Analysis of nonuniform aerated skimming flows on stepped channels

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Abstract: For the hydraulic design of steep stepped channels, it is important to elucidate the aerated flow characteristics of skimming flows both in nonuniform and quasi-uniform flows. For the nonuniform aerated flow region, an analytical equation for calculation of the aerated flow depth is developed, and the surface profile and specific energy are calculated using this equation together with the continuity equation for the air phase. The results agree with the experimental data.

Keywords: Stepped channel, nonuniform skimming flow, air concentration, aerated flow velocity, aerated flow depth, energy head of aerated flow.

1. INTRODUCTION

Stepped channels are effective for the energy dissipation of supercritical flow in steep channels, chutes, and spillways. In the skimming flow regime, the free surface air entrainment starts at the inception point (Fig. 1). To illustrate the aerated flow characteristics of skimming flows, Boes and Hager (2003) measured the aerated flow velocity $u$ and the air-concentration ratio $C$ for $30^\circ \leq \theta \leq 50^\circ$. In the nonuniform aerated skimming flow region, Felder and Chanson (2009b) measured $u$ and $C$ for $\theta = 22^\circ$ and Bung (2011) measured these values for $\theta = 18^\circ$ and $27^\circ$. In the quasi-uniform skimming flow region, Takahashi and Ohtsu (2012) evaluated the energy head of aerated skimming flows for $19^\circ \leq \theta \leq 55^\circ$ with the empirical equation for the depth-averaged air-concentration ratio, the velocity profile, and the friction factor, revealing the effect of the channel slope and step height on the specific energy of aerated skimming flows.

In this study, an analytical equation for calculation of the aerated flow depth is developed in the nonuniform aerated flow region, and the surface profile and specific energy of aerated flow for $\theta = 55^\circ$ are calculated using the analytical equation together with the continuity equation for the air phase. The results agree with the experimental data.

2. EXPERIMENTS AND EXPERIMENTAL SET-UP

The experiments were conducted in stepped channels of constant slope and uniform step height with a smooth crest (Table 1). The air-concentration ratio $C$ and the aerated flow velocity $u$ at the edge section (Fig. 2) in the nonuniform flow region were measured using a double-tip conductivity void probe (Chanson 2002b) with leading and trailing tips of 25 $\mu$m in diameter at a sampling frequency of 20 kHz and a sampling time of 20 s along the channel axis.

Regarding the magnitude and distribution of $C$ and $u$ in the quasi-uniform flow region, if the Reynolds number is $R \geq 4 \times 10^4$ where $R = q_w \nu_w / \nu$, $q_w$ = the discharge per unit width, and $\nu_w$ = the...
kinematic viscosity of clear water, it was confirmed that \( C \) and \( u/u_{0.9} \) are represented by the following functional relationship (Takahashi et al. 2005, 2006)

\[
C, u/u_{0.9} = \text{func}(y/y_{0.9}, S/d_c, \theta),
\]

where \( d_c \) is the critical flow depth and \( u_{0.9} \) is the mean velocity at \( y = y_{0.9} \) with \( y_{0.9} \) as the aerated flow depth defined as \( y \) at \( C = 0.9 \). For \( R \geq 4 \times 10^4 \) at a given section of \( H/d_c \) (Fig.1) in the nonuniform flow region, a Froude similitude with Eq. (1) may be applied specifically for the magnitude and distribution of \( C \) and \( u/u_{0.9} \) (Takahashi and Ohtsu 2013) except in terms of turbulent properties and bubble sizes (Pfister and Chanson 2012, Felder and Chanson 2009a). Thus, experimental data were collected in the range of \( 4 \times 10^4 \leq R \leq 9 \times 10^4 \) to satisfy these limits.

3. AIR-CONCENTRATION RATIO

The depth-averaged air-concentration ratio \( C_m \) is defined by

\[
C_m = \frac{1}{Y_{0.9}} \int_0^{y_{0.9}} C \text{dy} = \int_0^1 C \text{d}Y,
\]

where \( Y = y/y_{0.9} \) with \( y \) being the normal coordinate from the pseudo-bottom. If the depth-averaged air-concentration ratio \( C_m \) at the edge section is arranged in accordance with Eq. (3), Figure 3 is obtained.

\[
C_m = \text{func}\left(\frac{x_s-x_i}{d_c}, \frac{S}{d_c}, \theta\right),
\]

where \( x_i \) is the distance from the top of the stepped channel to the inception point of air entrainment, \( x_s (= H_{s}/\sin\theta) \) is the distance from the top of the stepped channel to the test section along the channel axis. The values of \( C_m \) for a given \( \theta \) and \( S/d_c \) in the nonuniform flow region increase with \((x_s-x_i)/d_c \). In the quasi-uniform flow region, \( C_m \) for a given \( \theta \) and \( S/d_c \) becomes constant. At the inception point \([(x_s-x_i)/d_c=0]\), the value of the depth-averaged air-concentration ratio \( C_m \) is nearly equal to 0.2, which agrees with the results of other researchers (Boes and Hager 2003, Bung 2011, Matos 2000).

