ISSN 1392 - 1207. MECHANIKA. 2012 Volume 18(1): 56-62

Air bubbles and water droplets entrainment and removal in turbulent water flows

A. Vaidelienė*, V. Vaidelys**
**Kaunas University of Technology, Studentų 50, 51368 Kaunas, Lithuania and Lithuanian Energy Institute, Breslaujos 3, 44403 Kaunas, Lithuania, E-mail: avaidel@mail.lei.lt*
***Kaunas University of Technology, Studentų 50, 51368 Kaunas, Lithuania, E-mail: vytautas.vaidelys@ktu.lt*
crossref http://dx.doi.org/10.5755/j01.mech.18.1.1282

1. Introduction

Anthropogenic activities are making considerable influence on the character of natural processes taking place in atmosphere as well as in open water reservoirs. With the continuous extension of manufacturing activities, the anthropogenic factor has an increasing impact on global environment, including both air and water pollution. The challenge we face is to evaluate and determine the maximal anthropogenic impact that the environment, i.e. water and atmosphere, can still be subjected to the level it can resist trough self-purification. Such an objective can not be achieved without investigation of the pure physical processes, which take place in interfaces between open water and atmosphere [1-4] as well as between separate deep water layers. Both interfaces are of significant importance for the water quality [5-7] of open water bodies. Usually those interfaces are considered separately one from another. Some references [8-11] specify that physical processes at the open water-air interfaces are stronger determinants of water quality than those taking place in deep water. Therefore the consideration of the present paper is focused on the open water-air interface. The above mentioned physical phenomena are fully determined by diffusion - based processes such as an aeration and reaeration or evaporation and adsorption processes [12-15]. Moreover, those processes can be regarded as separate cases of diffusion itself, where the character of processes rate is determined by ambient properties and their boundary conditions. Investigation and evaluation of those properties and boundary conditions in various specific cases obviously is a pure physical problem [16-18]. The right solution can be achieved only under the investigation of this problem related to diffusion process and its mathematical description. Determined significant dependences between the processes parameters allow to simulate the process mathematically and give practically useful tool for environmental engineering.

On the background of above mentioned considerations can be concluded that the investigation of diffusion processes on the air-water interface should be based on the classical theory of diffusion [19-22]. On the other hand, despite of common general diffusion process features, air-water interface has its own specific behaviour [23-25]. The factor determining this behaviour first of all is specific boundary conditions on the air-water interface. These specific boundary conditions are: roughness of water surface, due to it higher friction between air and water, kinetics of the streams rising from deep layers to the surface, etc. One of the most important factors making influence on diffusion processes is mass transfer over the weirs and through the hydro power plants turbines [26-28]. This falling water from weirs or flow through hydro power plants turbines is so called “white water” phenomenon. This water consists of air bubbles and water droplets mixed together in the water surface.

The goal of this paper is the mathematical simulation of physical mechanism of air bubbles entrainment and removal of water drops processes evaluating water turbulence generated by wears and hydro power stations.

2. Structural development of air and water dynamic mixing under conditions of falling water

2.1. Hydropower plants and weirs influence on bubbles entrainment

After weirs the water has falling stream or jet shape. As it’s known, under these conditions the local aeration is taking place and the air bubbles are entrained into the water due to jet impact to the water lower stream (Fig. 1).

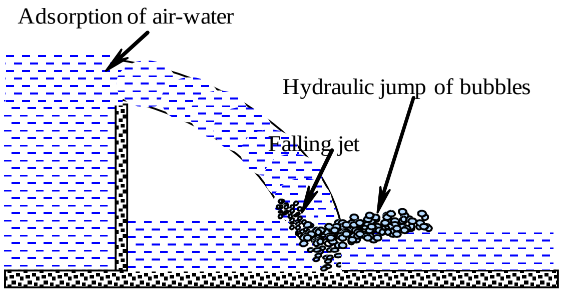

Fig. 1 Air bubbles and water droplets diffusion under falling down jet conditions

