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Residual Currents around Asymmetrical Pipes in Oscillatory Flow Fields

RESIDUAL CURRENTS AROUND ASYMMETRICAL PIPES IN OSCILLATORY FLOW FIELDS

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ABSTRACT

The effects of pipe shapes on residual currents in an oscillatory flow field were investigated using horizontal two-dimensional numerical model based on Reynolds-averaged Navier-Stokes equations (:RANS) and the k-ε turbulent model. In this research, pipes equipped with flanges were used as asymmetrical pipes to produce residual currents. Three basic types of flange were employed namely an outward flange type, an inward flange type, and a combination of both types. In simulations, angles or positions of flanges were varied in order to know their effects on the residual currents. The streamlines of residual currents show that the asymmetrical pipe which is formed with flanges can generate residual currents and water circulations around the pipe. The findings of this research also reveal that both the outward flange and the inward one are effective in producing residual currents and that the combination of both types can produce larger residual currents.

Keywords: asymmetrical pipe, residual current, oscillatory flow, numerical simulation

1. INTRODUCTION

In the resent years, water pollution in stagnant sea areas especially in a semi enclosed bay is the main cause of water deterioration because of the lack of water exchange with the open sea. Komatsu *et al*. (1997) suggested to use unidirectional residual currents produced in tidal current fields in order to activate the water exchange with the open sea. In addition, Komatsu *et al*. (2001) proposed to apply this method to control of sediment transport in wave fields. Those residual currents can be generated by asymmetrical structures placed under oscillatory flow fields produced by tides or waves. Recently, Kawano *et al*. (2006) suggested a specific pipe called *One-Way Pipe* which has small asymmetrical structures inside, hence it can produce unidirectional residual currents. However, it is not so easy to make such kind of pipe with small asymmetrical structures attached on the inside wall of the pipe. Therefore, a simple shape which is easy to be formed is required for a practical implementation of the *One-Way Pipe*. Physically, an asymmetrical characteristic of a pipe can be created by just transforming the inlet or the outlet shape of the pipe, so that residual currents should also be produced by this type of *One-Way Pipe*.

The laboratory experiment to study residual currents around such kind of asymmetrical pipe in a wave tank has been performed by Matsushita *et al*. (2008), which measured vertical profiles of longitudinal velocity inside the pipe using Laser Doppler Velocimetry. Figure 1 depicts vertical profiles of longitudinal dimensionless residual currents, u_w^*/U_w, where u_w^* is a time-averaged residual current, and U_w is the maximum longitudinal velocity calculated by using the Airy wave theory. Three profiles except the case of "inward flange" are the results from Matsushita *et al*. (2008). The data of the case with the inward flange is from unpublished experimental results recently obtained by us. In all the experiment, square cross section pipes were used, the total pipe length, l, was 55.0 cm and the inside scale of the square pipes, D, was 10.0 cm.

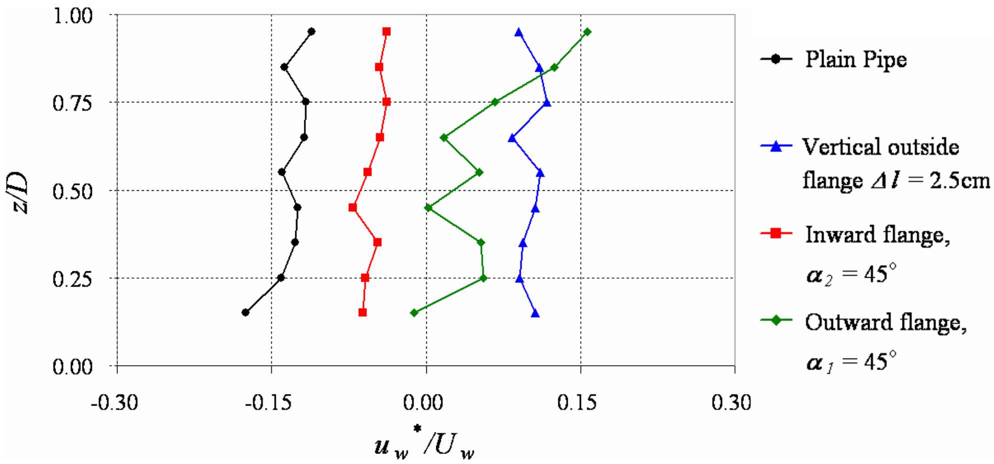

Figure 1 Vertical profiles of residual currents in the symmetrical plain pipe and the three asymmetrical pipes based on the laboratory experiments. Three profiles are quoted from Matsushita *et al*. (2008).

