Study on Behavior of Density Current in a Small Reservoir

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As for the inflow of the fluid which has the different density from the stagnation area, diffusion and mixing occur with the buoyancy and shear force of inflow fluid. In this study, the reservoir model equipment was employed to examine the effect of inflow mouth angle on the behavior of the density current and the flow characteristics in circulation and mixing. The plunge flow was influenced by the inflow fluid and the densimetric Froude number F_R. Changes in the inflow mouth angle with keeping small density layer thickness did not vary the plunge point. It was found out that the thickness of the density layer was not influenced by time but only influenced by F_R. The changes in the density and the fluid reflected at the end of the downstream in the reservoir are expressed as functions of the reservoir length, time and the buoyancy flux.

Key words: Reservoir, Density current, Mixing, Diffusion, Dimensionless Density, density layer, Inflow mouth angle

1. Introduction

A small reservoir means the reservoir of such a relatively small capacity one as a warm water pond or a settling basin. Especially, such a small reservoir is easily influenced by circumference environment. The flow and water quality in a reservoir are changed by inflow of fluid with high density to the reservoir. Since a reservoir is used as living environment and water resources, the study on behavior of the flow and/or changes in water quality by inflow will be necessary.

The flowing fluid which has different density and/or temperature into the stagnation water is called a density current. In general, the flows could be classified into three patterns of the underflow, the overflow, and the interflow by the density difference between flowing fluid and stagnation reservoir fluid. The flow moves to the downstream forming the underflow when the density of flowing fluid is higher than that of stagnation water. The movement of underflows from upstream to downstream leads to mixing in the reservoir. The degree of mixing is influenced by such characteristic of density current as the front speed and/or thickness of the underflow (Graf and Mortimer, 1979).

The fluid which flows in the stagnation waters moves until it reaches dynamic balance, while hori-
zontally pushing the fluid of the stagnation waters and eventually goes downward. In the process to plunge point, it takes water around being entrainment and forms an underflow. An initial mixture in this plunge point gives an important condition to decide the behavior of the density current. The example of the plunge phenomenon has inflow to the river and an adjustment pond where cold water which contains suspended matter is flown in caused by the heavy rain. Such a flow phenomenon influences farm products and the ecosystem. The knowledge of such plunge phenomenon is useful in designing the mouth of inflow and the scale of the pond when the temperature control is made in the pond for discharging water from the dam to the downstream of the river, when the selective withdrawal is not employed. It is necessary to forecast the flow characteristic and the density change in front of the density current in the stagnation waters to explain the plunge phenomenon.

Fietz and Wood (1967) studied the speed and the flow area of the density current by using experimental and theoretical analysis for three-dimensional density current. Britter and Simpson (1978) understood the flow characteristics in relating the ratio of density current thickness to water depth to the number of fluid, which was led from examining the density current front for unviscous fluid in the experimental and the theoretical methods. Heppurt et al. (1979) studied the moving distance and the speed of the density current both in the experimental and theoretical methods. Akiyama et al. (1984) proposed the equations from theoretical analysis to estimate the depth of the plunge water as functions of inflow densimetric Froude number, mixing ratio at the early stage of inflow, and base inclination.

Singh and Shah (1971) studied the formation of the plunging point and the stability of the 2-dimensional density current through the experiment and the dimension analysis in an inclinational channel. Britter and Linden (1968) examined the growing speed of the head of the density current by changing the bottom inclination in the experiment. It was elucidated that the front speed of the density current was constant regardless of the bottom inclination. Although numerous studies were conducted on the incline of density current, the influence of inflow mouth angle on the density current was scarcely found in the literature.

In this study, influences of rates of inflow and outflow, density difference, and inflow mouth angle on the characteristics of the density flow were examined as a spadework of the reservoir by use of a reservoir model equipment. Particularly, the influence of changing the inflow mouth angle in 30°-90° on the behavior of the density current and the flow characteristics are the major concern in the study to clarify the plunge phenomenon.