Often in the literature such an air bubbles and a water droplets mixing is known as a “self-aerated process”. If to be more exact should be noticed that there are two processes: one when the water falls through the wear free and the next – when flow impacts in to the water or when the water forces through hydropower stations turbines. In the latter case the jet forms under the water and air bubbles are entrained in to the water as well as small water droplets compose. The air bubbles and water droplets mixing together form a compound layers. Researchers started to investigate this phenomenon only in the middle of the 20 century. The first were Straub and Anderson [29] and Wood [30]. Straub and Anderson described a self-aeration process in the open channel water flows. Wood and Chanson were first who measured concentration and the rising rate of air bubbles. Later Chanson, Toobes, Gonzalez continued the investigation. These authors investigated only air bubbles entrainment into the water as a diffusion phenomenon, though did not investigate and did not describe mathematically dynamical mixing of air bubbles and water droplets. McKeogh first proved that jet's conditions at the moment of air entrainment can be described as a function of jet's turbulence [31]. Turbulent air bubbles diffusion appears under falling down jet conditions. This process is also known as advective diffusion [32-35]. This term denotes the movement of air bubbles from domains with higher spatial gas concentration to domains with lower concentration. The mixing of bubbles stimulates this process.

2.2. Entrainment – removal process in the air-water interface

The exchange of gases in the interface between the air and the water may be regarded as limited molecular diffusion. The simplest model of air-water kinetic exchange on liquid side at the boundary between the two air and water phases is shown in Fig. 2.

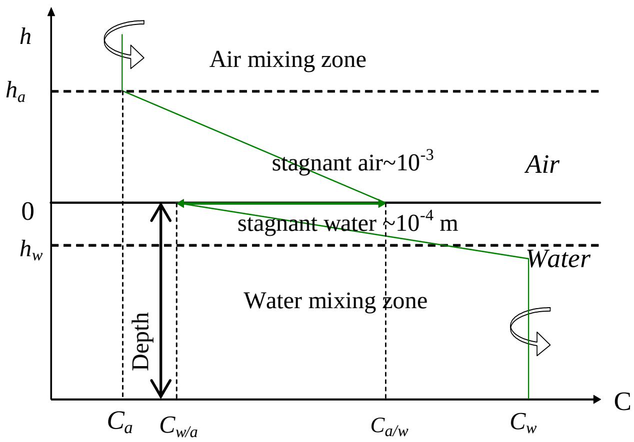

Fig. 2 Air-water kinetic exchange

With the water streaming over weirs, dams or through hydro turbines, the peculiar entrainment removal processes are taking place in the air-water interface (Fig. 3), generating air and water bubbles within the zone of falling jet. Thus, the layers with mixed air and water bubbles are formed. These layers are shown in Fig. 4.

Under particular conditions the similar mixtures of bubbles can be formed in lakes, large dams and oceans. In these cases breaking waves (wave breaking initiated at certain wind speeds) influence turbulent diffusion of air (oxygen and CO_2) and form water microlayers in the interface [36-39]. The following sections deal only with processes influenced by the turbulence of water falling from the weirs or forcing through hydropower plants.

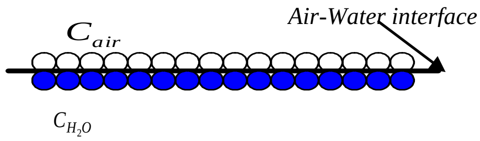

Fig. 3 Air-water interface without mixing

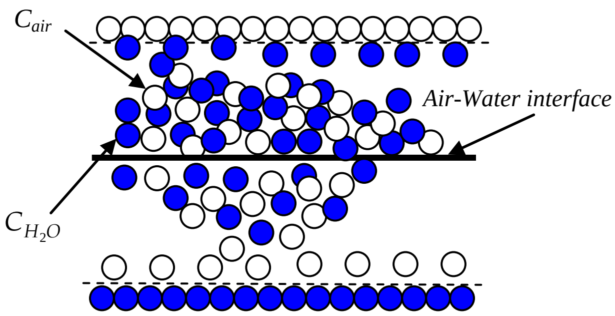

Fig. 4 Layers with together mixed air-water bubbles

3. Equations describing air bubbles and water droplets entrainment and removal in the open channel

The supercritical flows induce a visual impression of "white water". Such flows appear in the channels where the turbulence is sufficient for air bubbles entraining into the flow.