### Table 1 – Test conditions.

| \( \theta \) [°] | \( S \) [cm] | \( d_c \) [cm] | \( S/d_c \) [-] | \( R \times 10^4 \) | \( H_{dam} \) [cm] |
|----------------|-------------|--------------|----------------|-----------------|---------------|
| 55°            | 1.25        | 6.3          | 0.2            | 5               | 349           |
|                | 2.5         | 8.3          | 0.3            | 9               |
|                | 2.5         | 5.0          | 0.5            | 4               |
|                | 5.0         | 10.0         | 0.5            | 8               |
|                | 5.0         | 7.1          | 0.7            | 6               |

Note: \( S = \) step height, \( d_c = (q^2_w/g)^{1/3} \) being critical flow depth, \( g = \) gravity acceleration, \( H_{dam} = \) total drop height.
For the gradually varied flow region downstream of the inception point, the continuity equation for the air phase in a prismatic channel is expressed as (Wood 1985, Chanson 1993)

\[
\frac{1}{(1-C_{mu})} \ln \left( \frac{1-C_m}{C_{mu} - C_m} \right) - \frac{1}{(1-C_{mu})(1-C_m)} = k_o \frac{x_c/d_c - x_i/d_c}{d_{wi}/d_c} + K_o, 
\]

(4)

where \( k_0 \) and \( K_0 \) are

\[
k_0 = \frac{u_i d_{wi} \cos \theta}{\text{q}_w}
\]

and

\[
K_0 = \frac{1}{1-C_{mu}} \left[ \frac{1}{1-C_{mu}} \ln \left( \frac{1-C_{mv}}{C_{mu} - C_{mv}} \right) - \frac{1}{1-C_{mv}} \right].
\]

with \( C_{mu} \) = the depth-averaged air-concentration ratio in the quasi-uniform flow, \( d_{wi} \) = the clear water depth at the inception point, and \( u_i \) = a bubble rise velocity. Equation (4) with \( u_i = 0.4 \text{ m/s} \) (Chanson 2002a) enables the depth-averaged air-concentration ratio \( C_m \) to be calculated as a function of the distance along the channel axis if the boundary conditions \( C_{mv}, C_{mu}, \) and \( d_{wi} \) are given, obtaining the line in Fig. 3. For \( 0.2 \leq S/d_c \leq 0.7 \) and \( \theta = 55^\circ \), the lines agree well with the experimental data.

For the air-concentration ratio, the curved lines in Fig. 4 represent the values calculated from the air-bubble diffusion model of Eq. (5) (Chanson 2002a) with \( C_m \) obtained from Eq. (4).

\[
C = 1 - \text{tanh}^2 \left( k' \frac{1}{2D'} \right),
\]

(5)

where

\[
D' = \frac{0.848C_m - 0.00302}{1 + 1.1375C_m - 2.2925C_m^2}
\]

and

\[
k' = \text{tanh}^{-1} \sqrt{0.1 + \frac{1}{2D'}}.
\]
Figure 4 demonstrates that the profiles of $C$ in the nonuniform flow region are predicted by the air-bubble diffusion model Eq. (5) together with $C_m$ obtained from Eq. (4). The predicted lines approximately agree with the experimental data. Thus, the air-concentration profiles in the nonuniform aerated flow region can be obtained using the continuity equation for the air phase [Eq. (4)] and the air-bubble diffusion model [Eq. (5)].

4. VELOCITY PROFILES

The time-averaged aerated flow velocity $u$ for $R \geq 4 \times 10^4$ in the nonuniform flow region can be expressed as

$$\frac{u}{u_{0.9}} = \text{func}\left(\frac{y}{y_{0.9}}, \frac{x_a-x_i}{d_c}, \frac{S}{d_c}, \theta\right).$$

(6)

If the experimental data at the edge section are arranged in accordance with Eq. (6), Figure 5 is obtained, revealing that the velocity profile for a given $\theta$ and $S/d_c$ is independent of $(x_s-x_i)/d_c$. This result is in agreement with the observations of Bung (2011) for $\theta = 18^\circ$ and $27^\circ$.