Four types of asymmetrical pipe are shown in Figure 2. Type-1 is the pipe equipped with a vertical outside flange, Type-2 is the pipe attached with an outward oblique flange, Type-3 is the pipe equipped with an inward oblique pipe, and Type-4 is the pipe equipped with both an outward oblique flange and an inward oblique flange. Three of them, from Type-1 to Type-3, are the types of pipe shape examined by the experiment except the plain pipe in the Figure1. Type-4 is the shape suggested in this simulation research.

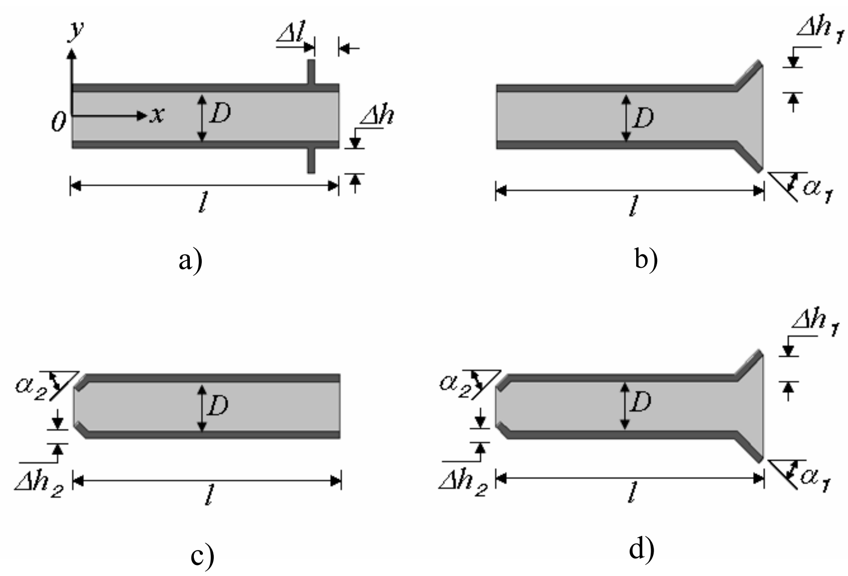

Figure 2 Shapes of the asymmetrical pipe used in the experiment by Matsushita *et al*. (2008) and in the simulations: a) Type-1 with a vertical outside flange; b) Type-2 with an outward oblique flange; c) Type-3 with an inward oblique flange; d) Type-4 with both an inward oblique flange and an outward one.

According to the experimental findings, such a flange put on the pipe should generate residual currents. Figure 1 shows that the plain pipe yields negative residual currents which happen as a compensating current of positive Stokes' drifts underneath water surface caused by wave propagation. In this situation, positive currents occur near the water surface while near the bottom the velocity is negative for compensation. In the figure, the pipe equipped with the vertical outside flange or the outward oblique flange yields positive residual currents. On the other hand, in the case that the inward oblique flange is fixed on the pipe, the residual currents are negative. However, their values are positively large compared with the case of the plain pipe. Hence the inward flange might be useful to produce residual currents practically.

The width of the wave tank used in the experiments was 25.0 cm and it was too small to estimate the horizontal influence of the flanges attached to pipes. Therefore, the present research will study horizontal distribution of residual currents and residual discharges inside and around the asymmetrical pipes by using a horizontal two-dimensional numerical model with a relatively wide computational domain.

Variations of the water surface and the velocity in a wave filed are not strictly sine curves. Hence, their curves are asymmetrical because of the nonlinearity of the water motion. An example of this condition was found in the case of the plain pipe where the residual currents were negative. It is very difficult to distinguish the asymmetry of the flow caused by the asymmetrical pipe from that due to the nonlinear wave motion. Therefore, oscillatory flow fields are employed in order to consider only the effects of asymmetry of the shape in this study.