As it is shown in Fig. 4 two fluxes come in to the water interface: water droplets flux and air bubbles flux. We suggest the following expressions of kinetic equations as a suitable for use in this case

$$\begin{cases} \dfrac{d\,C_{H_2O}}{d\,t} = -\chi_{12}\,C_{H_2O} + \chi_{21}\,C_{air} \\ \dfrac{d\,C_{air}}{d\,t} = \chi_{12}\,C_{air} - \chi_{21}\,C_{H_2O} \end{cases} \qquad (1)$$

where C_{H_2O} is concentration of water droplets, C_{air} is concentration of air bubbles, t is time. χ_{12} and χ_{21} are entrainment rates of water droplets and air bubbles respectively, which are expressed as $\chi_{12} = \alpha_{12} i_{H_2O}$, $\chi_{21} = \alpha_{21} i_{air}$, where α_{12} and α_{21} are sticking coefficients of water droplets and air bubbles to the surface respectively, which range from 0 to 1 and i_{H_2O} and i_{air} are the relative water droplets and air bubbles fluxes to the surface respectively.

Solution of differential Eq. (1), gives the following dependences

$$\left.\begin{aligned} C_{H_2O} &= \frac{\chi_{12} + \chi_{21} e^{-(\chi_{12}+\chi_{21})t}}{\chi_{12}+\chi_{21}} C_{H_2O}(0) - \\ &- \frac{\chi_{12}\left(e^{-(\chi_{12}+\chi_{21})t} - 1\right)}{\chi_{12}+\chi_{21}} C_{air}(0) \\ C_{air} &= -\frac{\chi_{21}\left(e^{-(\chi_{12}+\chi_{21})t} - 1\right)}{\chi_{12}+\chi_{21}} C_{H_2O}(0) + \\ &+ \frac{\chi_{21} + \chi_{12} e^{-(\chi_{12}+\chi_{21})t}}{\chi_{12}+\chi_{21}} C_{air}(0) \end{aligned}\right\} \qquad (2)$$

During entrainment process the upper layer gets in contact with air and concentration of air bubbles and water droplets changes. Proposed Eq. (1) describes character of this change. However, the process of water droplets removal from the surface is not involved in Eq. (1). Evaluating removal process the Eq. (1) takes the following form

$$\begin{cases} \dfrac{d\,C^{(1)}_{H_2O}}{d\,t} = -\,w_{12}\,C^{(1)}_{H_2O} + v_r C^{(2)}_{H_2O} + \chi_{12}\,C^{(1)}_{H_2O} - \chi_{21}\,C^{(1)}_{air} \\ \dfrac{d\,C^{(1)}_{air}}{d\,t} = -\,w_{21}\,C^{(1)}_{air} + v_r\,C^{(2)}_{air} + \chi_{21}\,C^{(1)}_{air} - \chi_{12}\,C^{(1)}_{H_2O} \end{cases} \quad (3)$$

where $C^{(1)}_{H_2O,air}$ and $C^{(2)}_{H_2O,air}$ are relative concentrations in first and second monolayer; w_{12} and w_{21} are removal rates of water droplets and air bubbles respectively; v_r is the total removal rate.

Two first components of Eq. (3) describe removal rate of air bubbles or water droplets from the surface monolayer and next two components describe entrainment rate of air bubbles or water droplets. Constituents with sign minus give the removal rate of air bubbles and water droplets from the surface monolayer and the constituents with sign plus give the entrainment rate of air bubbles and water droplets into the surface monolayer as a result of the entrainment of relocated bubbles also as a result of the arrival of air bubbles and water droplets from the next monolayer.

The monolayer approach of dynamic mixing process was used. Eq. (3) expresses this process. The variations of surface concentration in the second layer must be known for solving this equation. The mixing of water and air bubbles between the layers takes place because of continuous entrainment and removal. In case when due to entrainment and removal air and water particles move from K layer to $K-1$ or $K+1$, this concentration rate can be expressed as follows

$$\begin{cases} \dfrac{d\,C^{(K)}_{H_2O}}{d\,t} = v_r\left(C^{(K+1)}_{H_2O} - C^{(K)}_{H_2O}\right) + v_e\left(C^{(K-1)}_{H_2O} - C^{(K)}_{H_2O}\right) \\ \dfrac{d\,C^{(K)}_{air}}{d\,t} = v_r\left(C^{(K+1)}_{air} - C^{(K)}_{air}\right) + v_e\left(C^{(K-1)}_{air} - C^{(K)}_{air}\right), K \geq 2 \end{cases} \quad (4)$$

where v_e is the total entrainment rate.