The velocity profiles for $0 \leq y/y_{0.9} \leq 1$ follow the power-law velocity profile as (Fig. 5)

$$\frac{u}{u_{0.9}} = \left(\frac{y}{y_{0.9}}\right)^{-\frac{1}{N}}.$$  

(7)

For a given $\theta$ and $S/d_c$, the values of $N$ in the nonuniform flow region are nearly equal to those in the uniform flow region, noting that the values of $N$ are independent of $(x_s-x_i)/d_c$.

5. GRADUALLY VARIED EQUATION FOR AERATED SKIMMING FLOWS IN STEPPED CHANNELS

From high-speed video camera images, the time-averaged streamlines for $19^\circ \leq \theta \leq 55^\circ$ at the edge section are almost parallel to the pseudo-bottom (Takahashi and Ohtsu 2012). For $0 \leq y/y_{0.9} \leq 1$, aerated skimming flows are treated as a continuous fluid with a varying density and velocity. In the aerated skimming flows, the total energy head $E$ is generally expressed as (Ohtsu et al. 2004)
\[ E = \int_0^{y_{w0}} \left[ \rho g (z + y \cos \theta) + p \right] dy + \int_{y_{w0}}^{y_{w0}} \left[ \frac{1}{2} \rho u^2 \right] dy \]
\[ = \int_0^{y_{w0}} \left[ (1 - C) \rho_w g y \cos \theta + \int_{y_{w0}}^{y_{w0}} (1 - C) \rho_w g \cos \theta \right] dy + \int_0^{y_{w0}} \left[ \frac{1}{2} (1 - C) \rho_w u^3 \right] dy, \]

where
\[ p = \int_y^{y_{w0}} \rho g \cos \theta dy \]
is the pressure of aerated flows, \( p = (1 - C_m) \rho_w \) is the density of aerated flow, \( \rho_w \) is the density of clear water flow, \( z \) is the vertical distance of the pseudo-bottom above datum. If the total energy head \( E \) is expressed by the clear water depth \( d_w \) and the average velocity \( V_w = \frac{q_w}{d_w} \), then Eq.(8) can be simplified as
\[ E = z + C_p d_w \cos \theta + C_v \frac{V_w^2}{2g}. \]

Using the averaged air-concentration ratio \( C_m \), the clear-water depth \( d_w \) is given as
\[ d_w = \int_0^{y_{w0}} (1 - C) dy = (1 - C_m) y_{w0}. \]

The correction coefficients \( C_v \) and \( C_p \) are defined as
\[ C_v = \frac{\int_0^{y_{w0}} \frac{1}{2} \rho u^2 dy}{\int_0^{y_{w0}} \left[ (1 - C) \rho_w u^2 \right] dy} \]
\[ = \left[ 1 - \int_0^1 C dY \right] \int_0^1 \left[ (1 - C) U^2 \right] dY \]
\[ C_p = \frac{\int_0^{y_{w0}} (\rho g \cos \theta + p) dy}{\int_0^{d_w} (\rho_w g \cos \theta + \rho_w) V_w dy} \]
\[ = \frac{\int_0^1 \left[ (1 - C) Y + \int_Y^1 (1 - C) dY \right] U dY}{\left[ 1 - \int_0^1 C dY \right] \int_0^1 (1 - C) U dY}, \]

where
\[ \rho_w = \int_y^{d_w} \rho_w g \cos \theta dy \]
is the pressure of clear-water, \( Y = y/y_{w0} \), and \( U = u/u_{w0} \). Here, \( C_v \) in Eq. (12) is the ratio of the kinetic energy flux of the aerated flow to that of the clear-water flow, and \( C_p \) in Eq. (13) is the ratio of the potential energy flux plus the work done by the pressure of the aerated flow to that of the clear water flow. Both \( C_v \) and \( C_p \) depend on the magnitude and distribution of the aerated flow velocity \( U \) and the air-concentration \( C \), indicating that the values of \( C_v \) and \( C_p \) can be calculated using the air-bubble diffusion model [Eq. (5)] with \( C_m \) and the 1/N-th power law [Eq. (7)] with \( N \).
Differentiating both sides of Eq. (10) with respect to $x$ yields

$$\frac{dE}{dx} = \frac{dz}{dx} + C_p \cos \theta \frac{dd_w}{dx} + d_w \cos \theta \frac{dC_p}{dx} - C_v \frac{dC_v}{dx} \frac{1}{2} \left( \frac{dC_p}{dx} \right)^3 \frac{dC_v}{dx} \frac{1}{2} \left( \frac{dC_p}{dx} \right)^3 \frac{dC_v}{dx}.$$

