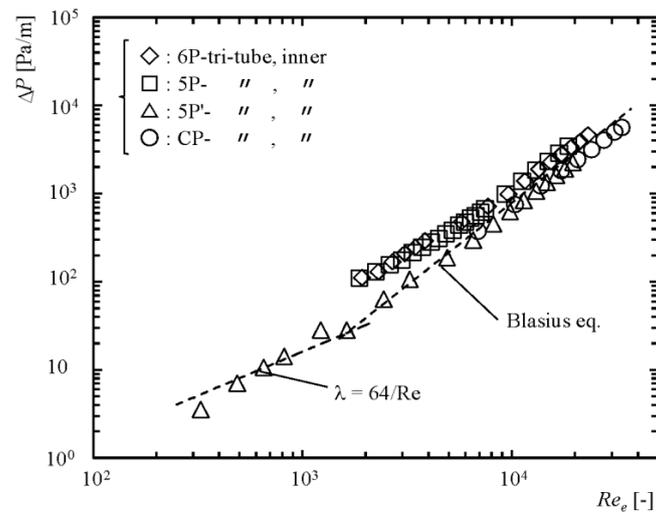
The above results are for a circular triple tube and not for the petal shaped triple tube, but although the shape and flow conditions are different from the petal shaped triple tube we try to find  $k$ , where the triple tube is a circular tube with the same equivalent diameter. That is,  $k$  is evaluated and deducted approximately as including the effects of different tube shape and flow conditions.

## 4. Experimental Results and Discussion

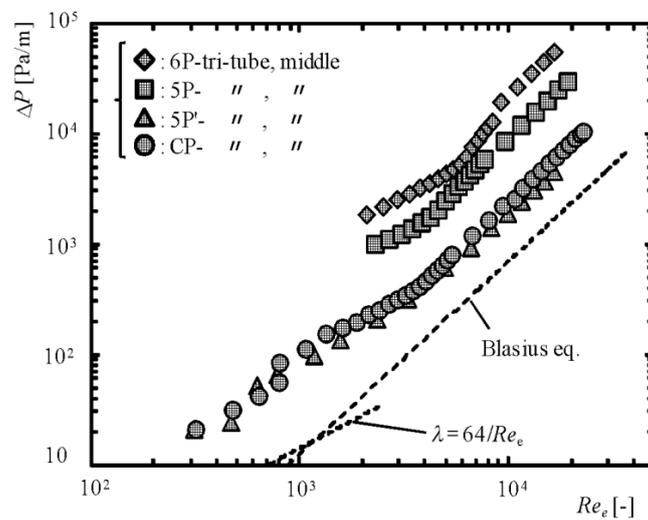
### 4.1. Flow Resistance, or Pressure Loss, $\Delta P$

Figure 4 shows the flow resistance, or pressure loss,  $\Delta P$ , of each tube of the 6P-, 5P-, 5P'-, and CP-tri-tubes as measured examples.

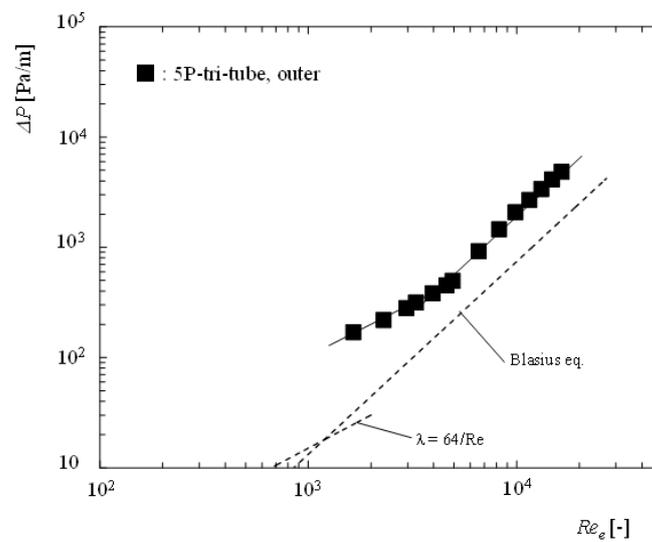
Figure 4a shows the  $\Delta P$  (Pa/m) of the inner tube of the 6P-, 5P-, 5P'-, and CP-tri-tubes. The abscissa is the  $Re_e$ . The dotted line in Figure 4a is the results by the Darcy-Weisbach and Blasius equations for the circular tube, and the transition from laminar to turbulent flows occurs at  $Re_e \approx 2.0 \times 10^3$ . The experimental results for inner tube of the circular-tube agree well with the equation. In either case, the  $\Delta P$  increases proportionally to the power of  $Re_e$  and increases with the wet perimeter. For example, the  $\Delta P$  for the inner tubes of the 6P-, 5P-, 5P'-tri-tubes at  $Re_e = 1.0 \times 10^4$  are about 1.5, 1.59, and 0.91 times as large as that of the CP-tri-tube, respectively. The reason why the 5P'-tri-tube is 0.91 times smaller than the CP-tri-tube is that the area of the cross section is approximately 6.0% larger (Table 1). A similar trend is observed in the middle- and outer-tubes, however, the middle tube of the 6P- and 5P-tri-tube consist of six and five separate flow channels, respectively, and consequently the  $\Delta P$  is a multiple of those. Incidentally, the increase in  $\Delta P$  reduces the heat transfer performance or efficiency.