It can be proved that Eq. (4) has the form of diffusion equation with moving boundary. After simple mathematical rearrangements Eq. (4) can be converted into the following form

$$\begin{cases} \dfrac{\partial C_{air}}{\partial t} = D^*\,\dfrac{\partial^2 C_{air}}{\partial x^2} + v_x\,\dfrac{\partial C_{air}}{\partial x} \\ \dfrac{\partial C_{H_2O}}{\partial t} = D^*\,\dfrac{\partial^2 C_{H_2O}}{\partial x^2} + v_x\,\dfrac{\partial C_{H_2O}}{\partial x} \end{cases} \quad (5)$$

where D^* is effective diffusion coefficient, v_x is surface movement velocity.

Bubbles exchange between air and water usually takes place in the upper layers. In the case which we investigated the element composition of air bubbles and water droplets was changeable also in lower layers.

4. Results and discussions

As Fig. 5 illustrates, air bubbles are entrained in to the water at the zone of falling water. The size and number of bubbles pooled in to water depends on weir high and on velocity of jet at the moment when the jets hit at the surface of the water. Jet hit to the water splashes small water droplets, which mix with the air bubbles together and makes mixed air-water layers. We simulated air bubbles and water droplets entrainment and removal processes with Eq. (4). Also we calculated Reynolds and Froude numbers according the following formulas

$$\left.\begin{aligned} Re &= \frac{\rho_w v\,d_1}{\mu_w} \\ Fr &= \frac{v}{\sqrt{d_1 g}} \end{aligned}\right\} \quad (6)$$

where ρ_w is density of the water (kg/m^3), v is jet impact velocity, d_1 is jet thickness at impact (m), μ_w *is* dynamic viscosity of the water (N s/m^2), g is gravity constant (m/s^2).

For the simulation we used experimental data published by H.Chanson, T. Brattberg [40], F.Murzyn, H.Chanson [41] and L.Toombes, H.Chanson [42], H.Chanson C.A.Gonzalez [43]. These authors obtained experimental data in artificial channel made for special purpose of their experiment. They determined concentration of air and water bubbles by means of conductivity measuring in different zones of the channel with changing height of weir, flow velocity and horizontal distance from weir to bubbles zone (Fig. 5). Determination of bubbles concentration was based on the feature, that conductivity in air burbles zone and in water bubbles zone differs thousands times.

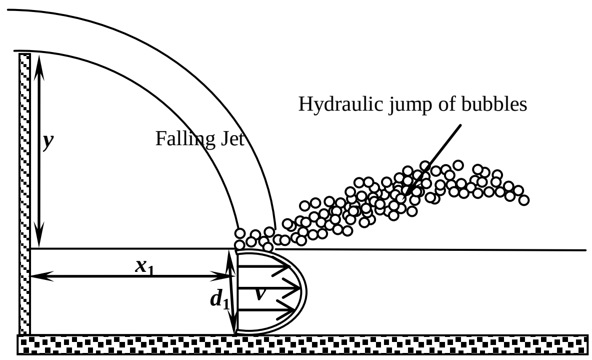

Fig. 5 Schematic meaning of parameters under changing during the experiment

Entrainment and removal processes take place at the moment of interaction. We described this process with Eq. (1) and solution of this equation with Eq. (2). Fig. 6 illustrates the solution equations calculated for different initial concentrations. The range of initial water droplets relative concentration we assumed from 0.01 to 0.3 and air bubbles initial concentration from 0.7 to 0.99 (Fig. 6).

As are can see from Fig. 6, with water and air sticking to the surface probabilistic coefficients α_{12} = 0.8 and α_{21} = 0.2 respectively air bubbles and water droplets concentration dependence on time changes according exponential law. Asymptotes values of all curves are equal to probabilistic sticking coefficients. The shape of curves depends on initial concentration of air bubbles and water droplets.

