An experimental investigation of reaeration and energy dissipation in hydraulic jump

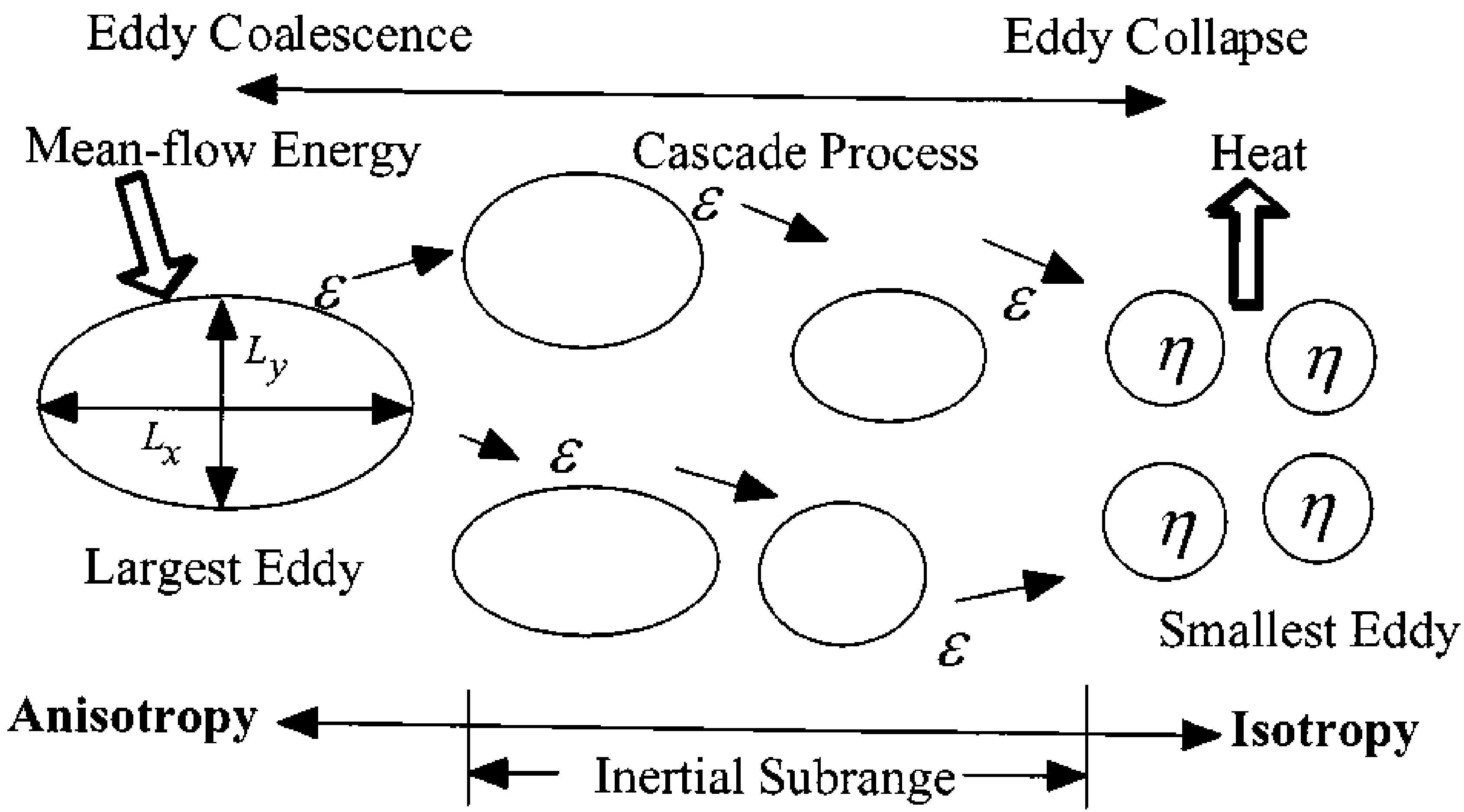
Dr. Serhat Kucukali and Dr. Sevket Cokgor

XXXVIII
International School of Hydraulics
21 - 24 May 2019 • Łąck • Poland

Literature Review

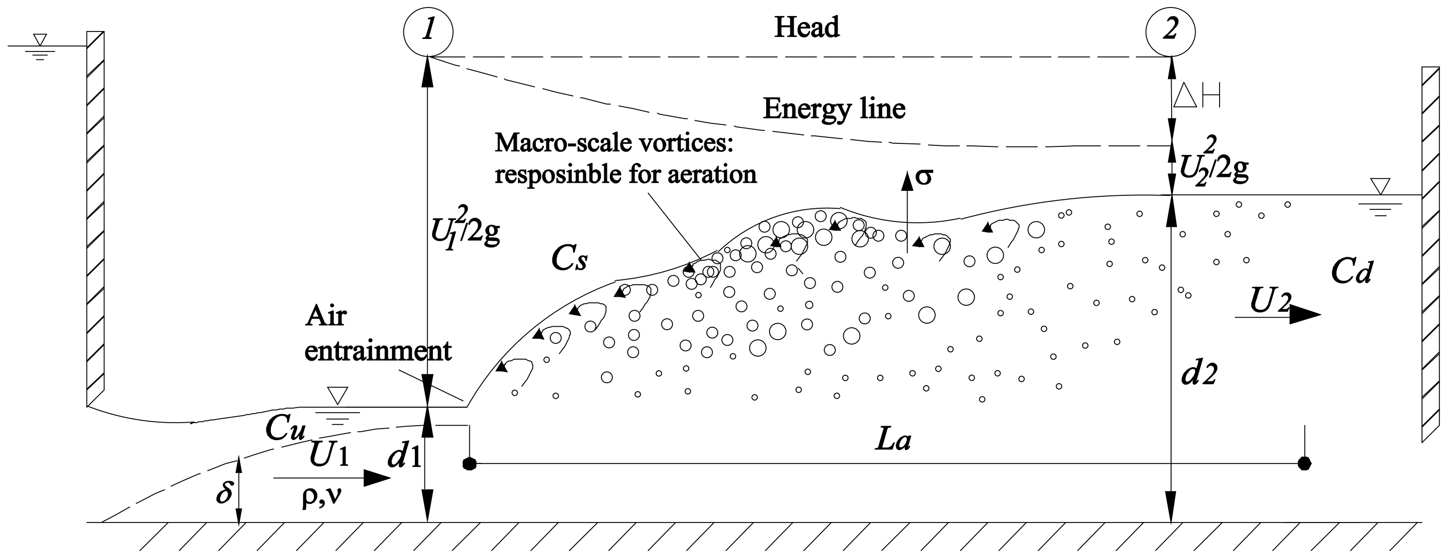
- The term self-aeration means transfer of oxygen from air into water and it has important environmental and ecological implications for polluted streams.
- For non-uniform flow conditions, Moog and Jirka (1998) related the gas transfer efficiency of macro roughness elements with the energy dissipation rate on the basis of small-eddy model. Kucukali and Cokgor (2008) investigated the aeration performance of boulder structures at sudden expansions and plunging jets; where they found an interrelation between the aeration efficiency and the energy dissipation.
- hydrodynamic processes which ensure the self-aeration mechanism such as: (1) hydraulic jump, (2) plunging jet or water fall, and (3) stepped channels have other common property: they are also used as energy dissipaters at hydraulic structures.
- From this point of view, one can expect to find a positive correlation between the aeration efficiency and the energy dissipation. It could be suggested that the macro-scale eddies which are responsible for the mixing and energy dissipation; also could be responsible for the suction of air into water too.