(a) Inner tube



(b) Middle tube



(c) Outer tube

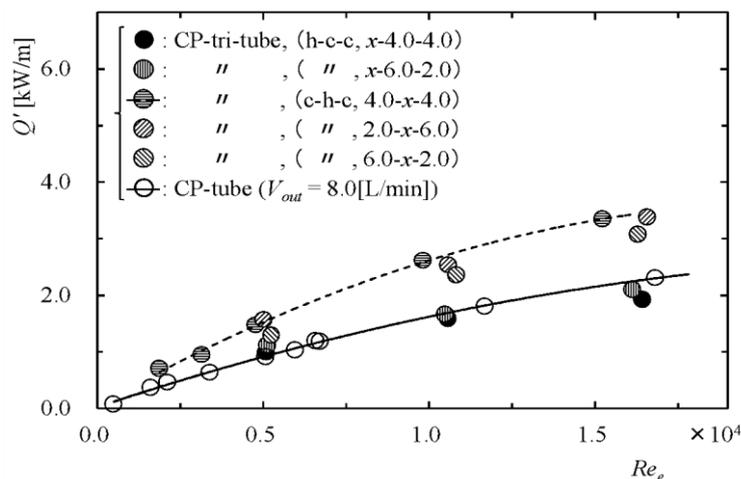
Figure 4. Pressure loss,  $\Delta P$  (Effect of tube configuration).

Figure 4b shows the  $\Delta P$  for the middle tubes of each triple tube. The  $\Delta P$  for the middle tubes of the 6P- and 5P-tri-tube are much larger than the CP-tri-tube, because they have six or five narrow flow channels; for example, at  $Re_e = 1.0 \times 10^4$ , they are approximately 9.57 and 3.95 times as large as the CP-tri-tube. The  $\Delta P$  of the middle tube of the 5P-tri-tube is approximately 0.81 times smaller than the CP-tri-tube.

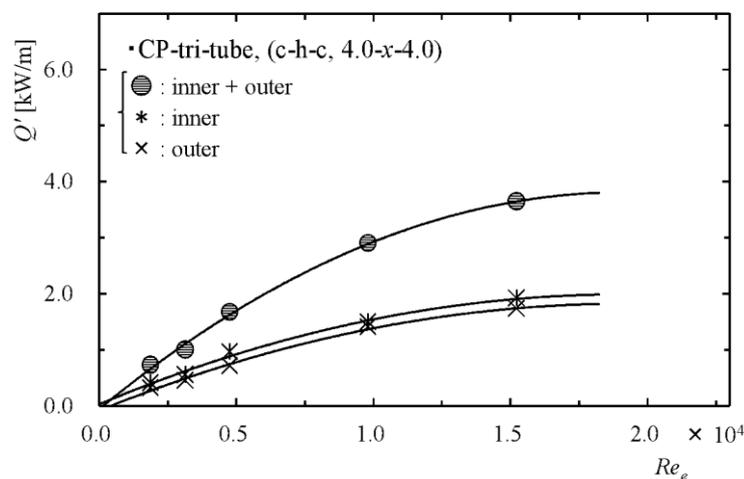
Figure 4c is the  $\Delta P$  of the outer tube of the 5P-tri-tube. The  $\Delta P$  of the outer annular tube is much larger than the circular tube with the same cross sectional area. For example, at  $Re_e = 1.0 \times 10^4$  it is about 2.65 times. Additionally, by reducing the volumetric flow rate of the outer tube from  $V_c = 8.0$  (L/min) ( $w = 1.02$  m/s) to 4.0,  $\Delta P$  reduces by approximately 0.3 times. That is, the  $\eta$  can be improved by decreasing the large  $\Delta P$  of the middle tube using the 5P-tri-tube in place of the 5P-tube. As mentioned previously, by flowing an equal flow rate of the cold water as in the outer tube of the double tube to the sum in the middle and outer tubes of the triple tube, the pressure loss can be decreased because of the decrease in the velocity.

#### 4.2. Heat Transfer, $Q'$

Figure 5 shows the effects of the flow condition of each triple-tube on heat transfer  $Q'$  (kW/m). The results for each double tube are also shown for reference.



(a) Heat transfer,  $Q'$



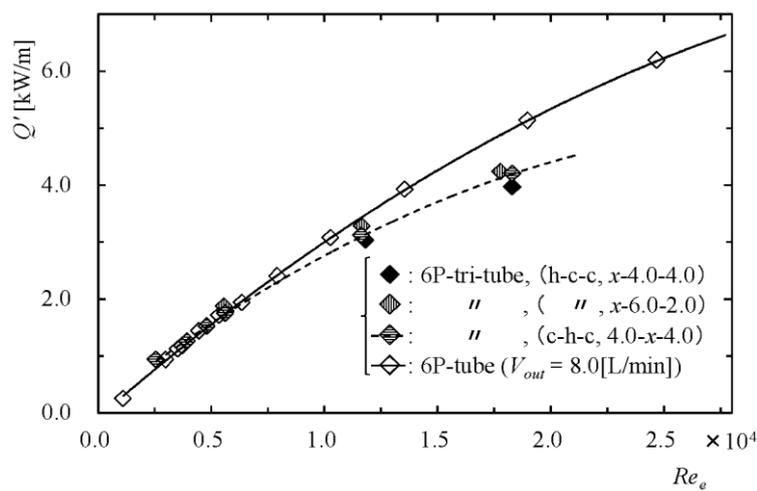
(b) Heat transfer to the inner and outer tubes (CP-tri-tube, (c-h-c, 4.0-x-4.0))

Figure 5. Heat transfer,  $Q'$  (CP-tri-tube, Effect of flow condition).