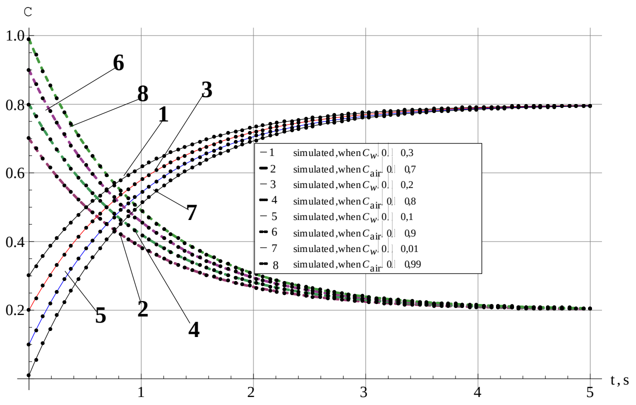

Fig. 6 Air and water entrainment and removal curves, with sticking coefficients of water droplets and air bubbles to the surface respectively $\alpha_{12} = 0.8$ and $\alpha_{21} = 0.2$. Curves *1, 3, 5, 7* – show waters droplets concentration. $C_w(0)$ – initial concentration of water droplets. Curves *2, 4, 6, 8* – show air bubbles concentration. $C_{air}(0)$ – initial concentration of air bubbles

As was mentioned above, the process of air bubbles and water droplets entrainment and removal takes place not only in surface layers, but also in deeper layers. We described this process with Eq. (4). Fig. 7 illustrates air and water bubbles concentration dependences on weir height, evaluating deeper layers.

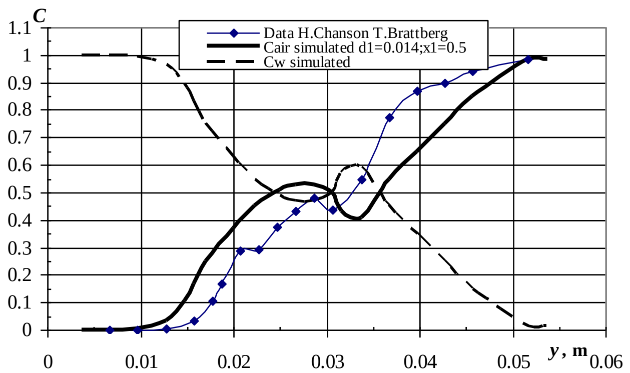

Fig. 7 Air bubbles and water droplets entrainment and removal dependences on weir height for experimental data [40] ($x_1 = 0.5$ m, $d_1 = 0.014$ m, $v = 3.47$ m/s, $Fr = 5.14$, $Re = 25000$). Results – C_{air} air bubbles concentration and C_w water droplets concentration is simulated with Eq. 4

The extreme points in the curves of Fig. 7 can be explained as follows: with the water flow trough the weir or trough hydro turbine the submerged jet forms (Fig. 8); this jet spreads in the surrounding liquid and at that same time loses its velocity.

Due to jet and surrounding liquid particles velocity transverse pulsation air bubbles are entrained into the jet. Jet velocity distribution is depicted in cross-sections a-a and b-b. Central initial velocity v_1 is constant. Initial sector of the jet is between cross-sections a-a and b-b. Maximum air bubbles concentration is in the centre of the jet while the minimum concentration is at the jet and surrounding liquid interface. Beyond this interface the recirculation zone forms. As can be seen from Fig. 7 at the $y = 0.026$ air bubbles concentration is maximum, therefore can be concluded that this point coincides the jet centre. Point $y =$ 0.0325 coincides boundary between jet and surrounding water, because at this point air bubbles concentration is minimum. Further air bubbles concentration increases until reaches 1. With $y > 0.0325$ recirculation zone begins. Naturally that water drops concentration run has opposite character.

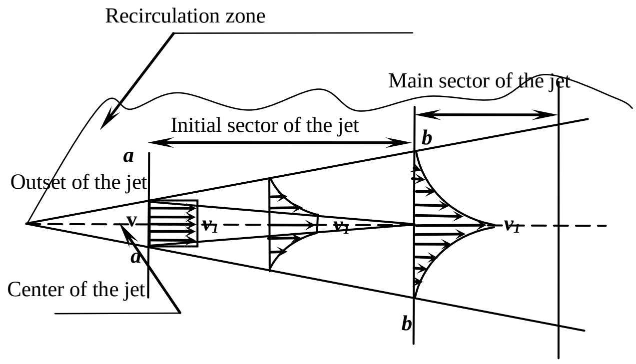

Fig. 8 Submerged jet

With the weir height growth the absorption of air bubbles into water grows till reaching maximal air bubbles concentration. Depending on distance x_1 and d_1 (Fig. 5) and on weir height breaking points of the curves change their position (Figs. 7 - 11).