Energy Cascade Process



Adapted from Nezu (2005)

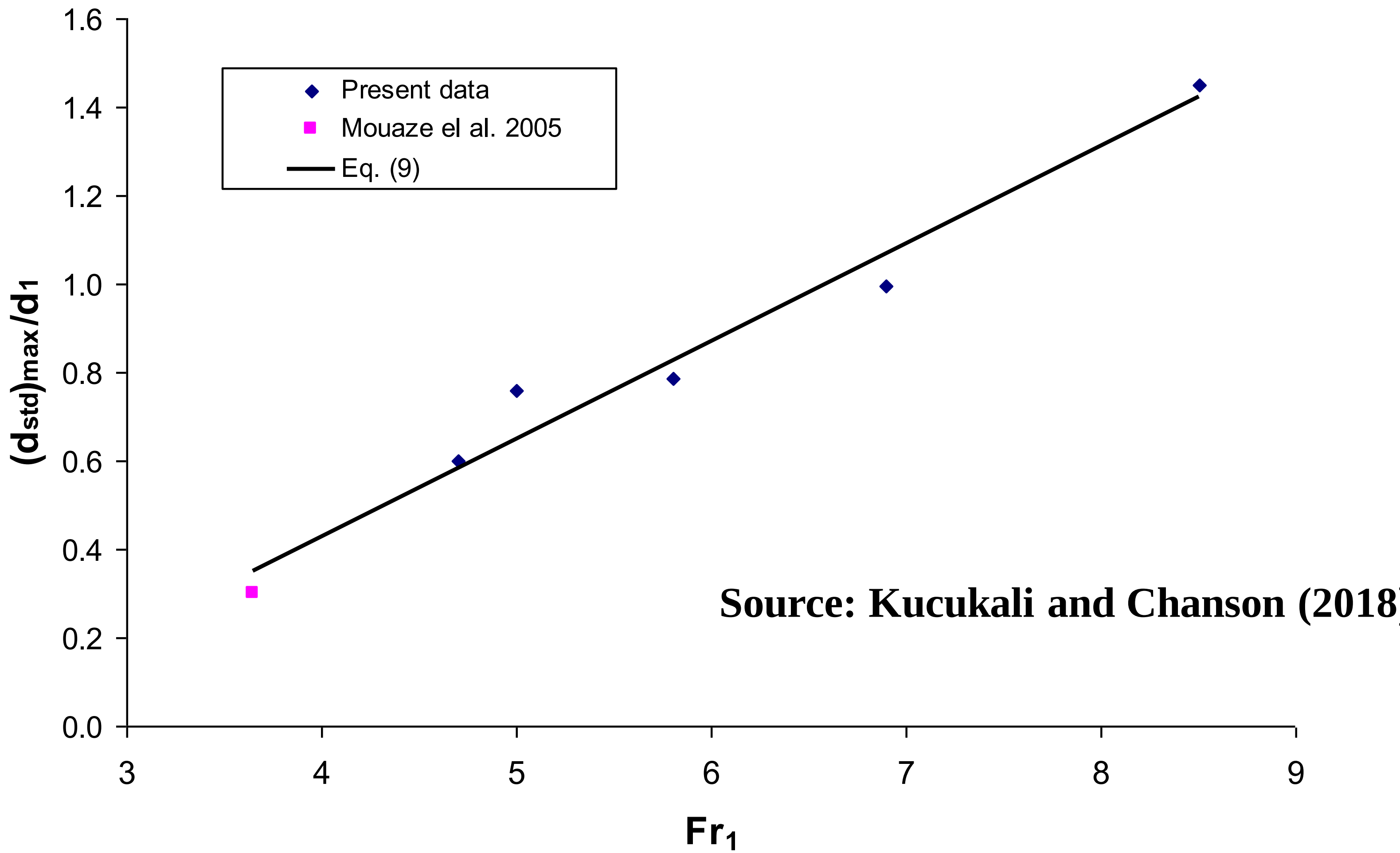
Definition sketch for reaeration in a hydraulic jump



$$Fr_1 = \frac{U_1}{\sqrt{g \times d_1}} \qquad \mathrm{Re} = \frac{U_1 \times d_1}{\nu}$$

$$\Delta H = \left(d_1 + \frac{U_1^2}{2g}\right) - \left(d_2 + \frac{U_2^2}{2g}\right) \qquad \varepsilon_a = \frac{\Delta H \times Q \times g}{(d_1 + d_2) \times 0.5 \times L_j}$$

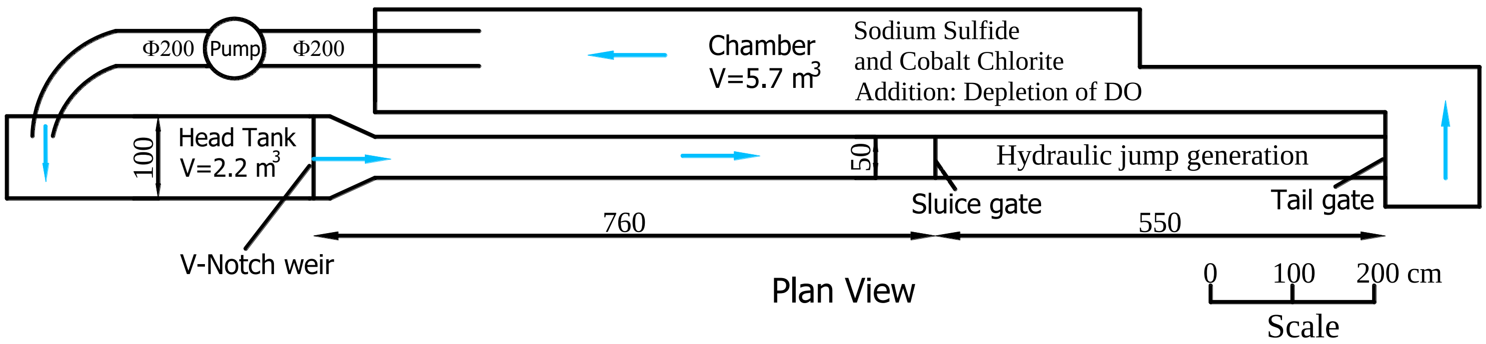
$$E = \frac{C_d - C_u}{C_s - C_u} = 1 - \frac{1}{\exp(K \times t)}$$