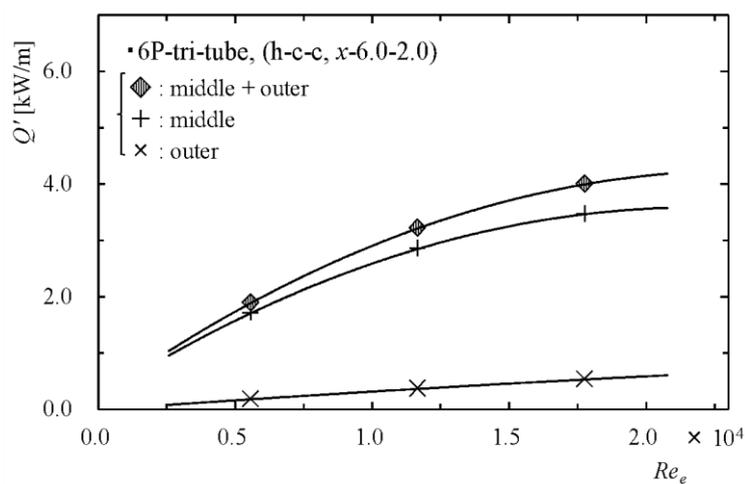
Figure 5a shows the results of the CP-tri-tube with the flow condition of the (h-c-c) and (c-h-c). The heat transfer  $Q'$  increases as  $Re_e$  increases, and the (c-h-c, 4.0-x-4.0) takes a maximum. The (c-h-c) is larger than the (h-c-c) and the CP-tube with the flow rate of cold water  $V_c (= V_{out}) = 8.0$  (L/min). This is because in the heat transfer process of the (c-h-c) the heat can be transferred to both sides of the inner and outer tubes with a large temperature difference.

Figure 5b is the heat transfer to the inner and outer tube for the CP-tri-tube, (c-h-c, 4.0-x-4.0). Both are approximately equal, however, in the case of the (c-h-c, 6.0-x-2.0) the  $Q'$  of the inner tube was approximately 1.56 – 2.31 times of the outer tube for  $Re_e \approx (0.5 - 1.75) \times 10^4$  because of the large flow rate of  $V_c = 6.0$  (L/min). In the case of (c-h-c, 2.0-x-6.0) the  $Q'$  to the inner and outer tubes was qualitatively opposite.

Figure 6 shows the results for the 6P-tri-tube. In the case of  $Re_e \approx 0.75 \times 10^4$ , every  $Q'$  is approximately equal and the 6P-tube takes a maximum unlike the case of CP-tri-tube and CP-tube shown in Figure 5 because of the large wet perimeter and large flow rate of  $V_c = 8$  (L/min). Further, the (h-c-c, x-6.0-2.0) and (c-h-c, 4.0-x-4.0) are approximately equal because larger flow rate of 6.0 (L/min) flows in the middle tube than that of the (c-h-c, 4.0-x-4.0).



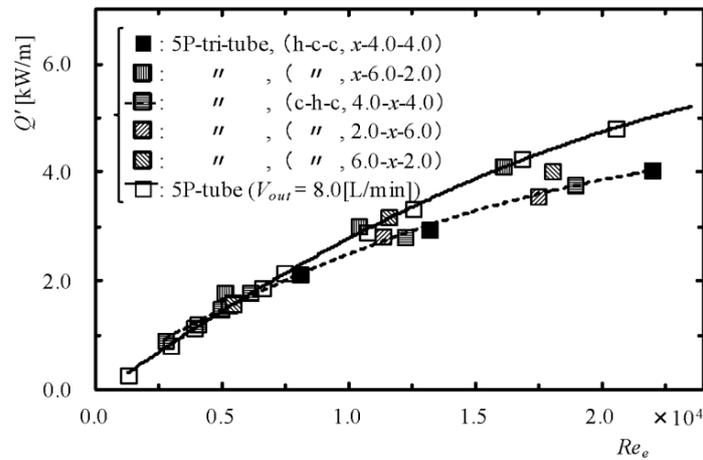
(a) Heat transfer,  $Q'$



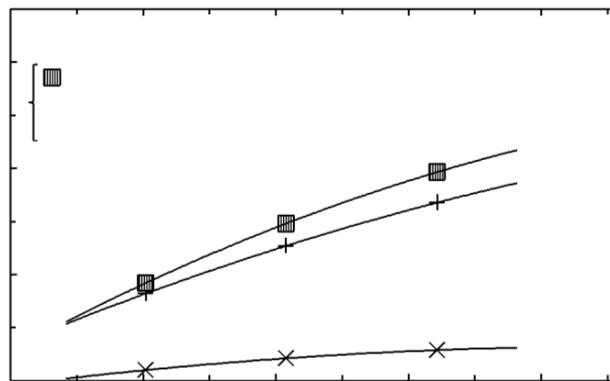
(b) Heat transfer to the inner and outer tubes (6P-tri-tube, (h-c-c, x-6.0-2.0))

Figure 6. Heat transfer,  $Q'$  (6P-tri-tube, Effect of flow condition).