II. DIMENSION ANALYSIS

On the one hand, the factors which affect the plunging phenomenon and the flow characteristics of the underflow neighboring the inflow mouth are expressed the relation of the variable characterized by the density style using the formula of Fietz and Wood (1967) by eq (1)  

\[ X_p \cdot R \cdot h \cdot U_f = f(H, Q_e, M_e, t, g', \beta, B_s, x, y, z) \] (1)

The left side of eq (1) is the distance of plunge point \( X_p \), the progress distance of the front of density current \( R \), the thickness of the density layer \( h \), the speed of density current front \( U_f \). The right side is the depth of water area \( H \), the inflow flow rate \( Q_e \), the inflow momentum flux \( M_e \), the time \( t \), the gravitational acceleration \( g' \), the density of ambient fluid \( \beta \), the density of the inflow \( \rho_e \), the density of local fluid \( \rho \), the kinematic viscosity \( \nu \), the inflow buoyancy flux \( B_s \), the flow direction \( x \), the transverse buoyancy \( y \), and the vertical direction \( z \).

On the other hand, the factors which influence the flow inside the reservoir are the distance of plunge point \( X_p \), the progress distance of front \( R \), the thickness of the density layer \( h \), the speed of density current front \( U_f \). The relationship among these factors could be expressed to characterize the flow of density current.

I. Position of plunge point

In this study, the density current was treated as a 2-dimensional side view phenomenon. When inflow
fluid which has higher density than stagnation area flows into the stagnation basin, the fluid proceeds pushing the stagnation water in the horizontal direction until it reaches the dynamic balance. Here, the dynamic balance is made when impellent force of inflow is equal to the resistant force of the stagnation water. The impellent force is represented by the sum of the momentum generated by the change of inflow fluid and the hydrostatic pressure of the high density inflow fluid which is formed under the surface of the stagnation water. On the other hand, the resistant force is represented with the shear force which is generated in the boundary between the inflow fluid which is formed in the downstream from the plunge point and the stagnation water.

$Q_o$ and $M_e$ are the functions of $U_e$, $b_e$, and $h_e$ in the eq(1). When dimension analysis is carried out by choosing $Q_o$, $M_e$, $\Pi$ as the repetition variable, the following dimensionless equation could be deduced.

\[
X_p/b_e = f(h/b_e, U_e/(g h_e)^{1/2}, U_d/b_e, x/b_e, y/b_e, z/b_e) \quad \text{(2a)}
\]

Here, $F_{re}=U_d/(g h_e/b'_e)$, the width of inflow $b_e$, the speed of inflow $U_e$, the depth of the inflow $h_e$, $U_e/(g h_e/b'_e)$ is derived from $g'$ and $B_e$ and defined as $F_{re}$. When the depth of water area $H$ is constant, $H/b_e$ could be ignored. $\Pi/h_d U_e$ is the reciprocal of the Reynolds number $R_e$. Because the $R_e$ range of this study is between 500-2500, the influence on the density current could be eliminated.

The dimensionless variable formula to the plunge point distance $X_p$ turns into a eq(2b) in dimension analysis.

\[
X_p/b_e = f(R_e, U_d/b_e, x/b_e, y/b_e, z/b_e) \quad \text{(2b)}
\]

The inflow fluid is moved to plunge point on the surface of the water. When the inflow is continuing to flow in to the stagnation area, the fluid forms plunge point in the fixed distance from the inflow mouth (Arita et al., 1996; Fukushima et al., 1981; Kan et al., 1981) The fixed plunge point is called steady plunge point. The plunge point of the eq(2b) is related to the steady plunge point, where the time clause could be ignored, because dimensionless plunge point $X_p/b_e$ is always constant for changes in time. $X_p$ is the distance from the inflow mouth to the plunge point in the direction of the flow. It is also ignored in the horizontal and the vertical direction for the direction of the flow. The dimensionless variable, which influences on $X_p/b_e$ in eq(2b), therefore, becomes only $F_{re}$ as eq(3).

\[
X_p/b_e = f(F_{re}) \quad \text{(3)}
\]

2. Density current front speed

The density current front progress distance of the underflow $R$, the density current front speed $U_f$, and the thickness of density layer $h$ are represented as functions of dimensionless variables as eq(4a-4c)

\[
R/h_e = f(R_e, U_d/h_e, x/h_e, y/h_e, z/h_e) \quad \text{(4a)}
\]

\[
h/h_e = f(R_e, U_d/h_e, x/h_e, y/h_e, z/h_e) \quad \text{(4b)}
\]

\[
U_f/U_e = f(R_e, U_d/h_e, x/h_e, y/h_e, z/h_e) \quad \text{(4c)}
\]