2. COMPUTATIONAL METHOD

Numerical Solver

The numerical solver used is based on the CADMAS-SURF code (CDIT, 2001). Some minor modifications have been done to use it for oscillatory flows with the specific pipes. The basic equations consist of the horizontal two-dimensional Reynolds-averaged Navier-Stokes (:RANS) equations and the k-ε turbulent model. These equations are discretized into the Cartesian-staggered grid by means of the finite different technique. The orthogonal coordinate system used is shown in the Figure 2. The Simplified Marker and Cell (:SMAC) method (Amsdem and Harlow, 1970) is adopted to solve the continuity equation and the momentum ones. The donor scheme is used to calculate the advection terms and time integrations are solved by using the Euler method. The numerical solver is the same as that used in the study by Rusdin *et al*. (2007).

Boundary Conditions

For the fixed boundary on the surface of pipes, the standard logarithmic law is applied for velocities and the zero normal gradient condition is used to determine a pressure p. The boundary conditions of k and ε at the fixed boundary are defined by means of the wall function method. At the two side boundaries of the computational domain in the y-direction, the free slip boundaries are set for flow velocities, and the zero normal gradient condition is used for p, k and ε. The velocity components and the pressures at the two open boundaries in the x-direction are based on the analytical solution of a sinusoidal oscillatory flow. The conditions can be written as follows:

$$u = U_0 \sin(\sigma t) \tag{1}$$

$$\frac{\partial v}{\partial x} = 0 \tag{2}$$

$$\frac{\partial p}{\partial x} = -\rho U_0 \sigma \cos \sigma t \tag{3}$$

where u, v, t and σ denote x-directional velocity, y-directional velocity, time and angular frequency, respectively. σ is expressed as $2\pi/T$, where π and T are the circular constant and the oscillatory flow period. U_0 is the amplitude of the longitudinal velocity at the open boundaries.

Computational Domain

In this research, an asymmetrical pipe is placed centrally in a computational domain. The domain is taken $13.0l \times 6.4l$, where l (=55.0 cm) denotes the longitudinal pipe length described in the Figure 2. A stretched rectangular grid is used in the domain where the grid sizes at the first grid near the wall boundaries are 2.5 mm and are extended away from the wall. The criteria of grid stretching are restricted to $0.9 \leq \Delta x_i/\Delta x_{i-1}$, $\Delta y_i/\Delta y_{i-1} \leq 1.1$ in order to suppress the influence of the grid stretching from Kimura and Hosoda (1999).

Computational Conditions (Shapes of Asymmetrical Pipe and Flow Conditions)

Firstly, the shape of the asymmetrical pipe with two vertical outside flanges set at one side is investigated because the vertical outside flange (Type-1 in the Figure 2) seemed to be most effective in the Figure 1. As Series-1, the longitudinal position of the two vertical outside flanges, Δl, is varied in the same flow condition (see Table-1). Δh and R_l denote the height of the vertical flange and the rate of Δl to the pipe length l, respectively.

Table 1 Computational conditions of Series-1 for the Type-1 pipe.

Sub-Type	Δh (cm)	Δl (cm)	$R_l = \Delta l/l$	U_0 (m/sec)	T (sec)
Type-1a	5.0	0.0	0	0.27	1.86
Type-1b	5.0	2.5	0.0455	0.27	1.86
Type-1c	5.0	5.0	0.0909	0.27	1.86
Type-1d	5.0	7.5	0.136	0.27	1.86
Type-1e	5.0	10	0.182	0.27	1.86
Type-1f	5.0	15	0.273	0.27	1.86
Type-1g	5.0	20	0.364	0.27	1.86
Type-1h	5.0	25	0.455	0.27	1.86
Type-1i	5.0	27.5	0.500	0.27	1.86

Secondly, the optimum angle of two outward oblique flanges set at one side is studied since both the vertical outside flange and the oblique flange (Type-2 in the Figure 2) were useful to generate unidirectional residual currents in the Figure 1. The optimum angle of the two outward oblique flanges, α_1, is studied in the flow condition as Series-2 (See Table-2). Δh_1 denotes the vertical height of the outward oblique flange.

Table 2 Computational conditions of Series-2 for the Type-2 pipe.