(15)

with the energy slope $S_f = -\frac{dE}{dx}$ and $S_0 = -\frac{dz}{dx} (=\sin \theta)$,

$$\frac{dd_w}{dx} = \left( \frac{d_w}{d_c} \right)^3 (S_0 - S_f) - \left( \frac{d_w}{d_c} \right)^4 \frac{dC_p}{d(x/d_c)} \cos \theta \frac{1}{2} \frac{dC_v}{d(x/d_c)} \cos \theta - C_v.
$$

(16)

As the terms $(d_w/d_c)^4[dC_p/d(x/d_c)]\cos \theta$ and $dC_v/d(x/d_c)$ are negligibly small compared with the other terms, Eq. (16) simplifies to

$$\frac{dd_w}{dx} = \frac{S_0 - S_f}{C_p \cos \theta - C_v F_w^2 \cos \theta}.
$$

(17)

with the Froude number defined as $F_w = V_w/(gd_w \cos \theta)^{1/2} = 1/[(d_w/d_c)^3 \cos \theta]^{1/2}$. If $C_p = C_v = 1$, Eq. (17) coincides with the drawdown equation of clear water flow.

When the head loss $dh_L$ is expressed as $dh_L = (f_g/4)(dx/d_w)(V_w^2/2g)$, the energy line slope is

$$S_f = -\frac{dE}{dx} = \frac{dh_L}{dx} = \frac{d}{dx} \left( f_g \frac{dx}{4} \frac{V_w^2}{d_w 2g} \right) = \frac{f_g q_w^2}{8g d_w^3},
$$

(18)

where $f_g$ is a friction factor in the gradually varied flow. In the quasi-uniform flow (subscript $u$) region,

$$q_w = d_{wu} V_{wu} = \frac{8g}{\sqrt{f_u}} \sqrt{d_{wu}^3 \sin \theta},
$$

(19)

where $d_{wu}$ is the clear water depth in the quasi-uniform flow, $V_{wu}$ is the averaged velocity in the quasi-uniform flow, and $f_u = 8(d_{wu}/d_c)^3 \sin \theta$ is a friction factor in the quasi-uniform flow. Substituting Eq. (19) into (18) yields

$$S_f = \frac{f_g}{f_u} \frac{d_{wu}^3}{d_w^3} \sin \theta.
$$

(20)

If it is assumed that the value of $f_g$ is equal to that of $f_u$, then from Eqs. (17) and (20)

$$\frac{dd_w}{dx} = \sin \theta \frac{d_{wu}^3 - d_w^3}{C_p \cos \theta - C_v d_c^3}.
$$

(21)

For non-aerated flow ($C = 0$), $C_p = 1$ and $C_v = a$ (the Coriolis coefficient), indicating that Eq. (21) agrees with the gradually varied flow equation for non-aerated flows in rectangular channels. In consideration of the aerated flow characteristics of $C$ and $U$, the clear water depth $d_w$ and the aerated flow depth $y_{0.9}$ along the channel axis are obtained according to the flow chart presented in Fig. 6. Equation (21) is integrated numerically with respect to $x$ subject to the boundary condition $d_w = d_{wi}$ at the inception point $x = x_i$. The calculated values of $d_w/d_c$ and $y_{0.9}/d_c$ for $\theta = 55^\circ$ are shown in Fig. 7. The lines agree well with the experimental data for $\theta = 55^\circ$ and $0.2 \leq S/d_c \leq 0.7$, and the predicted lines clearly demonstrate the effect of $(x - x_i)/d_c$ on $d_w/d_c$ and $y_{0.9}/d_c$. Note that $d_w/d_c$ decreases as $(x - x_i)/d_c$ increases while $y_{0.9}/d_c$ increases. In the quasi-uniform flow region, the values of $d_w/d_c$ and those of $y_{0.9}/d_c$ approach a constant value. In addition, the difference between the calculated value of $d_w/d_c$ considering $C_v$ and $C_p$ and that of $C_v = C_p = 1$ is within 1.3%.
If the data of Matos (2000) for $\theta = 53^\circ$ are compared to the predicted lines of $C_m$, $d_w/d_c$, and $y_{0.9}/d_c$ using the flow chart (Fig. 6) with the values of $C_{mu}$, $N$, and $d_w$ given by the empirical equations of Takahashi and Ohtsu (2012), Figure 8 is obtained and the predicted lines are in agreement with the data of Matos (2000).