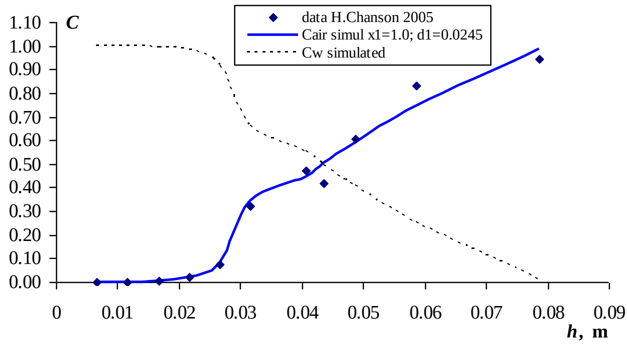

Fig. 9 Air bubbles and water droplets entrainment and removal curves depending on weir height for experimental data of [44] with $x_1 = 1.0$ m and $d_1 = 0.0245$ m, $Fr = 7.9$, $Re = 94000$, C_{air} – air bubbles concentration and C_w – water droplets concentration was simulated with Eq. 4

As can be seen from Figs. 7 and 9 the curves in these figures are different. The reason was that these curves were calculated not for two air and water layers like in Fig. 6, but for many layers. Fig. 9 shows entrainment curve for $x_1 = 1.0$ m and $d_1 = 0.0245$ m (experimental data were taken from [44]). Initial air bubbles concentration equals zero. With the weir height growing air bubbles concentration remains uniform and at $y = 0.02$ m starts to change. The points $y = 0.032$ and $y = 0.04$ are the points of breaking of the curves.

Therefore depending on initial conditions and the number of taken layers entrainment and removal curves can be expressed from exponential dependence curves with breaking points and points of maximums and minimums (Figs. 7 - 11). Peak maximum on the air bubbles curve correspond water bubbles minimum on the water bubbles curve and vice versa. The curves simulated by us coincide with experimental data [44]. As it can be seen from Fig. 10 each air bubbles and water drops curve have maximum and minimum. All these maximums and minimums well coincide with experimentally obtained maximums and minimums [42].

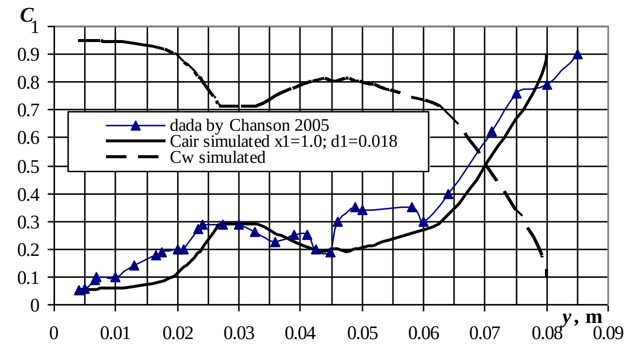

Fig. 10 Air bubbles and water droplets entrainment and removal curves for experimental data [42] (d_1 = 0.018 m; *Fr* = 5.1, *Re* = 38000)

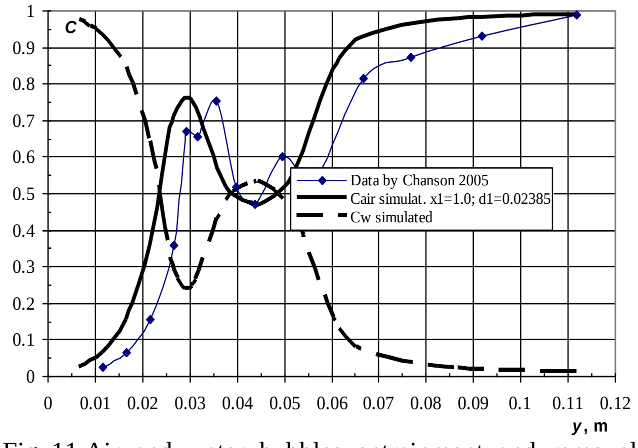

Fig. 11 Air and water bubbles entrainment and removal curves for d_1 = 0.0238 m according data taken from [43]; *Fr* = 5.0, *Re* = 77000

As it can be seen from Fig. 11 air and water curves have two extreme points.