Source: Kucukali and Chanson (2018)

Variation of the maximum free-surface fluctuation with a function of Fr_1 number

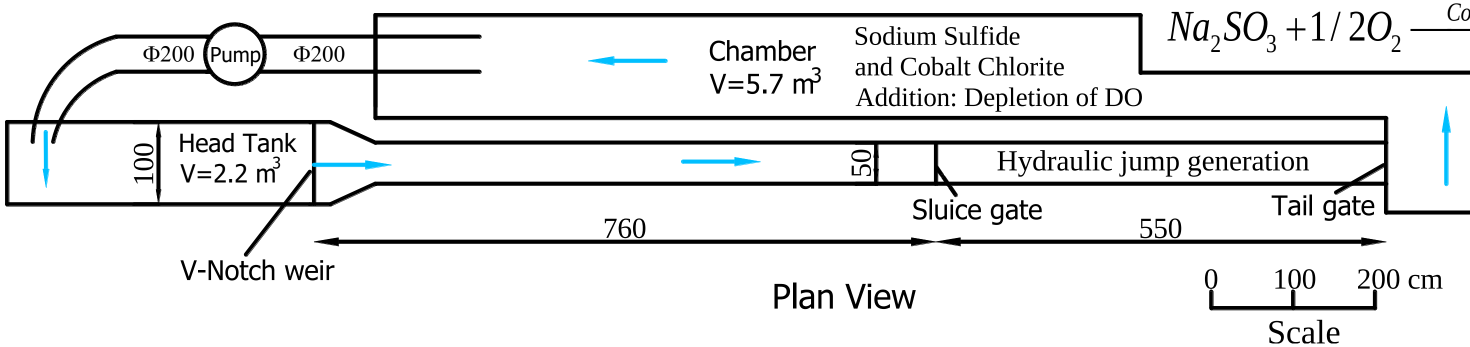
Experimental Test Procedure

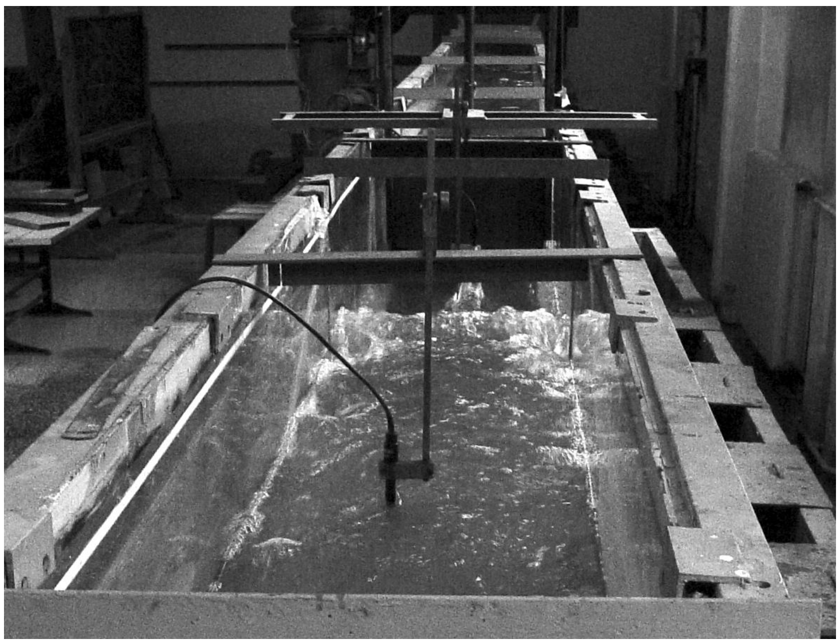


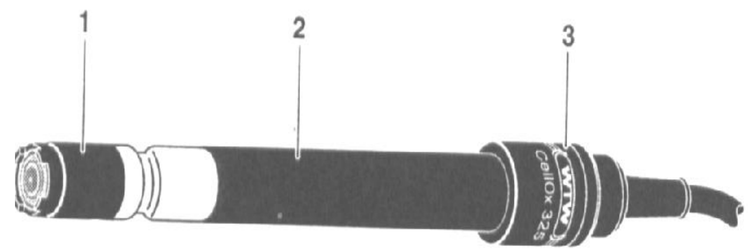
Test No	Re	Fr_1	d_1 (mm)	U_1 (m/s)	d_2(mm)	Lj (cm)	ΔH (m)	r_{20}	K_{20} (1/day)	e_a (m^2/s^3)
1	2.0E+04	3.9	14	1.43	71	43	0.05	1.034	5719	0.13
5	1.4E+04	4.5	10	1.42	61	39	0.05	1.039	6982	0.14
10	2.5E+04	5.1	13.5	1.85	92	57	0.10	1.060	9303	0.20
15	2.5E+04	3.3	18	1.39	77	43	0.04	1.034	5730	0.11
17	3.0E+04	6.5	13	2.31	113	74	0.17	1.115	16353	0.27
26	4.0E+04	5.8	17	2.35	128	82	0.16	1.103	13821	0.26
27	4.0E+04	2.6	29	1.38	88	43	0.02	1.019	3477	0.08
34	4.6E+04	5.6	19	2.42	140	82	0.17	1.103	14257	0.29
40	5.3E+04	4.0	26	2.03	136	77	0.09	1.076	9884	0.20