Sub-Type	α_1 (degree)	Δh_1 **(cm)**	U_0**, (m/sec)**	T **(sec)**
Type-2a	30	5.0	0.27	1.86
Type-2b	45	5.0	0.27	1.86
Type-2c	52.5	5.0	0.27	1.86
Type-2d	60	5.0	0.27	1.86
Type-2e	75.5	5.0	0.27	1.86
Type-2f	90	5.0	0.27	1.86

Next, we examine the inward oblique flange (Type-3 in the Figure 2) in detail because the Figure 1 showed the hopeful experimental results. The appropriate angle of the two inward oblique flanges set at one side, α_2, is studied in Series-3 (See Table-3). Δh_2 denotes the vertical height of the inward oblique flange.

Table 3 Computational conditions of Series-3 for the Type-3 pipe.

Type-3				
Sub-Type	α_2 (degree)	Δh_2 **(cm)**	U_0**, (m/sec)**	T **(sec)**
Type-3a	30	2.0	0.27	1.86
Type-3b	37.5	2.0	0.27	1.86
Type-3c	45	2.0	0.27	1.86
Type-3d	52.5	2.0	0.27	1.86
Type-3e	60	2.0	0.27	1.86
Type-3f	90	2.0	0.27	1.86

In this study, the combinations of Type-3 and Type-1 or Type-2 are also discussed as Type-4. Some combinations of the two outward flanges at one side and the two inward flanges at another side are tested as Series-4 (See Table-4). q^* denotes the dimensionless residual discharge as mentioned later.

Table 4 Computational conditions of Series-4 for the Type-4 pipe.

Sub-Type	α_1 (degree)	α_2 (degree)	U_0**, (m/sec)**	T **(sec)**	q^*
Type-4a	90	52.5	0.27	1.86	0.138
Type-4b	60	52.5	0.27	1.86	0.150
Type-4c	45	45	0.27	1.86	0.156

Finally, the effects of the flow conditions on the residual currents generated by the asymmetrical pipe are investigated as Series-5 (see Table-5). For an oscillatory flow in a large enough area with the pipe, the flow is mainly characterized by the Keulegan-Carpenter number KC (Keulegan and Carpenter, 1958) and the Reynolds number Re. KC and Re can be expressed as U_0T/l and U_0D/υ, respectively, where υ is the coefficient of the kinematic viscosity. In this study, only KC is varied under a constant Re because effects of KC are usually much larger than those of Re. In addition, it is possible to estimate the appropriate length of the asymmetrical pipe from the optimal KC in which the maximum residual currents are generated.

Table 5 Computational conditions in Series-5.

Sub-Type	α_1 (degree)	α_2 (degree)	U_0 **(m/sec)**	***T*** **(sec)**	***Re***	***KC***
Type-4c	45	45	0.27	1.00	27000	0.49
Type-4c	45	45	0.27	1.86	27000	0.91
Type-4c	45	45	0.27	6.50	27000	3.19
Type-4c	45	45	0.27	10.50	27000	5.15

3. RESULTS AND DISCUSSIONS

The simulations of oscillatory flows through the asymmetrical pipe with flanges were performed to examine the effects of the pipe on the residual currents. The residual current was defined as the Eulerian velocity averaged over one period of an oscillatory flow. In this study, the residual current was calculated from the sixth cycle of the period which is the final cycle. This criterion was chosen because the computational results seemed to be sufficiently stable after 5 cycles.

Vertical outside flange (Series-1)

Vertical outside flanges should be set at the edges of one side of the pipe. The relationship between the dimensionless residual discharge, q^*, and R_l are shown in Figure 3 from Series-1. In this study, q^* is calculated by the integral of $u\Delta y$ over the inside of the pipe at x/l = 0.5 and normalized by DU_0, where Δy is the grid size in the transversal direction. The largest q^*, that equals to 0.097, is found at R_l = 0, and q^* decreases from the maximum value to zero where R_l = 0.18. q^* is almost constant where $0.18 \leq R_l \leq 0.5$.