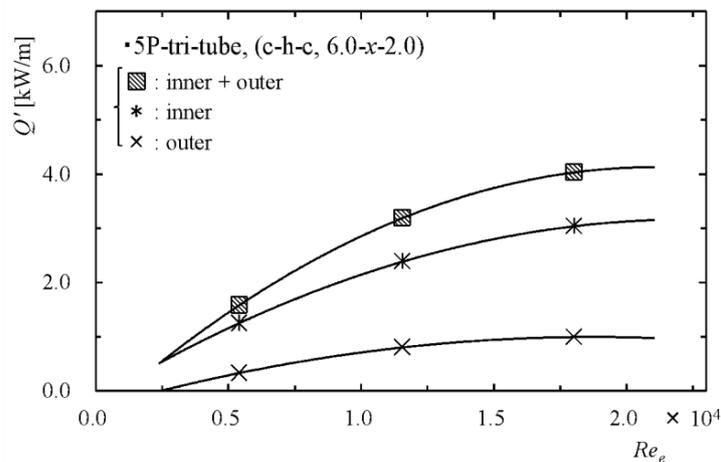
Figure 7a shows the  $Q'$  for the 5P-tri-tube. In the case of  $Re_e \approx 0.75 \times 10^4$ , every  $Q'$  is approximately equal and the  $Q'$  for the 5P-tube and 5P-tri-tube, (h-c-c, x-6.0-2.0) is approximately equal and maximum. This seems to indicate that the amount of heat transfer is saturated below  $Q_c = 6.0$  (L/min). Furthermore, the (c-h-c, 6.0-x-2.0) is equal to them within approximately 8% difference at  $Re_e = 1.8 \times 10^4$ .



(a) Heat transfer,  $Q'$



(b) Heat transfer to the inner and outer tubes (5P-tri-tube, (h-c-c, 6.0-x-2.0))



(c) Heat transfer to the inner and outer tubes (5P-tri-tube, (c-h-c, 6.0-x-2.0))

Figure 7. Heat transfer,  $Q'$  (5P-tri-tube, effect of flow condition).

Figure 7b is the heat transfer to the inner and outer tube for the 5P-tri-tube, (h-c-c, x-6.0-2.0). In this case, most of the heat is carried away by the middle tube in contact with hot water.

Figure 7c shows the results for the (c-h-c, 6.0-x-2.0). In this case, much heat is carried away by the petal shaped inner tube with the large wet perimeter and the large velocity of cold water.

Figure 8 is the  $Q'$  of the 5P'-tri-tube. The 5P'-tri-tube, (c-h-c, 4.0-x-4.0) and 5P'-tube have the maximum value in the whole range of  $Re_e$ .

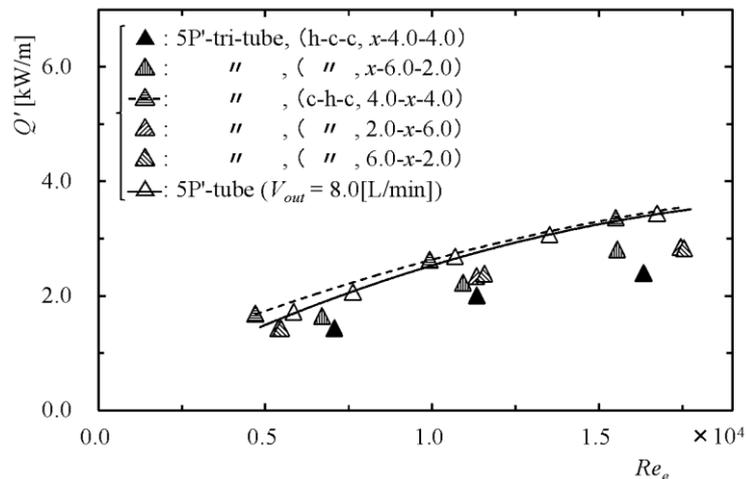


Figure 8. Heat transfer,  $Q'$  (5P'-tri-tube, Effect of flow condition).

Among the above tri- and double-tubes, the  $Q'$  for 6P-tube with  $V_{out} (= V_c) = 8.0$  (L/min) is the maximum because of the large wet perimeter and the large flow rate of  $V_c = 8.0$  (L/min).

#### 4.3. Overall Heat Transfer Coefficient, $k$

Figure 9a shows the overall heat transfer coefficients for the inner tube  $k_1$  and for the middle tube  $k_2$  of the CP-tri- and 5P-tri-tubes, (c-h-c, 4.0-x-4.0). Both are increase with increasing.

$Re_e$  and the  $k_2$  for the 5P-tri-tube are larger than that for the CP-tri-tube. The  $k_1$  for the CP-tri-tube is larger than  $k_2$  because the inner and middle tubes have approximately the same amount of heat transfer and the middle tube has a larger wet perimeter. On the other hand, the  $k_2$  of the 5P-tri-tube is larger. This is because the flow condition is different considerably depending on the different configuration of flow path. Around the corner of the inner and middle tubes of the 5P-tri-tube flow disturbance or longitudinal vortex flow would generate and consequently the heat transfer between them seems to be enhanced. The  $k_2$  for the 5P-tri-tube is approximately twice of that for the CP-tri-tube.

Figure 9b shows the results for the CP-tri- and 5P-tri-tubes, (c-h-c, 2.0-x-6.0). In this case with small flow rate of 2.0 (L/min) through the inner tube, the  $k_1$  and  $k_2$  for the CP-tri-tube are approximately equal, however, the  $k_2$  for the 5P-tri-tube is larger because of the larger flow rate of  $Q_c = 6.0$  (L/min) through the outer tube.