Dissolved Oxygen Measurements

$$Na_2SO_3 + 1/2O_2 \xrightarrow{CoCl_2} Na_2SO_4$$





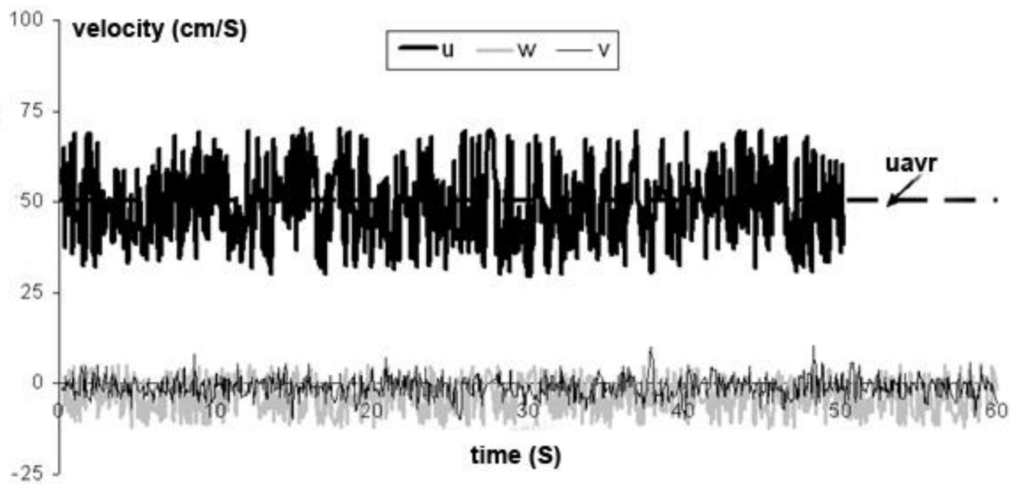


$$E = \frac{C_d - C_u}{C_s - C_u} = 1 - \frac{1}{\exp(K \times t)}$$

Turbulence Measurements

Reference	Fr_1	Re	U_1 (m/s)	d_1 (mm)	d_2 (mm)	e_a (m^2/s^3)	k_{max} (m^2/s^2)
Liu et al. (2004)	2	118,570	1.67	71	172	0.235	0.060
	2.5	147,680	2.08	71	216	0.493	0.096
	3.3	86,100	2.10	41	165	0.864	0.102
Present study	1.9	34,500	1.05	33	70	0.173	0.038
	2.3	34,500	1.19	29	80	0.207	0.048

The turbulence quantities were collected at low Froude numbers by a Nortek 10 MHz type Acoustic Doppler Velocimeter (ADV) at 25 Hz during a sampling time of two minutes.

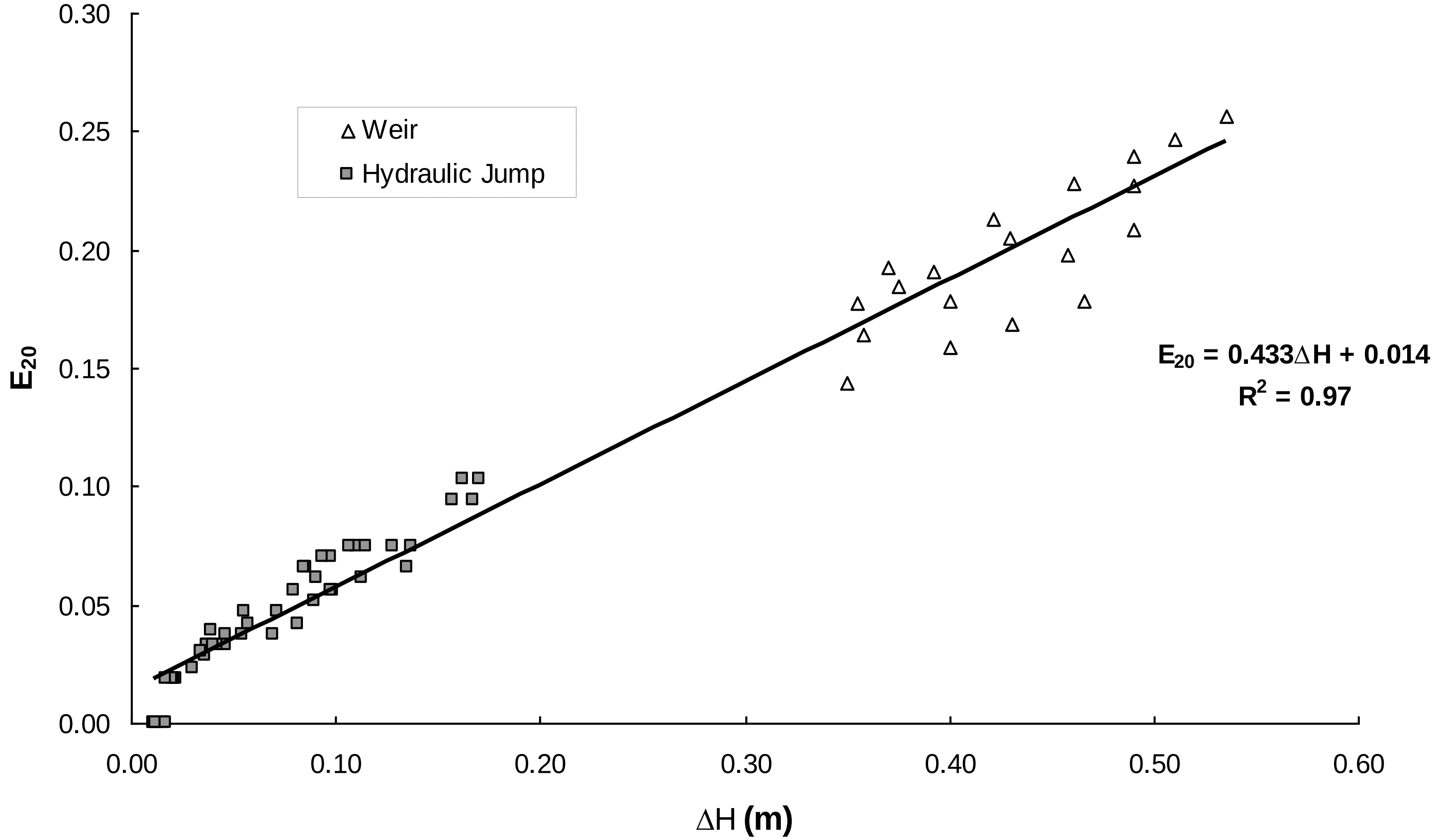


$$TI_x = \frac{\sqrt{\overline{u'^2}}}{U_1} \qquad TI_y = \frac{\sqrt{\overline{v'^2}}}{U_1}$$