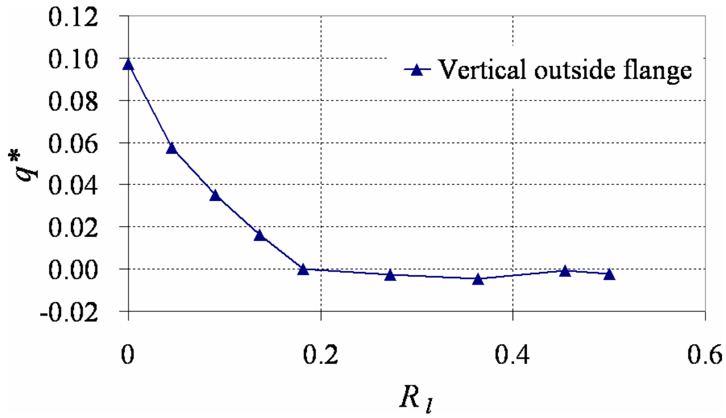

Figure 3 The residual discharges inside the pipe with two vertical flanges at one side depending on their longitudinal position in Series-1.

Oblique flanges (Series-2 & Series-3)

In the case that the two oblique flanges are set at one side, the optimum angle of the outward oblique flanges and that of the inward ones are 60^o and 52.5^o, respectively. q^* of Type-2 and Type-3 cases for various values of the flange angles are presented in Figure 4. In

Series-2 and Series-3, the oblique flanges are attached to the pipe edges in consideration of the results of Series-1. On the outward oblique flanges of Series-2, the maximum q^* is found at $\alpha_1 = 60^o$ although the difference between the maximum q^* and the minimum q^* is about 30% and not so outstanding. On the other hand, in Series-3, the maximum q^* is found at $\alpha_2 = 52.5^o$, and the difference between the maximum value and the minimum one is about 50%.

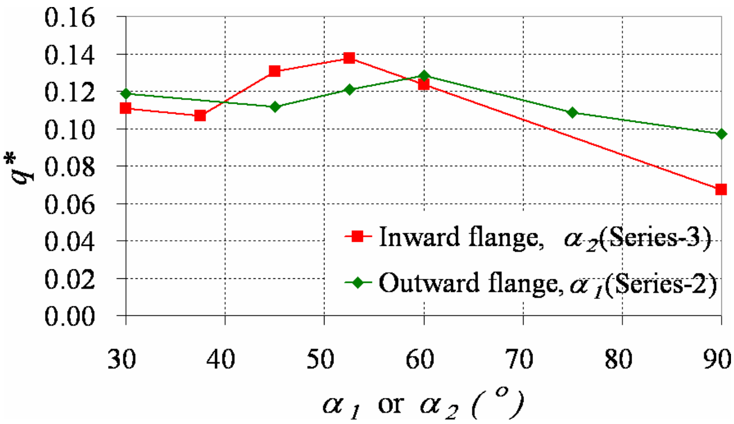

Figure 4 The relationships between the residual discharge q^* and the outward angle α_1 from Series-2 or the inward angle α_2 from Series-3.

In the Figure 4 based on the computational results, q^* of the outward oblique flanges are larger than that of the vertical outside flanges which correspond to the condition of 90^o in the abscissa. It should be possible that the outward oblique flange is more practical than the vertical outside flange. Judging from the only laboratory experiments, the vertical outside flange was found to be more effective than the outward oblique flange. The computational results can not be directly compared with the experimental ones because of the differences of hydrodynamic conditions. The oscillatory flow field with $U_0 = 0.27$m/sec and $T = 1.86$ sec is used for the simulations, while the wave field with 5.0 cm wave height and 1.2 sec wave period was applied to the laboratory experiments.

The inward oblique flange might be more effective than the outward oblique flange. The $q^* = 0.138$ at $\alpha_2 = 52.5^o$ is somewhat larger than the $q^* = 0.128$ at $\alpha_1 = 60^o$ in the Figure 4 although the flange height $\Delta h_2 = 2.0$ cm in Type-3 is considerably smaller than that $\Delta h_1 = 5.0$ cm in Type-2. Contrastively in the experiments, the residual currents in the outward oblique flange were larger than those in the inward one.

Combinational Type flanges (Series-4)

The combination of the outward oblique flange and the inward one is useful to generate the unidirectional residual currents and the discharges. The combinational types (Type-4) are examined in this study as Series-4. In order to estimate the best combination, the results from Series-1 to Series-3 are considered. In addition, 45^o inward and outward oblique flanges are tested as references because the shapes are easy to be formed.