Air bubbles and water drops rising rate, size and frequency depend on jet velocity at the moment of jet hit at the water surface. A bubble rising frequency depends on the distance from weir to jet hit point. With the jet hit at the water surface air bubbles are pooled into the water. Some delay in creating air bubbles process appears and it increases with the distance. This delay explains the character of frequency dependence on distance.

5. Conclusions

1. Water turbulence highly influences processes of air bubbles and water droplets diffusion. These processes can be described by mathematical equations.

2. The bubbles and droplets created in the falling water flow stimulate the processes of air and water entrainment and removal.

3. Initial conditions of air bubbles and water droplets entrainment and removal processes determine run of proposed simulation equations solutions curves.

4. Good coincidence of theoretical and experimental results was achieved with more than two air-water layers on the air-water interface.

References

1. **Gulliver, J.S**. 1990. Introduction to air-water mass transfer, Proc. 2rd International Symposium on Gas Transfer at Water Surfaces, Air-Water Mass Transfer, ASCE Publ., Minneapolis MN, USA, 1-7.
2. **Higbie, R.** 1935. The rate of absorption of a pure gas into a still liquid during short period of exposure, AIChETransatctions 31: 365-390.
3. **Danckwerts, P.V.** 1951. Significance of liquid-film coefficients in gas absorption, Industrial and Engineering Chemistry 43: 1460-1467. http://dx.doi.org/10.1021/ie50498a055
4. **Donelan, M.; Wanninkhof, R.** 2002. Gas transfer at water surfaces-components and issues, Geophysical Mono-graph 127, Gas transfer at Water Surfaces, 1-10.
5. **Yeghiazarian, L.; Samorodnitsky, G.; Montemagno, C.D.** 2009. A Poisson random field model of pathogen transport in surface water, Water Resources Research, Vol. 45, W11415: 1-10.
6. **Doyle, M.W.; Stanley, E.H.; Harbor, J.M.** 2003. Hydrogeomorphic controls on phosphorus retention in stream, Water Resources Research, Vol. 39, WR002038: 1-17.
7. **Vaidelienė, A.; Mihailov, N**. 2008. Influence on the river self-purification. Environmental engineering: 7th international conference, Vilnius Gediminas Technical University, May 22-23, 2008. Vilnius: VGTU Press" Technika", 2008. Vol II.: 748-757.
8. **McNeil, D.A.; Stuart, A.D.** 2004. Vertically upward two-phase flow with a highly viscous liquid-phase in a nozzle and orifice plate, Heat and Fluid Flow, 25: 58-73. http://dx.doi.org/10.1016/j.ijheatfluidflow.2003.08.003
9. **Kim, H.; Rao, P.S.C; Annable, M.D.** 1999. Gaseous tracer technique for estimating air-water interfacial areas and interface mobility, Soil Sci. Soc. Am., 63: 1554-1560. http://dx.doi.org/10.2136/sssaj1999.6361554x
10. **Stewart, P.S.** 2003. Diffusion in biofilms, Journal of bactery 185(5): 1485-1491.
11. **Yang, M.W.; Hung, Y.L.; Huang, H.F.; Lin, S.Y.** 2007. A study of $C_{12}E_4$ adsorption kinetics – considering pedant bubble shape, Colloids and Surfaces A: Physicochem. Eng. Aspects 317: 462-472. http://dx.doi.org/10.1016/j.colsurfa.2007.11.023
12. **Picard, C.; Davoust, L.** 2006. Dilation rheology of an air-water interface functionalized by biomolecules: the role of surface diffusion, Rheol Acta 45: 497-504. http://dx.doi.org/10.1007/s00397-006-0083-5
13. **Margaret C. Henk** 2004. Method for collecting air-water interface microbes suitable for subsequent microscopy and molecular analysis in both research and teaching laboratories, Applied and Environmental Microbiology 70(4): 2486-2493. http://dx.doi.org/10.1128/AEM.70.4.2486-2493.2004
14. **Šinkūnas, S.; Kiela, A.** 2011. Heat transfer for film condensation of vapour, Mechanika 17(2): 144-148.
15. **Panday, P.K.** 2003. Two-dimensional turbulent film condensation of vapours flowing inside a vertical tube and between parallel plates: a numerical approach, Int. J. of Refrigeration 26: 492-503.