$$\tau = -\rho \overline{u'v'}$$

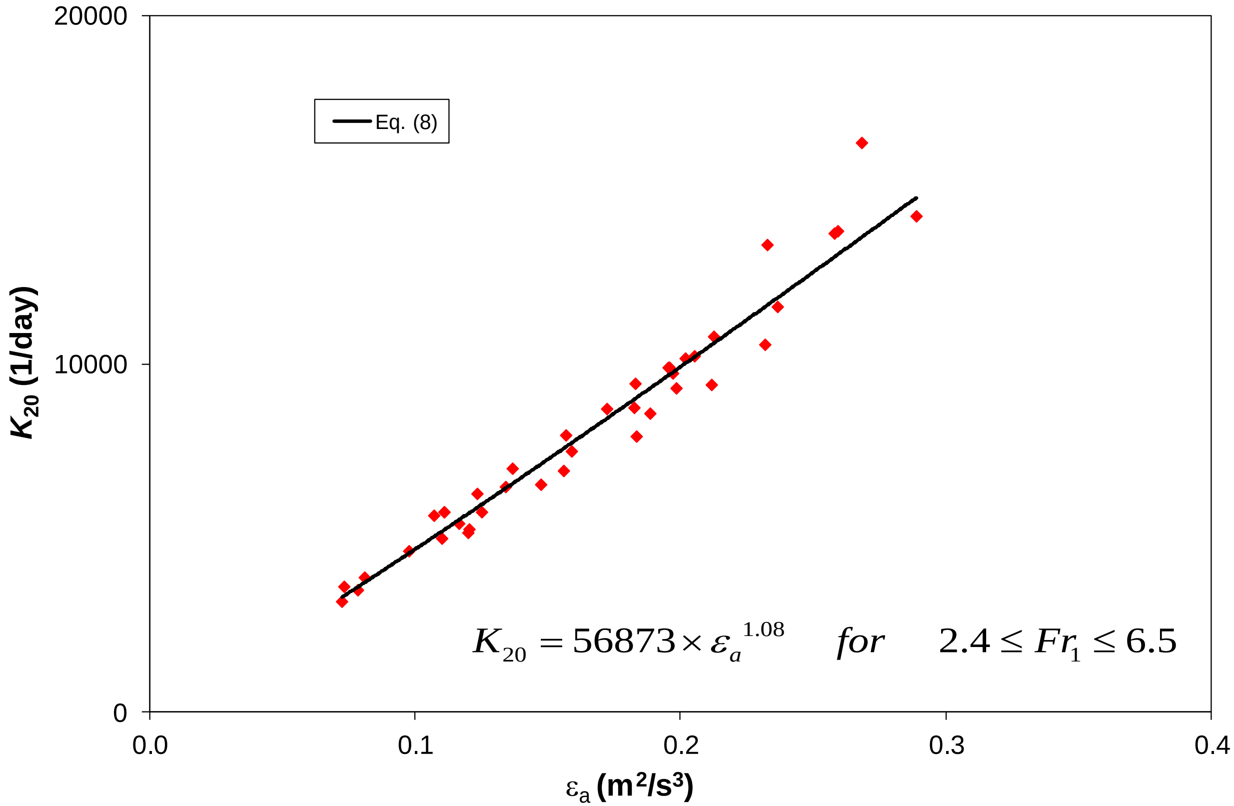
$$k = \frac{1}{2}(\overline{u'^2} + \overline{v'^2} + \overline{w'^2})$$

Experimental Results



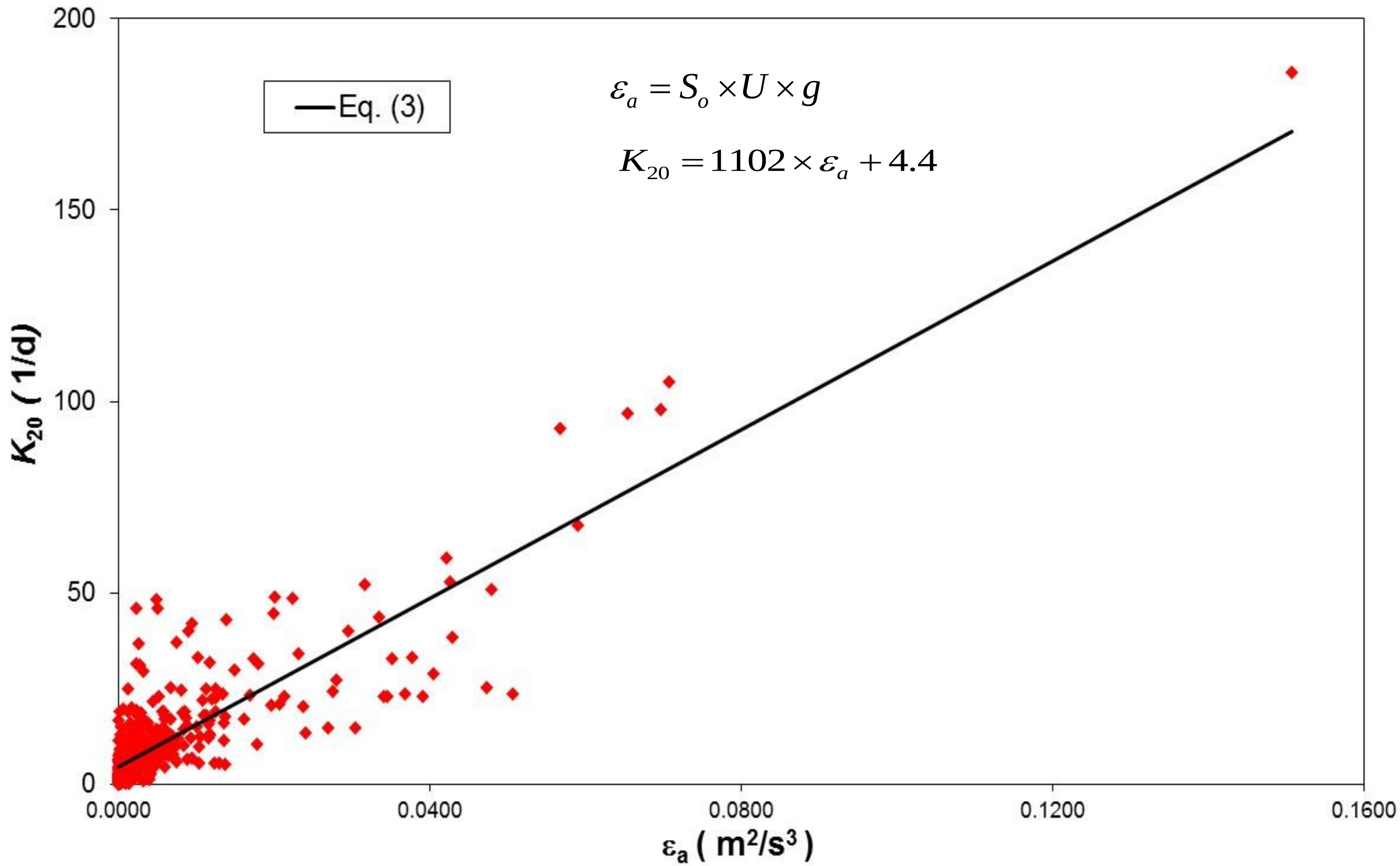
Variation of aeration efficiency as a function of head loss at a hydraulic jump and weir