Figure 9c is the results of the CP-tri- and 5P-tri-tubes, (c-h-c, 6.0-x-2.0). The  $k_1$  is larger than the  $k_2$  for both case, and the  $k_1$  and  $k_2$  for the 5P-tri-tube are larger than those for the CP-tri-tube. This depends on the large flow rate of  $Q_c = 6.0$  (L/min) through the inner tube. The overall heat transfer coefficient  $k$  increases at a large flow rate and at the petal shaped tube.

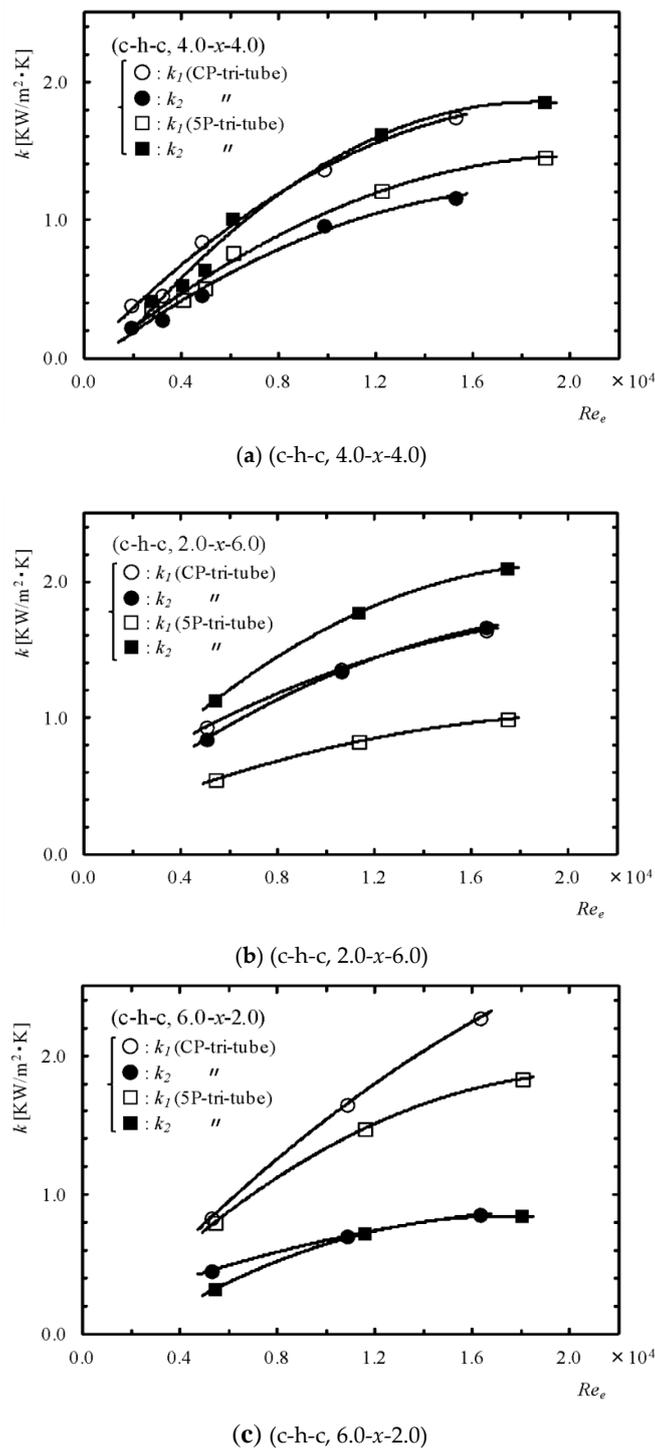


Figure 9. Overall heat transfer coefficient,  $k_1$  and  $k_2$  (CP-, 5P-tr-tube).

#### 4.4. Heat Transfer Efficiency, $\eta$

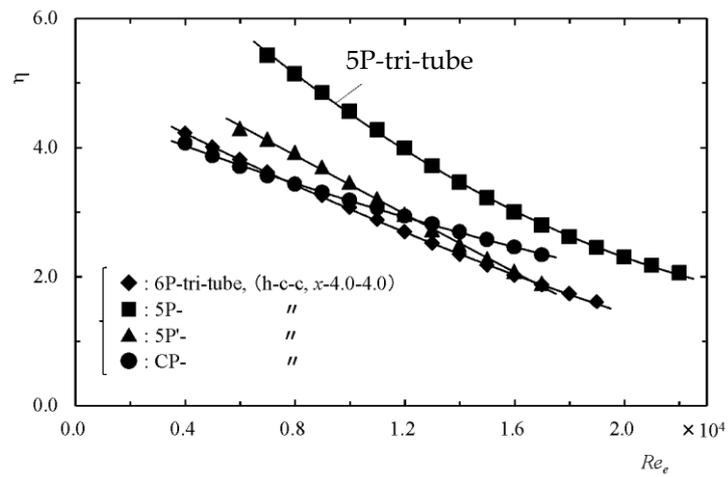
For the heat exchanger, the large heat transfer and small operation power are important. Here, in order to estimate the heat transfer performance the following heat transfer efficiency is introduced.

The heat transfer efficiency  $\eta$  of the triple tube was defined as the total heat transfer  $Q_t$  of the triple tube per unit operation power  $V\Delta P$  (where,  $V$ : volumetric flow rate) and the ratio with the CP-tube.