Since the time and the distance are independent of the dimensionless density current front speed $U_f/U_e$, the $U_f/U_e$ could be a function of $F_{re}$ as eq(5).

\[
U_f/U_e = f(F_{re}) \quad \text{(5)}
\]

Fig. 1 shows the density current schematically. The density current front speed $U_f$ by use of the equations of the Bernoulli and the hydrostatic pressure under the conditions of the thickness of density layer of $h$, the neighbor stagnant water density $\rho_a$, and the local flow density $\rho$. Analyzing two-dimensional underflow front speed $U_f$ it was proposed that the density current in the steady state moved at the constant speed (Kao, 1977).

The Bernoulli equation could be applied in the hydrostatic pressure between point $\bar{a}$ and $\bar{b}$ in Fig. 1 as eq(6) assuming the stagnation condition, and then the density current front speed being transferred to constant.

\[
P_a + \rho_a U_f^2/2 = P_b \quad \text{(6)}
\]

Fig. 1 Flow chart of the 2-D underflow.
The pressure of point \( C \) could be represented as eq(7) because the pressures in the reservoir were under the condition of hydrostatic pressure distribution.

\[
P_c = P_a - \varrho g \Delta H
\]  

(7)

The pressures in the water were expressed as eqs. (8 and 9) by applying hydrostatic pressure distribution between point \( d \) and \( C \).

\[
P_e = P_d + \varrho g (H - h) + \varrho g \Delta H
\]  

(8)

\[
P_c = P_d, \quad P_b = P_e
\]  

(9)

Then, the density current front speed \( U_f \) is derived from eqs. (6 \& 9) as shown in eq(10).

\[
U_f = \left[ 2 \frac{\varrho g \Delta H}{\varrho_a} \right]^{1/2} = \left( 2g \varrho^2 \right)^{1/2}
\]  

(10)

Here, \( g^* = \varrho / \varrho_a \) \( x \), \( \varrho / \varrho_a = \varrho - \varrho_a \).

The density deficiency flux between the inflow and a given point in the density current is represented as follows.

\[
\varrho_e \cdot q_e = \varrho / q
\]  

(11)

Here, \( \varrho_e = \varrho / \varrho_a \), \( q_e \) is the inflow rate and \( q \) is the local flow rate of density current.

When the average speed of the density current layer and the density current front speed are the same, local flow rate \( q \) is expressed as follows(Kao, 1977)

\[
q = U_f \cdot h
\]  

(12)

The eq(13) could be derived from the eq(10) (12) \( U_f \) could be expressed as functions of density difference \( \varrho \) \( \varrho_e \) between the inflow fluid and the reservoir, and inflow rate \( q_e \).

\[
U_f = \sqrt{2 \frac{\varrho_e - \varrho_a}{\varrho_a} g q_e}
\]  

(13)

The eq(13) could be represented as a function of \( F_{re} \) as eq(14)

\[
\frac{U_f}{U_e} = 2^{1/2} F_{re}^{1/2}
\]  

(14)

Britten and Linder(1968) used the variables of inflow rate \( q_e \), density of the inflow \( \varrho_e \), an angle of inclination \( \varrho \) and the influence of the kinematic viscosity \( \varrho \) for the expression of the density current flow of the inclined channel, in which a density current front speed \( U_f \) can be described by dimension analysis as follows.

\[
U_f = (g^* q_e)^{1/2} \times \varrho \Delta R_e
\]  

(15)

Here, \( g^* = 2g (\varrho_e - \varrho_a) \times (\varrho_e + \varrho_a) \)

When the eq(15) is applied to this study, the eq. (15) can be represented as follows because an angle of inclination \( \varrho \) and \( R_e \) can be ignored

\[
U_f = C g^* q_e^{1/3}
\]  

(16)

The eqs(13 \& 16) were expressed in the difference in dimensionless density and the function of the inflow flow rate. The density current front speed can be predicted by the inflow initial conditions with using the equations.