Type-4c should be the optimal combinational type of the outward oblique flange type and the inward one because Type-4c has the largest q^* in Series-4 (see Table-4). Hence, the combination of the best outward angle $\alpha_1 = 60^o$ and the best inward one $\alpha_2 = 52.5^o$ might not be an appropriate combination. The combination of inward oblique flanges and the vertical outside flanges is not effective because q^* in Type-4a is the same as q^* in Type-3d which had the maximum q^* (=0.138) in Series-3. It seems to be difficult to conclude the best combinational type since the difference between q^* (=0.156) in Type-4b and q^* (=0.150) in

Type-4c is small. However, in this study, Type-4c is assumed to be the best combinational type in consideration of simplicity in the following discussions.

Residual Flow Patterns around Asymmetrical Pipes

The effectiveness of the combination of the outward flange and the inward one is confirmed in comparison among the residual currents for three cases; the case with the two outward flanges at one side (Type-2b): the case with the two inward flanges at one side (Type-3c): the combinational case (Type-4c). The transversal distributions of x-directional residual currents, u^*, inside the pipe at x/l = 0.5 are presented in Figure 5, where u^* is normalized by U_0. It can be seen that the residual currents in Type-4c is totally larger than those in Type-2b or Type-3c.

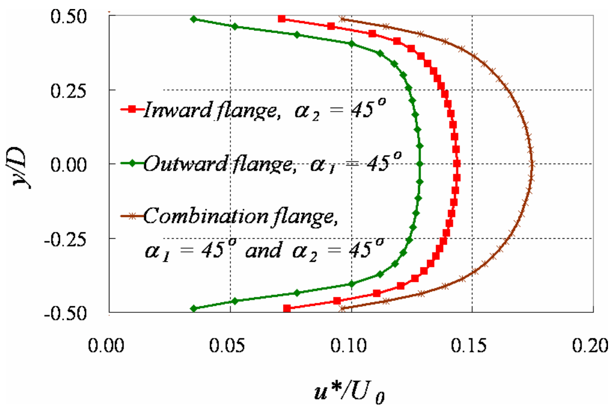

Figure 5 Transversal distributions of x-directional residual currents at the centre of the inside pipe.

Residual currents around the pipes are found to be effective in controlling substance transport. The streamlines of the residual currents produced by the three types: a) Type-2b; b) Type-3c; c) Type-4c are depicted in Figure 6. It seems that the water circulations occur and cover large areas around the pipes. Positive directional flows are induced throughout the pipes in all cases. This situation can be used to encourage substance transport from one end to another end of the pipe.

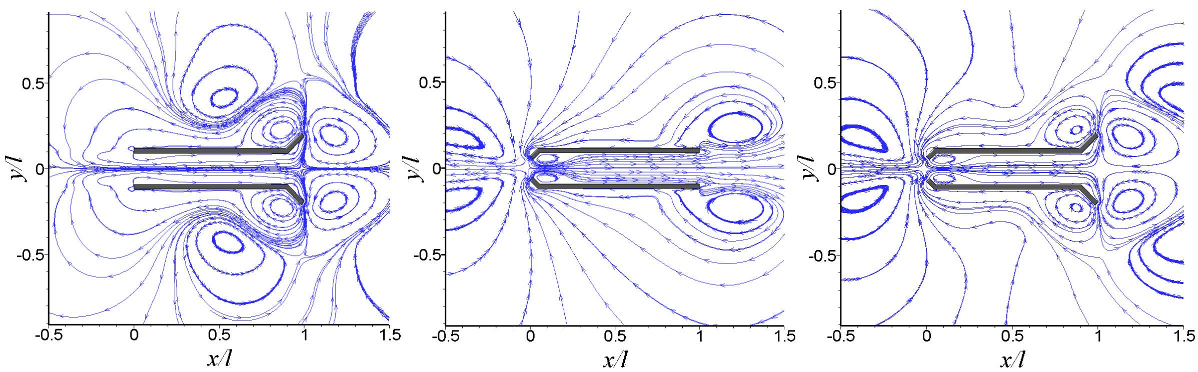

Figure 6 Streamlines of residual currents in the three cases: a) Type-2b with two outward oblique flanges at one side; b) Type-3c with two inward oblique flanges at one side; c) Type-4c with both the outward oblique flanges and the inward ones.