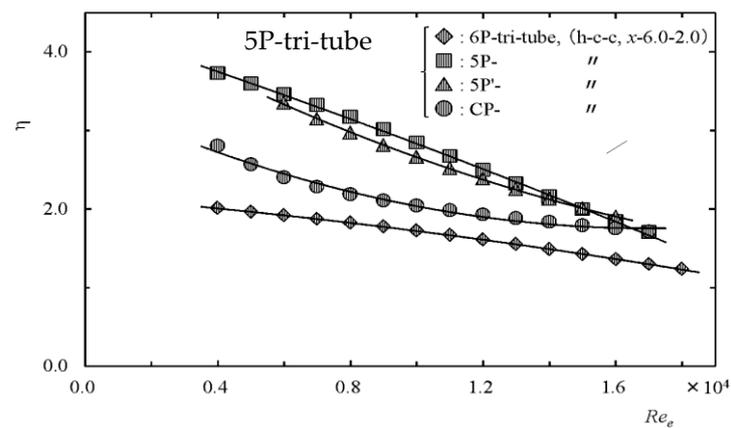
$$\eta = \frac{Q_t/Q_{CP}}{(V\Delta P)_t/(V\Delta P)_{CP}} \tag{16}$$

where, subscript CP: CP-tube

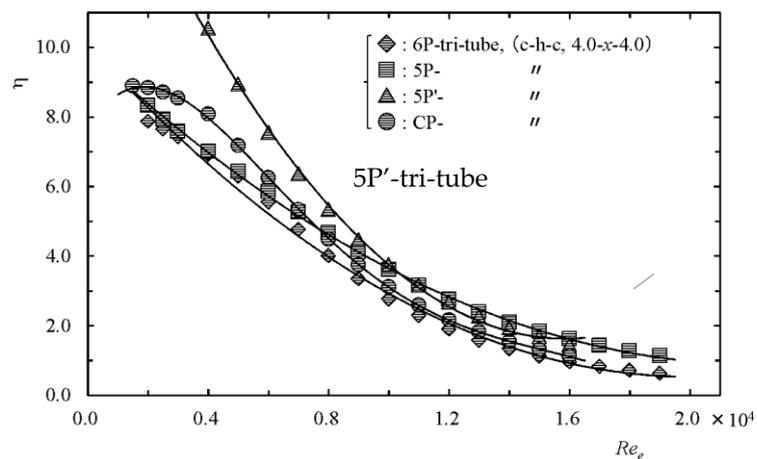
Figure 10 shows some examples of the effect of flow condition on the  $\eta$ . The abscissa is Reynolds number  $Re_e$  of the hot water.



(a) (h-c-c, x-4.0-4.0)

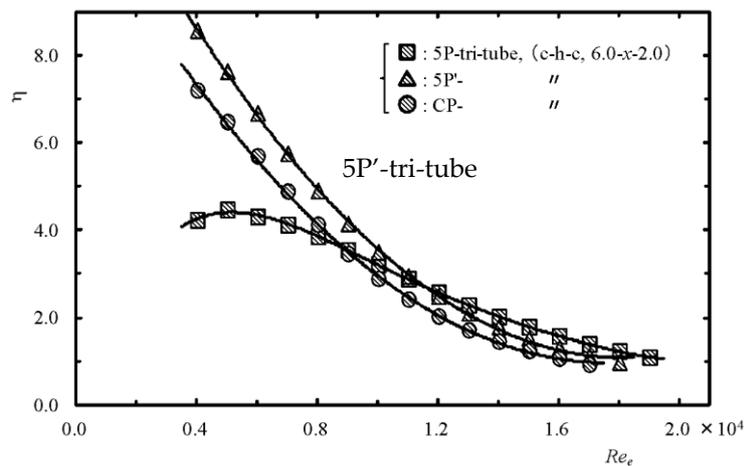


(b) (h-c-c, x-6.0-2.0)

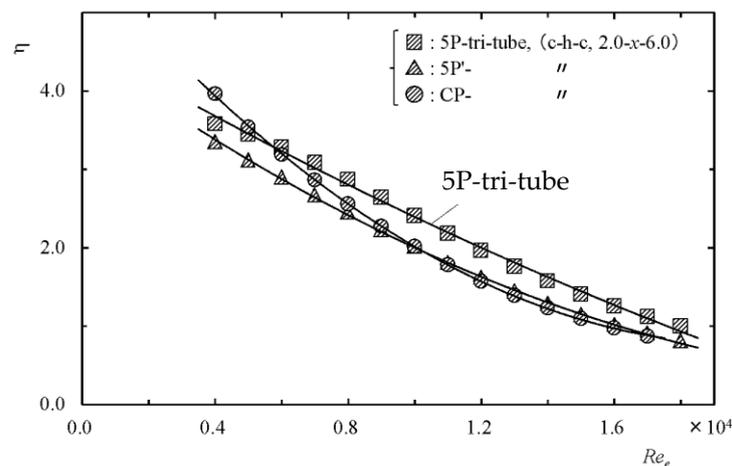


(c) (c-h-c, 4.0-x-4.0)

Figure 10. Cont.