### 3. Density current front progress distance

Since the density current front progress distance of \( R \) is the same direction as \( x \) in the factors which influence on the dimensionless density current front progress distance of \( R/h_e \) in eq(4a), the distance of the direction of \( z \) is unrelated to \( R \). Consequently, the related factors for eq(4a) are \( F_{re} \) and time clauses. The density current front progress distance \( R \) being functions of speed and time, eq(4a) could be drawn as eq(17)

\[
\frac{R}{h_e} = f(F_{re}, \frac{U_f}{h_e})
\]  

(17)

Substituting the eq(5) by the relation of \( R = U_f t \), the density current front progress distance \( R \) could be expressed as a function of \( F_{re} \) shown in eq(18) which is a transformation of eq(17).

\[
\frac{R}{U_f t} = f(F_{re})
\]  

(18)

### 4. Thickness of the density layer

The density layer thickness being constant for the direction of the flow, the distance of directions of \( x \) and \( z \) which is the same as \( h \) could be ignored in the factors influencing on the dimensionless density layer of \( h/h_e \) in the dimensionless equation of eq. (4b) When the density flow is the two dimensional underflow, the equation is expressed as \( h_1 U_1 = h_2 U_2 \), where \( h_1, h_2, U_1, \) and \( U_2 \) are density layer thicknesses and average speed of the two sections, respectively. The dimensionless variables considered in eq(4b) are \( F_{re} \) and time clauses.

\[
\frac{h}{h_e} = f(F_{re}, \frac{U_f}{h_e})
\]  

(19)

Since the direction of density current front is equal to the direction of the inflow before the flow of the density current is reflected, the thickness of the density layer is independent of time, and the eq(19) could be expressed as a function of \( F_{re} \) as the eq.
(20)
\( h/h_e = f_1(F_{re}) \)  

III. Experimental Equipment and Method

The schematic of experimental setup is shown in Fig. 2. Water tank of width of 20cm, height of 25cm, and length of 110cm was employed as a reservoir model equipment. The angle of inflow was varied at 90°, 60°, 45° and 30°. When cold water flows into warm water pond in practice, the density current is formed by their density difference. The mixture of the cold and warm water at desired temperature, which is formed at the downstream of the pond, is discharged to the river. The density difference was made by employing salt water as cold water in the experiment instead of cold inflow water, because it would be difficult to keep temperature of cold water at a constant temperature. A buoyancy-buoyancy flow - bottom density current - inside density current was formed by higher density water flowing into the stagnation reservoir. The inflow fluid was colored with Methylene Blue for photographing and visual observation.

The higher density salt water was poured from the upstream through the 3cm wide open channel into the 20cm wide tank to make a density current. The five 1ml sampler was installed at 1, 5, 10, 15, and 19 cm depth from the surface of the stagnation water in the vertical directions. They were also installed at 5 sections in the direction of the flow to gathered 25 specimen in total as shown in Fig. 2. The 25 specimen were gathered at the same time by linking the 25 sampler to the pipe. The sampling was made for 7 times at intervals. Samplings were made at the time of 15, 30, 45, 60, 75, 90 and 120 seconds. Each experiment was repeated for 5 times. The experimental data were obtained as the average of each of the 5 measured values. The salinity was obtained by using S/Mill-E refractometer with which both the salt concentration and density could be measured at the same time. The experimental conditions were tabulated in Table 1.

IV. Results and Discussion

1. Density current mixing process

When high density inflow fluid sank and reached the tank bottom, the fluid formed a bottom density current at the shape similar to impact jet with generating inner hydraulic jump as shown in Fig. 3 (a). After a bottom density current was formed, the current flow was proceeded with the constant density layer thickness \( h \) as shown in Fig. 3 (b). When the density current front reached the end of the downstream of the tank reservoir and then reflected, the density current front rose in the vertical direction by the driving force generated by momentum of the continuous inflow current from the upstream. The density current front would rise until the momentum of the density current front becomes zero at the vertical directions. The risen density current front was moved to the direction of the upstream with the layer thickness \( h \) behind the current front as shown in Fig. 3 (c). When the density current rise was smaller than the vertical

<table>
<thead>
<tr>
<th>Exp. No.</th>
<th>Salinity (%)</th>
<th>( Q_0 ) (cm/s)</th>
<th>( h_e ) (cm)</th>
<th>( u_e ) (cm/s)</th>
<th>( \rho_e ) (g/cm³)</th>
<th>( \rho_r ) (g/cm³)</th>
<th>( F_{re} )</th>
<th>( R_e )</th>
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* The same value of \( F_{re} \) was set as experimental conditions in each Exp. No. for all inflow mouth angle (90°, 60°, 45°, 30°).
Fig. 3 The density current forming and the process of the mixing at 90 degree.