Figure 6 – Flow chart for determination of clear-water depth $d_w$ and aerated flow depth $y_{0.9}$.

Figure 7 – Clear-water depth $d_w$ and aerated flow depth $y_{0.9}$ for $\theta = 55^\circ$ and $S/d_c = (a) 0.3$, (b)0.7.

Figure 8 – Comparison between data of Matos (2000) and predicted lines for $\theta = 53^\circ$ and $S/d_c = 0.5$. (a) $C_m$, (b) $d_w/d_c$ and $y_{0.9}/d_c$.

Figure 9 – Specific energy of aerated flow for $\theta = 55^\circ$ and $S/d_c = (a) 0.3$, (b)0.7.
6. SPECIFIC ENERGY

The step edge section is selected as the reference section to estimate the specific energy $E_s$. The relative specific energy $E_s/d_c$ is given by

$$
E_s/d_c = C_p \frac{d_w}{d_c} \cos \theta + C_v \left( \frac{d_w}{d_c} \right)^2.
$$

The values of $E_s/d_c$ plotted in Fig. 9 result from Eqs. (22), (12), and (13) with $V_w = q_w/d_w$ and Eq. (11), using the measured data of $C$ and $u$. For a given $\theta$ and $S/d_c$, the predicted $E_s/d_c$ lines in Fig. 9 follow from Eq. (22), in which $d_w/d_c$ is given by Eq. (21), and $C_v$ and $C_p$ by $C(Y)$ [Eq. (5)] with $C_m$ [Eq. (4)] and $U(Y)$ [Eq. (7)] with $N$. The lines agree well with the experimental data for $\theta = 55^\circ$ and $0.2 \leq S/d_c \leq 0.7$. For the nonuniform flow region, $E_s/d_c$ increases with $(x_s - x_i)/d_c$, while for the uniform flow region, $E_s/d_c$ for a given $\theta$ and $S/d_c$ approaches a constant value. The difference between the calculated values of $E_s/d_c$ considering $C_v$ and $C_p$ and that of $E_s/d_c$ given by $C_v = C_p = 1$ is within 9.7%, indicating that the values of $E_s/d_c$ with $C_v$ and $C_p$ are more precise and larger than those with $C_v = C_p = 1$.

7. CONCLUSIONS

For the stepped channel angle $\theta = 55^\circ$ and the relative step height $S/d_c$ from 0.2 to 0.7, the flow depth and the specific energy of aerated skimming flows can be analytically calculated. The results are summarised as follows:

(i) The depth-averaged air-concentration ratio $C_m$ in the nonuniform flow region follows the continuity equation for the air phase [Eq. (4)] with boundary conditions of $C_{mi}$ at $x_i$ and $C_{mu}$ in the quasi-uniform flow region. The air-concentration profiles in the nonuniform flow region are approximated using the diffusion model [Eq. (5)] with the continuity equation for the air phase [Eq. (4)].

(ii) The profile of the time-averaged aerated flow velocity $u$ at the edge section both in the nonuniform and quasi-uniform flow regions is approximated by the $1/N$-th power law [Eq. (7)]. The values of $N$ in the nonuniform flow region is equal to those in the uniform flow region.

(iii) The basic equation for the clear water depth $d_w$ in the nonuniform aerated flow region is developed using the energy equation. For a given channel slope $\theta$, step height $S$, and critical flow depth $d_c$, the clear water depth $d_w$ and the aerated flow depth $y_{0.9}$ can be obtained together with the continuity equation for the air phase and is represented in Fig. 7, revealing the effect of $(x_s - x_i)/d_c$ on $d_w/d_c$ and $y_{0.9}/d_c$. In the nonuniform flow region, the clear water depth $d_w/d_c$ decreases as the relative distance $(x_s - x_i)/d_c$ increases, while the aerated flow depth $y_{0.9}/d_c$ increases with $(x_s - x_i)/d_c$.

(iv) The specific energy of aerated flows in nonuniform flow regions is calculated using Eq. (22) with the correction coefficients $C_v$ and $C_p$ given by normalised velocity profile $u/u_{0.9}(Y)$ [Eq. (7)] and the air-concentration ratio profile $C(Y)$ [Eq. (5)], indicating that the calculated values of $E_s/d_c$ with $C_v$ and $C_p$ are more precise than those obtained using $C_v = C_p = 1$.

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