(d) (c-h-c, 6.0-x-2.0)



(e) (c-h-c, 2.0-x-6.0)

**Figure 10.** Heat transfer efficiency,  $\eta$  (effect of tube configuration).

Figure 10a is the results for the (h-c-c,  $x$ -4.0-4.0) of each tri-tubes. The  $\eta$  decreases with increasing  $Re_e$  because of a large increase of operation power, and the 5P-tri-tube is the largest in the whole range of  $Re_e$ . For example, the  $\eta$  of the CP-tri- and 5P-tri-tubes at  $Re_e = 0.8 \times 10^4$  are approximately 5.2 and 3.5 times of the CP-tube with  $V_{out} (= Q_c) = 8.0$  (L/min), respectively, and consequently the  $\eta$  for the 5P-tri-tube is approximately 1.5 times of that for the CP-tri-tube. The  $\eta$  of the 5P-tri-tube is larger than the 5P-tube because the flow resistance is smaller than that of the 5P-tri-tube. The cold water of 8.0 (L/min) of the CP-tube is divided into two equal flow rates of 4.0 (L/min), and consequently the flow resistance decreases because of the flow velocity through the middle and outer tubes decreases. In the 6P-tri-tube, since the heat transfer is large but flow resistance is considerably large, and consequently the  $\eta$  does not become so large.

Figure 10b shows the  $\eta$  for the (h-c-c,  $x$ -6.0-2.0). The flow rate through the middle tube increases from 4.0 (L/min) in the previous case of (c-h-c, 4.0- $x$ -4.0) to 6.0 (L/min). The  $\eta$  is larger than that of the others, however it is smaller than that of the 5P-tri-tube, (h-c-c,  $x$ -4.0-4.0). In this case, the amount of heat transfer that the cold water can absorb may be reached saturation at the flow rate of 4.0 (L/min) through the middle tube.

Figure 10c shows the results for (c-h-c, 4.0- $x$ -4.0) of each tri-tube. In this case, hot water is cooled from both sides. The  $\eta$  of the 5P-tri-tube is larger than the others in the range of  $Re_e < 1.0 \times 10^4$ , and for example, the  $\eta$  for the CP-tri- and 5P-tri-tubes at  $Re_e = 0.4 \times 10^4$  are approximately 8.0 and 10.5 times

of that for the CP-tube with  $V_{out} = 8.0$  (L/min), respectively, and consequently the  $\eta$  for the 5P-tri-tube is approximately 1.3 times of the CP-tri-tube. In this case, since the hot water is cooled from both the inner and outer tubes, the amount of heat transfer increases, and the flow resistance of the 5P'-tri-tube is considerably small as shown in Figure 3.

Figure 10d is the results for the (c-h-c, 6.0-x-2.0) of the 5P-, 5P', and CP-tri-tubes. The  $\eta$  for the 5P'-tri-tube is larger than the others in the range of  $Re_e < 1.1 \times 10^4$ , however it is smaller than that for the (c-h-c, 4.0-x-4.0).

Figure 10e is the results of the (c-h-c, 2.0-x-6.0) of the 5P-, 5P', and CP-tri-tubes. The  $\eta$  for the 5P-tri-tube is larger than the others, however it is much smaller than the 5P'-tri-tube, (c-h-c, 4.0-x-4.0) shown in Figure 10c.

The heat transfer efficiency for the 5P'-tri-tube, (c-h-c, 4.0-x-4.0) is largest among the test tube, and it is much larger than the CP-tube.

#### 4.5. Heat Transfer, $Q'$ and Efficiency, $\eta$

Heat transfer is important factor for heat exchangers, however heat transfer efficiency is also important. Hear, the relation between heat transfer and efficiency is examined.

Now, we examine the heat transfer efficiency,  $\eta$  when heat transfer is  $Q' = 2.0$  (kW/m). For example,  $Re_e$  at  $Q' = 2.0$  (kW//m) of the CP-tri-tube, (c-h-c, 4.0-x-4.0) can be obtained from Figure 4a to  $Re_e = 0.69 \times 10^4$ , and consequently the heat transfer efficiency results in  $\eta = 5.3$  from Figure 10c. The  $\eta = 5.3$  means that the efficiency of the CP-tri-tube, (c-h-c, 4.0-x-4.0) is 5.3 times of that for CP-tube. For other cases,  $\eta$  can be obtained in the same manner.

The results obtained are shown in Table 2. The efficiency of every case of the tri-tube for  $Q' = 2.0$  (kW/m) is larger than the CP-tube, and the maximum efficiency is  $\eta = 7.0$  for the 5P'-tri-tube, (c-h-c, 4.0-x-4.0). This means that use of the 5P'-tri-tube, (c-h-c, 4.0-x-4.0) increases efficiency by 7.0 times of the CP-tube and by 1.32 times of the CP-tri-tube, (c-h-c, 4.0-x-4.0). The high efficiency of the 5P'-tri-tube, (c-h-c, 4.0-x-4.0) is mainly due to the fact that the flow resistance is smaller than the CP-, and CP-tri-tube.

**Table 2.** Heat transfer efficiency  $\eta$  for  $Q' = 2.0$  (kW/m).

$Q' =$ 2.0 (kW/m)	c-h-c		h-c-c	
	(4.0-x-4.0)	(6.0-x-2.0)	(x-4.0-4.0)	(x-6.0-2.0)
*CP-tri-tube	$Re_e = 0.69 \times 10^4$	—————	$1.75 \times 10^4$	$1.36 \times 10^4$
	$\eta = 5.3$	—————	3.65	2/36
*6P-tri-tube	$Re_e = 0.66$	—————	0.66	0.66
	$\eta = 5.3$	—————	3.65	1.96
*5P-tri-tube	$Re_e = 0.66$	0.66	0.66	0.66
	$\eta = 5.6$	4.2	5.6	3.36
*5P7-tri-tube	$Re_e = 0.66$	0.93	1.18	0.93
	$\eta = 7.0$	4.0	4.2	3.3.6

As another example, the same applies to the case where the heat transfer is larger,  $Q' = 3.0$  (kW/m), the maximum efficiency was  $\eta = 3.82$  for the 5P-tri-tube, (h-c-c, x-4.0-4.0) and it was 1.91 times of that for the CP-tri-tube. In addition, the efficiency for the 5P'-tri-tube, (c-h-c, 4.0-x-4.0) which was maximum for  $Q' = 2.0$  (kW/m) was  $\eta = 3.6$ .