Experimental Results



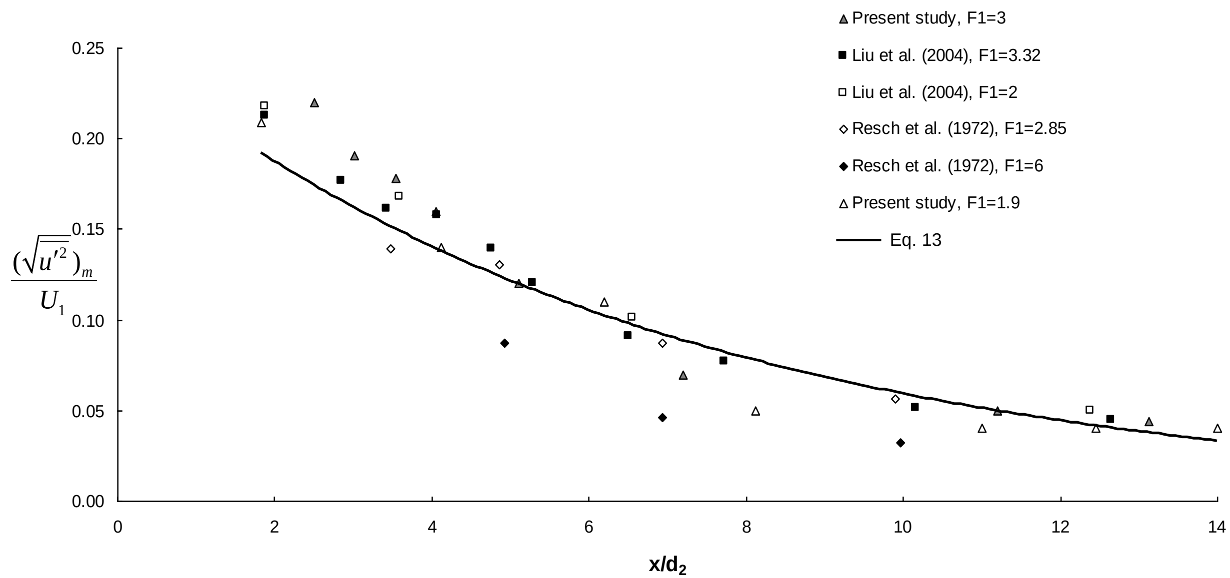
Reaeration K_{20} versus average energy dissipation rate per unit mass ε_a for hydraulic jump

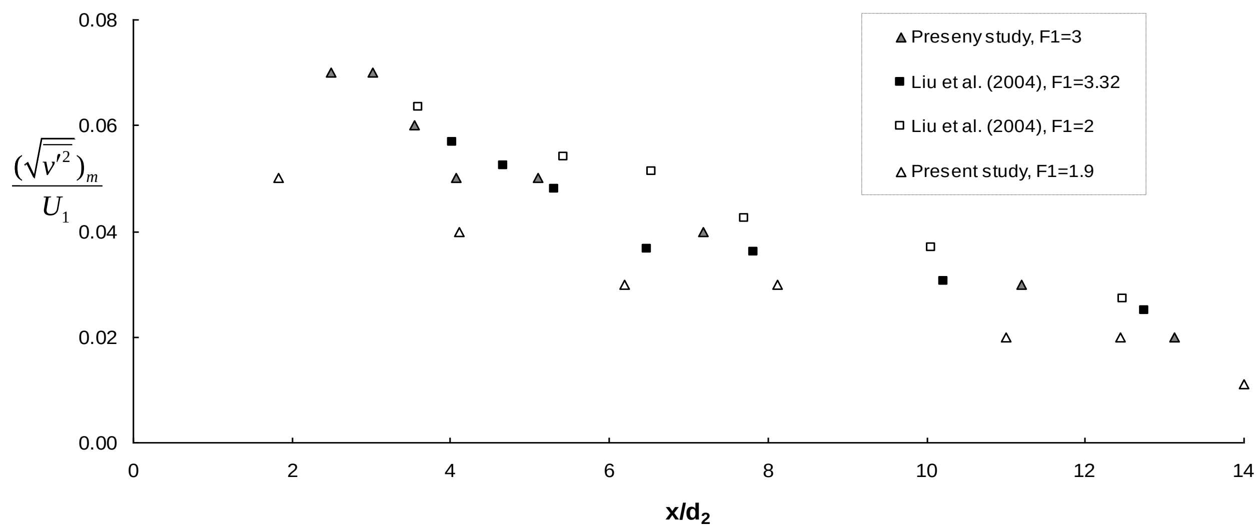
Uniform Flow Conditions



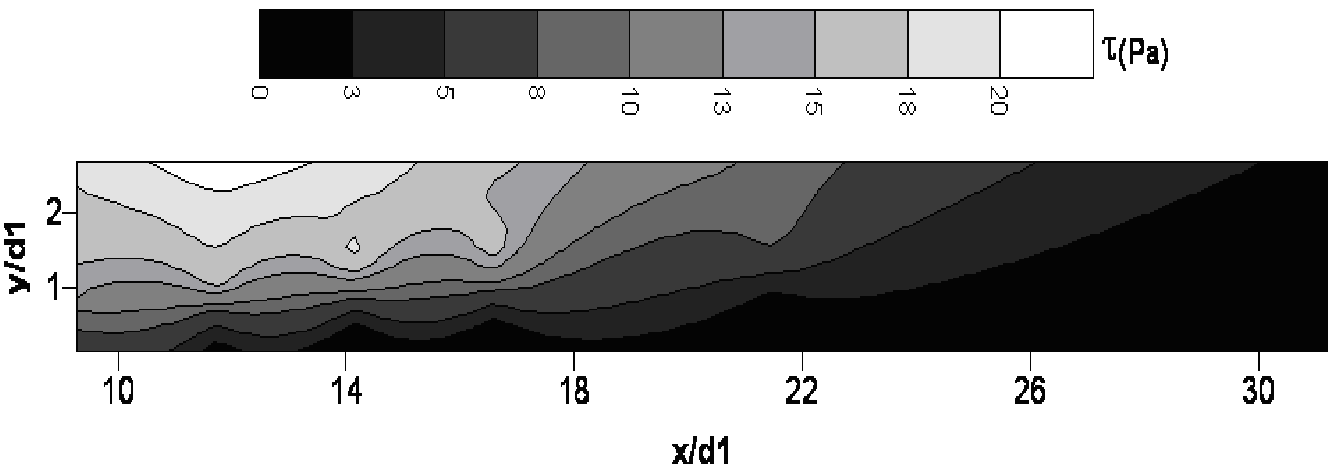
Reaeration K_{20} versus average energy dissipation rate per unit mass ε_a for uniform flow conditions (Data source: Melching and Flores (1999))

Variation of normalized maximum streamwise and vertical turbulence intensities in central plane with x/d_2