momentum of the stagnant water, the density current front sank proceeding in the horizontal direction. The continuous rising of density current front in the vertical direction proceeded with the equilibrium between the force of density current front rise and the hydraulic pressure at the circumference reservoir. When the higher density current continues to pour into the tank, the impellent force of density current would become greater than the hydrostatic pressure of the circumference reservoir. Then the density current would proceed in pushing circumference fluid upon the side of the upstream. The current front proceeded vibrating up and down in the horizontal direction as a result.
2. Position of plunge point

As shown in Fig. 4, the distance between the inflow mouth and the plunge point decreased the \( F_{re} \); the inflow fluid tends to sink into the bottom of the reservoir, because the inflow momentum is small for the small \( F_{re} \).

It was found out that the position of plunge point was not influenced by the angle of the inflow mouth but by the flow condition in the reservoir. When high density fluid flows into the reservoir, the fluid sinks in proceeding to the downstream along the surface of the reservoir. The distance of plunge point is the distance of the surface of the high density inflow fluid started sinking under the stagnation water.

The relationship between the dimensionless plunge point and \( F_{re} \) could be quantitatively represented like eq( 21 ) from the experimental result.

\[
X_p/b_e = 0.132F_{re}^{-0.37} \quad (21)
\]

The position of plunge point was determined by the value of \( F_{re} \) indicating that the plunge point was influenced by the inflow mouth scale, the inflow quantity of the reservoir, and the density of inflow fluid.

3. Density current front speed and the progress distance

Fig. 5 and the eq( 22 ) represent the relationship between the ratio of dimensionless front speed \( U_f/U_e \) and the densimetric Froude number \( F_{re} \) derived from the experimental results.

\[
U_f/U_e = 0.36F_{re}^{-0.65} \quad (22)
\]

The \( U_f/U_e \) value for 30° in the angle of the inflow mouth is greater than that for 90°. It would be caused by the relatively small declining of the initial speed of the inflow fluid in the stagnant reservoir for the angle of 30°.

Experimental results were deviated from the theoretical results derived by using Bernoulli equation exhibited though a similar slope was obtained. The coefficient in the eq( 22 ) from experimental and theoretical results were 0.36 and \( 2^{2/3} \), respectively. The difference between the theoretical and experimental coefficients could be attributed to the decrease in density difference by mixing, resulting in the decrease in \( U_f \) after forming the underflow of density current. The dimensionless ratio of density current front speed to inflow mouth speed \( U_f/U_e \) was represented as a function of \( F_{re} \), and inversely proportional to \( F_{re} \) from the experimental results.

The relationship between the density current front speed of \( U_f \) and \( g'q_e \) was represented by eq. ( 23 ) as shown in Fig. 6.

\[
U_f = 0.37g'q_e^{1/3} \quad (23)
\]

The eq( 24 ) was the density current front speed as a function of \( g'q_e \) derived from the experimental results of Britter and Linder ( 1968 ) in which the bottom slope was varied from 5° to 90°.

\[
U_f = (1.5 \pm 0.2) g'q_e^{1/3} \quad (24)
\]

The exponential factor derived from this experiment was different from that derived from Britter and Linder ( 1968 ). Since the exponential factor of

Fig. 4  The dimensionless plunge point \( X_p/b_e \) by \( F_{re} \).

Fig. 5  The dimensionless density current front speed \( U_f/U_e \) as a function of \( F_{re} \).
Britter and Linder (1968) was derived from the experiment of the two-dimensional slope channel, the difference would also be caused by the difference in the density. The results of the experiment showed that the density current front speed \( U_f \) is a function of \( g'q_e \), and proportional to the power of one third \( g'q_e \).

### 4. Thickness of density layer

Figs. 7-9 show the experimental results concerning the density current thickness. Fig. 7 shows the relation between the dimensionless density layer thickness and time before the density current front reached the end of the reservoir tank. The thickness of the density layer was not influenced by time but by densimetric Froude number \( F_{re} \). The results indicated that the large inflow mouth angle made the density layer thickness \( h \) increase.