Using the triple tube, CP-tri-tube, and a certain favorite flow condition, the heat transfer and efficiency can be increased than those for the double tube, CP-tube, and moreover using the petal-shaped inner tube they can be increased more.

## 5. Conclusions

In this study, to improve the heat transfer performance, h.t.p., of a double tube type heat exchanger, the use of a circular- or petal-shaped-triple tube were examined, and the effect of flow rate of cold water on the h.t.p. was examined by comparing with CP-, 6P-, 5P-, and 5P'-tri-tubes. Furthermore, the effect of changing the flow path of the hot- and cold-water flows on the h.t.p. was examined. The primary results are as follows.

(1) The pressure loss,  $\Delta P$ , of the 6- and 5-petal-shaped inner tubes were larger than that for the CP-tri-tube, for example, they were approximately 1.5 and 1.59 times of that for the CP-tube at  $Re_e = 1.0 \times 10^4$ , respectively, because it has a large wet perimeter and narrow petal shaped flow channels, and the  $\Delta P$  for the middle tube were much larger than that for the CP-tri-tube, for example, they were approximately 9.57 and 3.95 times at  $Re_e = 1.0 \times 10^4$ , because they have small separated flow channels.

(2) The heat transfer,  $Q'$ , of the petal-shaped double and triple tubes increased with  $Re_e$ , and the 6P-tube had a largest heat transfer in the range of  $Re_e > 0.7 \times 10^4$ , because it has a largest wet perimeter. The next largest  $Q'$  was those for the 5P-tube and 5P-tri-tube, (h-c-c,  $x$ -4.0-4.0), and, for example, it was approximately 0.9 times of the 6P-tube at  $Re_e = 1.75 \times 10^4$ .

(3) The heat transfer characteristics of the inner and middle tubes were estimated by overall heat transfer coefficient.

(4) The heat transfer efficiency,  $\eta$ , of the CP-tube could be improved considerably by using the CP-tri-tube and petal-shaped triple tubes. The  $\eta$  of the 5P'-tri-tube, (c-h-c, 4.0- $x$ -4.0) was the largest; for example, it was approximately from 10.5 to 3.6 times of the CP-tube in the range of  $Re_e = (0.4 - 1.0) \times 10^4$ .

**Author Contributions:** Conceptualization, T.S., Methodology, T.S. and K.Y., Software: T.S. and K.Y., Formal analysis: T.S. and K.Y., Investigation: T.S., K.Y., K.T. and T.A., Data curation: T.S. and K.Y., Formal analysis: T.S. and K.Y., Funding acquisition, T.S. and K.T., Investigation, T.S., K.Y., K.T. and T.A., Supervision: T.S., Validation, T.S., K.Y., K.T. and T.A., Writing- Review and editing, T.S., K.Y., K.T. and T.A., Visualization, T.S. All authors have read and agreed to the published version of the manuscript.

**Funding:** A part of this research was funded by Chubu Electric Power Co., Inc., and Tohkai Shipbuilding & Engineering Co., Ltd., Japan.

**Acknowledgments:** We thank Chubu Electric Power Co., Inc., and Tohkai Shipbuilding & Engineering Co., Ltd., Japan for their supports of this study.

**Conflicts of Interest:** The authors declare no conflict of interest.

## Nomenclature

$A$	Area of cross section
CP-tri-tube	Circular pipe triple tube heat exchanger
CP-tube	Circular tube heat exchanger
DHE	double tube heat exchanger
$d$	Tube diameter
$d_e$	Equivalent diameter
h.t.p	heat transfer performance
$K$	Overall heat transfer coefficient
$L_c$	Reference length
$m$	Mass flow rate
Nu	Nusselt number ( $= \alpha L_c / \lambda$ )
Pr	Prandtl number ( $= C_p \mu / \lambda$ )
$P$	Pressure
$p$	Wet perimeter
$Q$	Heat transfer
$Q'$	Heat transfer per unit length
Re	Reynolds number ( $= \omega \rho L_c / \mu$ )
$Re_h$	Reynolds number scaled by hydraulic diameter ( $= \omega \rho d_h / \mu$ )

$r$	Coordinate in radius direction
$T, t$	Temperature
THE	Triple tube heat exchanger
$V$	Volumetric flow rate
$w$	Mean velocity
$x$	Flow rate and path of hot water
$\alpha$	Heat transfer coefficient
$\Delta P$	Pressure loss
$\eta$	Heat exchange efficiency
$\lambda$	Thermal conductivity
$\mu$	Viscosity
$\rho$	Density
c-h-c	Flow pattern: Cold water flows in the inner- and outer-tubes, and hot water flows in the middle tube as a counter flow
h-c-c	Flow pattern: Hot water flows in the inner tube, and cold water flows in the middle- and outer-tubes as a counter current flow
6P-tri-tube subscript	6 petal shaped triple tube heat exchanger
CP	CP-tube (CP-double-tube)
C	Center
c	Cold
H, h	Hot
i, in	inner
o, ou	outer
1, 2	Inlet and exit of tube, respectively
6P	6P-tube

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