Plural vortexes are found around each pipe in the Figure 6. The streamlines of Type-2b and Type-3c show considerably different circulation patterns, which are predominantly characterized by the dissimilarity of the vortex sizes and the locations. The streamlines of Type-4c seems to be a mixture of streamlines of Type-2b and that of Type-3c.

Effects of Flow Conditions on Residual Currents and Discharges

The unidirectional residual currents can be produced by the asymmetrical pipe in various flow conditions. The magnitude of the residual currents produced by the asymmetrical pipe depends on the *KC* number especially. Figure 7 shows the transversal profiles of dimensionless longitudinal residual currents, u^*/U_0. The findings show that *KC* number influences the magnitude and the profile of the residual currents. The comparison among the maximum residual currents, which can be found at $y/D = 0$ for each profile, pointed out that the residual currents do not increase monotonically with *KC* number. The maximum dimensionless residual current is 0.193 which is obtained at *KC*=3.19.

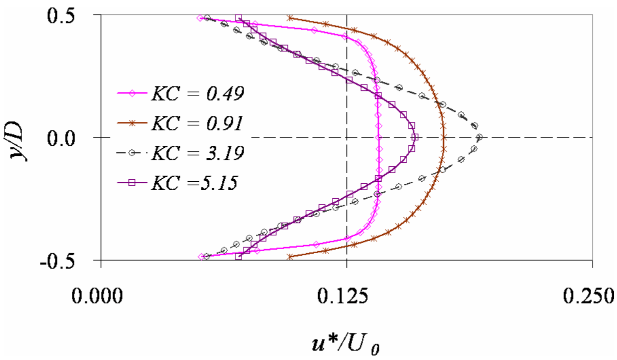

Figure 7 Transversal distributions of *x*-directional residual currents inside the pipe at x/l = 0.5 in Series-5.

The residual discharge inside the asymmetrical pipe is maximal where *KC* = 0.91. Figure 8 shows q^* for various *KC* in Series-5. The maximum value of q^* is 0.156 obtained at *KC* = 0.91 although the maximum u^*/U_0 was obtained at *KC* = 3.19.

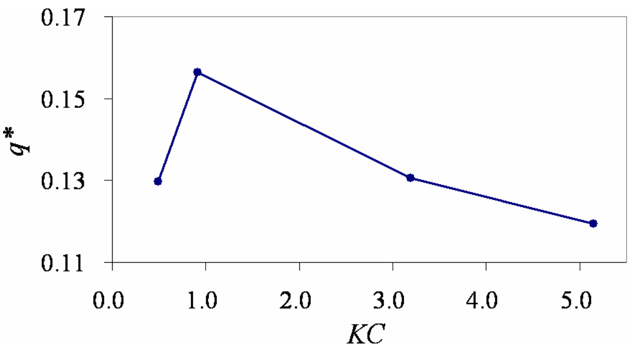

Figure 8 The relationship between q^* and *KC* in Series-5.

4. CONCLUSION

The generation of the residual currents around the asymmetrical pipe was confirmed by the numerical simulations for the oscillatory flow field. The computational results specified that the outward flanges and the inward ones set to the pipe are useful in generating the residual currents. Moreover, the combination type of the outward oblique flange and the inward one can produce larger residual currents compared with each type.

The residual discharge inside the asymmetrical pipe was largest where $KC = 0.91$. The magnitude of the residual currents and the discharges produced by the asymmetrical pipe depends on flow conditions, especially the KC number. It is possible to estimate the appropriate longitudinal length of asymmetrical pipes from the optimal KC number. Therefore, the each pipe should be formed so that the local KC number corresponds to approximately unity using dominant waves in the sea. We have to confirm this finding under wave fields since oscillatory flows used in this study are independent of wavelengths.

It is thought that water pollution in a stagnant sea area can be improved by the new *One-Way Pipe* with the flanges because the residual currents can be produced by the pipes in quite large areas. Residual currents are closely associated with the substance transport. Therefore, the effective control of substance transport by using the *One-Way Pipe* can be expected.

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