Fig. 8 shows the relation between the ratio of dimensionless density thickness \( h/h_e \) and \( F_{re} \) before the reflection. The resultant equation was as eq. (25)

\[
h/h_e = 14F_{re}^{-0.2}
\]

After the density current front reached the end of the downstream and then reflected, the density layer thickness increased as shown in Fig. 9. The ratio of thickness of the density layer after the reflection of density current front can be expressed with the \( U_d/t/h_e \) as shown in eq. (26)

\[
h/h_e = 0.37(U_d/t/h_e)^{5}
\]

The inflow densimetric Froude number is not expressed explicitly in the equation, since the function \( F_{re} \) were included in the term \( U_d/t/h_e \). The \( F_{re} \) could be ignored in the equation, for the function variables of \( U_e \) and \( h_e \) for the function \( F_{re} \) were included in the term \( U_d/t/h_e \). The front speed would be influenced by

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**Fig. 6** The relationship between the density current front speed \( U_f \) and \( g'q_e \).

**Fig. 7** The relationship between time and density layer thickness.

**Fig. 8** The relationship with density layer thickness to \( F_{re} \).
the density layer thickness after the reflection from the experimental results.

5 . Dilution
The relationship between the dilution S and $F_{re}$ in the density layer was shown in Fig. 10.

The concentration of density layer head of S could be expressed by the following equation (Roberts, 1979) As the difference in density is increased, S value is increased. When there is no density difference, S is equal to one.

\[ S = \frac{\partial h}{\partial x} = \frac{q}{q_a} = 4.9F_{re}^{-0.81} \quad (27) \]

The eq (27) could be valid until the density current front is reached at the end of the downstream. The concentration of the density layer behind the density head could be represented by the eq(27) at any head wave location.

Since the front density after reflection is in contact with the density current before the reflection, the density current after the reflection could be considered to be small compared with the current which is assumed to be advanced linearly without reflection.

V . CONCLUSIONS

The reservoir model equipment was employed to examine the effect of inflow mouth angle on the behavior of the density current and the flow characteristics in circulation and mixing. The following results were obtained in conclusion.

1) The experimental results exhibited similar tendency with the theoretical results in the formation of density current and the process of mixing.

2) The plunge flow was influenced by the inflow fluid and the densimetric Froude number. Changes in the inflow mouth angle did not vary the plunge point when $F_{re}$ is constant on the one hand. On the other hand, if the inflow angle of mouth increases, $U_f$ will be decreased and $h$ will be increased.

3) The density current proceeded to the direction to the upstream after it was reflected at the end of the downstream. The base density layer gradually reached the surface of reservoir water by the repetition of such reflection process.

4) The aspect of the density current in the reservoir was significantly different before and after the density current front reached the end of the downstream; before the density current front reached the end of the downstream, the density layer thickness could be represented as a function of $F_{re}$, whereas it could be expressed as functions of time and front speed after it reached the end.

5) It was found out that the thickness of the density layer was not influenced by time but only influenced by $F_{re}$. From the experiments, the density layer thickness was influenced by the front speed rather than the difference in density between the inflow fluid and the neighboring stagnant reservoir.

6) The changes in the density and the fluid reflected at the end of the downstream in the reservoir...
voir are expressed as functions of the reservoir length, time and the buoyancy flux.

LIST OF SYMBOLS

\( X_p \) : distance of plunging point  
\( R \) : progress distance of front  
\( h \) : thickness of the density layer  
\( U_r \) : speed of density current front  
\( H \) : depth of water area  
\( Q_e \) : inflow flow rate  
\( M_e \) : inflow momentum flux  
\( h_e \) : inflow water depth of fluid  
\( U_e \) : inflow speed of fluid  
\( \rho_e \) : density of the reservoir  
\( \rho_a \) : density of ambient fluid  
\( \rho_l \) : density of local fluid  
\( F_{re} \) : inflow densimetric Froude number  
\( B_e \) : inflow buoyancy flux  
\( U_f \) : density current front speed  
\( b_i \) : width of inflow  
\( q_i \) : flow rate for unit width  
\( \nu \) : kinematic viscosity  
\( t \) : time  
\( S \) : dilution  
\( x \) : flow direction  
\( y \) : transverse direction  
\( z \) : vertical direction

REFERENCES


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