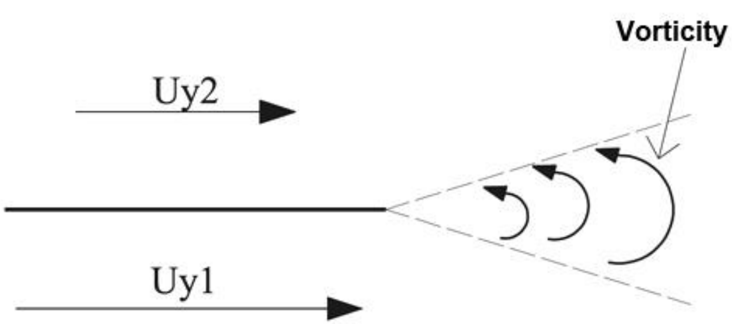


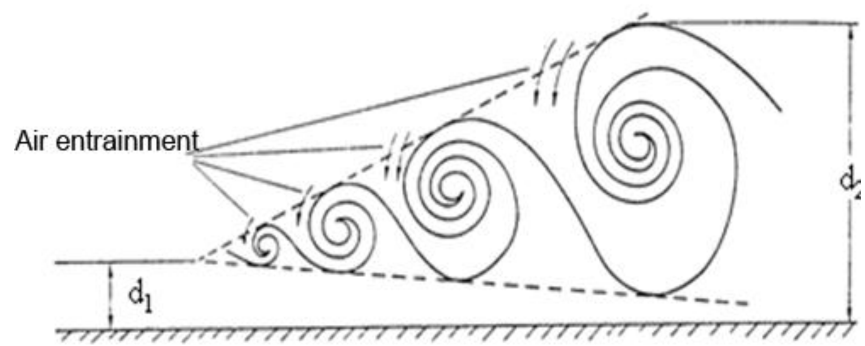


Experimental Results

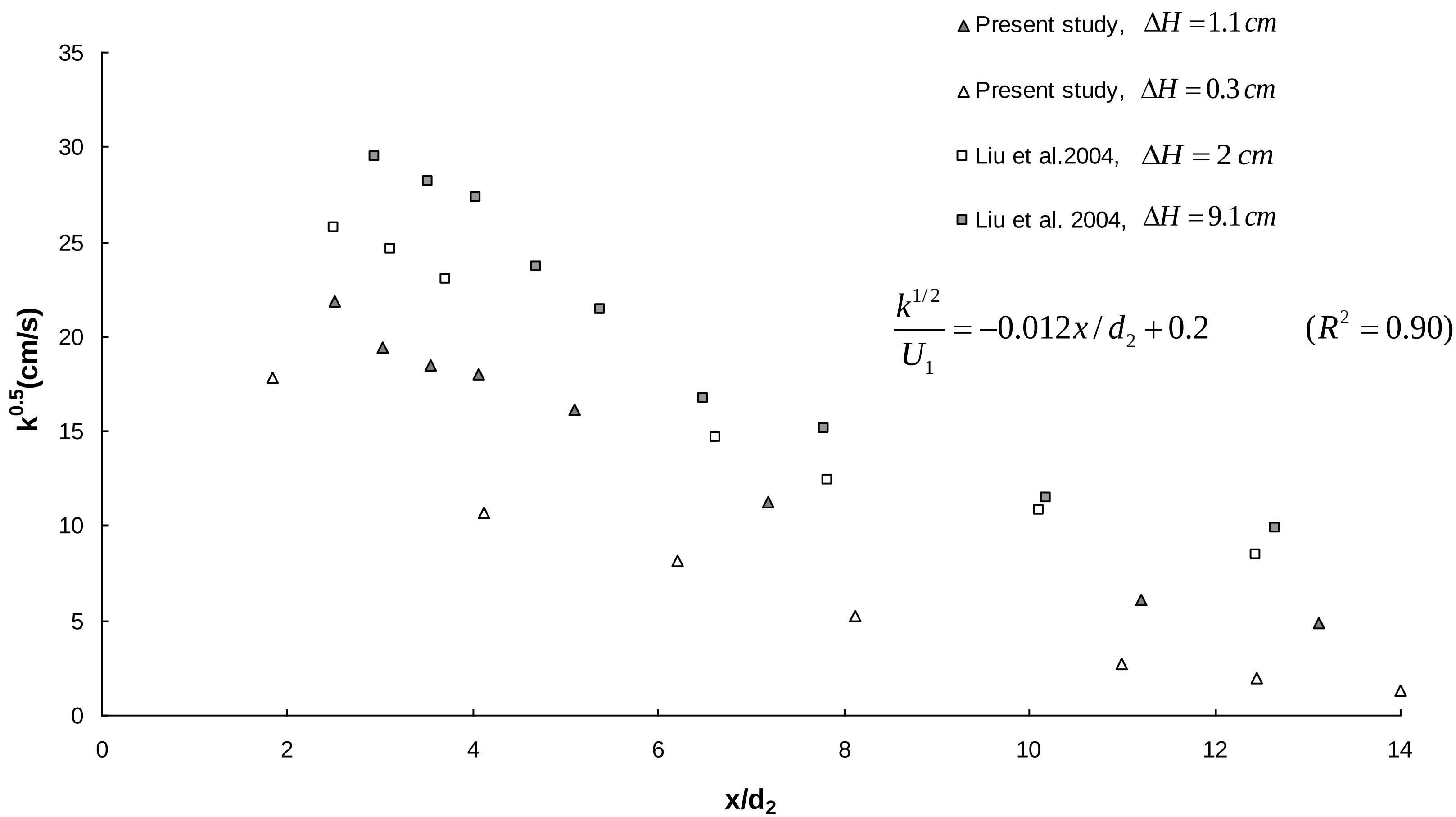


Reynolds shear stress contour for Fr_1=3.35; *Re*=86,100





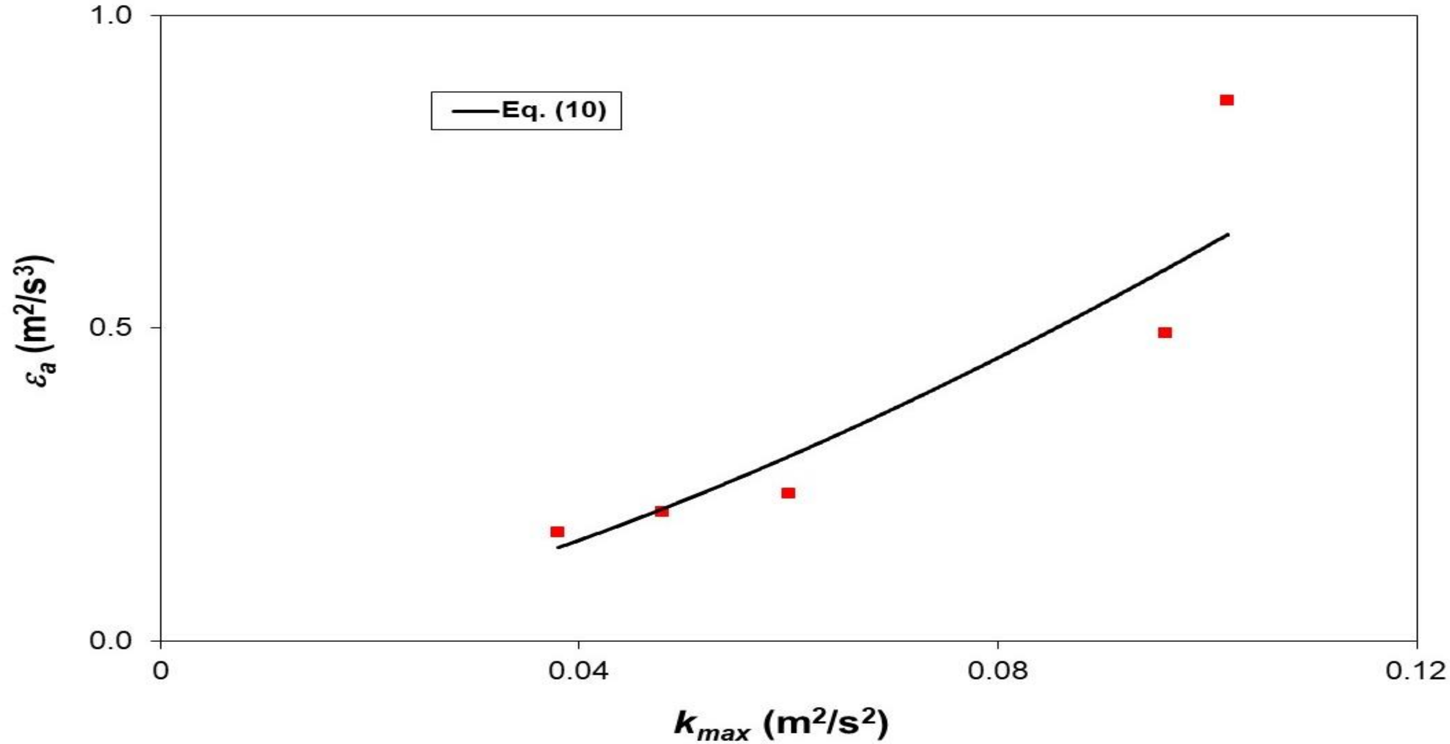
Experimental Results



Variation of the maximum turbulence kinetic energy along the hydraulic jump

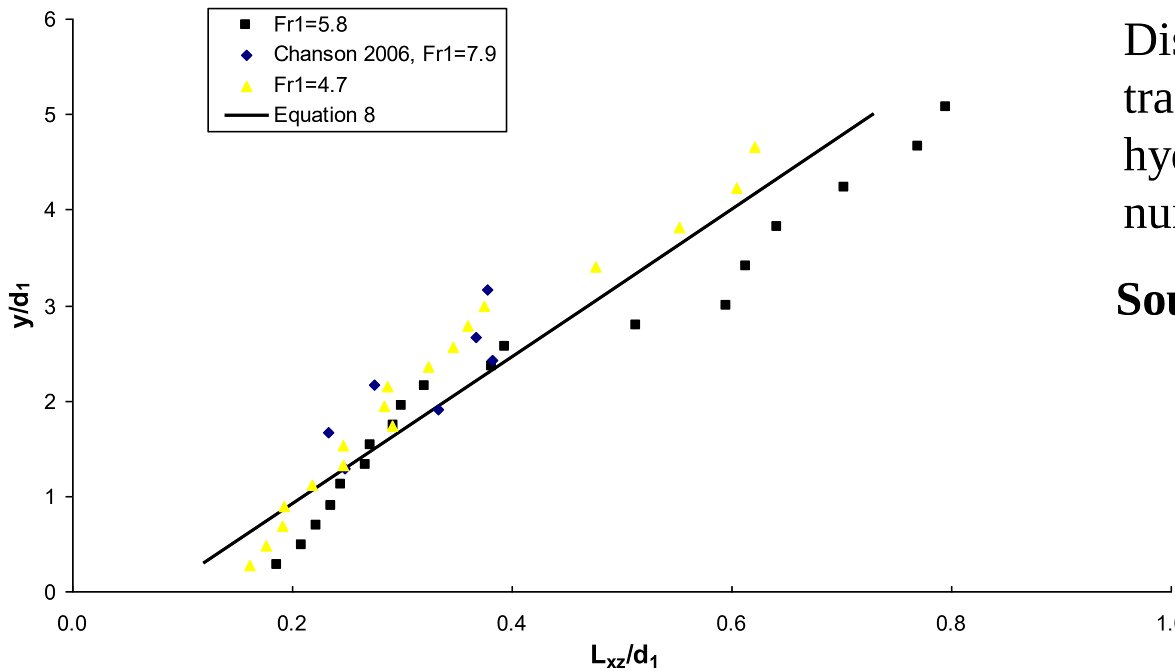
Experimental Results

$$K_{20} = 56873 \times \varepsilon_a^{1.08} \quad for \quad 2.4 \le Fr_1 \le 6.5$$



Variation of the average energy dissipation rate per unit mass ε_a with the function of the maximum turbulent kinetic energy per unit mass k_{max}

Integral Turbulent Length Scale in Hydraulic Jumps



Distribution of dimensionless air-water transverse length scales L_{xz}/d_1 in a hydraulic jump for various Fr_1 numbers: $x-x_1=0.2$ m

Source: Kucukali and Chanson (2008)

If we take the average of the upstream flow depths as the integral turbulent length scale:

$$\varepsilon_a = 0.97 \times \frac{k_{\max}^{1.5}}{L}$$

Equation is consistent with the formula *of Prandtl-Kolmogorov* formula:

$$\varepsilon = 0.168 \times \frac{k^{1.5}}{L}$$

Conclusions

- The proposed equation predicts and captures the system dynamics. It is a single parameter equation (ii) it may be tested for other rapidly varied flow conditions like plunging jets and sudden expansions.
- It is discussed that functional relationship between rearation and energy dissipation rate exists both for unifom and nonuniform flow conditions. At site conditions, measuring energy dissipation is much easier than measuring turbulence quantities. The functional dependence between the reaeration and energy dissipation rate can provide engineers to estimate gas transfer coefficients in the field.
- The overall contribution of this study thought to be that we showed the macro turbulence main role in self-aeration and energy dissipation mechanisms.
- Consequently, experimental findings suggest that hydraulic jump can be used as a self-aerator device in waste water treatment plants to enhance the DO levels of an effluent.