http://dx.doi.org/10.1016/S0140-7007(02)00162-7
16. **Saffari, H.; Dalir, N.** 2011. Effect of friction stress of droplets with film on prediction of pressure changes in condensing tubes, Mechanika 17(1): 50-56. http://dx.doi.org/10.5755/j01.mech.17.1.203
17. **Šinkūnas, S.; Kiela, A.** 2010. Effect of liquid physical properties variability on film thickness, Mechanika 1(81): 25-29.
18. **Senthil Kumar, H.; Thyla, P.R.; Anbarasu, E.** 2010. Numerical analysis of hydrodynamic journal bearing under transient dynamic conditions, Mechanika 2(82): 37-42.
19. **Zuev, B.K.; Chudinova, V.V.; Kovalenko, V.V.; Yagov, V.V.** 2001. The conditions of formation of the chemical composition of the sea surface microlayer and techniques for studying organic matter in it, Geochem. Int. 39: 702-710.
20. **Kowal, J.J; Turchan, A.; Heller, K.; Brenizer, J.; Mench, M.M.** 2006. Liquid water storage, distribution, and removal from diffusion media inPEFCS, Journal of the Electrochemical Society 153(10): 971. http://dx.doi.org/10.1149/1.2258049
21. **Gulbinienė, A.; Jankauskaitė, V.**; **Urbelis, V**. 2008. The Influence of laminated leather structure on the vapour absorption and desorption behaviour, Materials Science (Medžiagotyra) 14(1): 44-50.
22. **Morel, A.; Gentili, B.** 1991. Diffuse reflectance of oceanic waters: its dependence on Sun angle as influenced by the molecular scattering contribution, Applieds optics, Vol. 30 No 30: 4427-4438.
23. **Li, W; Yang, K.; Xia, M.; Rao, J.**, **Zhang, W.** 2009. Influence of characteristics of micro-bubble clouds on backscatter lidar signal, Optical Express 17(20): 17772-17783. http://dx.doi.org/10.1364/OE.17.017772
24. **Berthier, J; Davoust, L.** 2003. Method of concentrating macromolecules or agglomerates of molecules or particles, CEA/CNRS patent, PCT International Application WO 2003/080209 A3.: 313-325.
25. **Davoust, L; Picard, C.** 2005. Ageing of a gas liquid interface elongated by standing waves, Colloids Surf A Physicochem Eng Asp 270-271: 182-188. http://dx.doi.org/10.1016/j.colsurfa.2005.05.060
26. **Vaidelienė, A.; Galdikas, A.; Vaidelys, V.** 2009. Water turbulence after hydropower's plants influence on gas diffusion processes. International scientific conference energy efficiency and agricultural engineering (EE&AE'2009): proceedings of the union of scientists, Rousse fourth conference, Bulgaria, October 1-3, 2009. Bulgaria: Association of agricultural engineering in Southeastern Europe: 883-889.
27. **Hutson, M.S.; Hauger, S.A.; Edwards, G.** 2002. Thermal diffusion and chemical kinetics in laminar biomaterial due to heating by a free-electrons laser. Physical rewiew E., 65(061906): 061906-1 – 061906-6
28. **Vaidelienė, A.; Vaidelys, V.** 2011. Mathematical simulation of aeration and diffusion processes in the air-water interface. Environmental engineering: 8th international conference, Vilnius, Lithuania, May 19-20, 2011. Vilnius: VGTU Press 'Technika", 2011. Vol. 1: 401-407.
29. **Straub, L.G.; Anderson, A.G.** 1985. Experiments of Self-Aerated Flow in open Channels, J. of Hyd. Div., Proc ASCE, Vol. 84, No. HY7 paper 1890. 1958: 1-35.
30. **Wood, I.R.** 1991. Air Water Flows, Proc 21st IAHR Congress, Melbourne, Australia: 18-29.
31. **McKeogh, E.J.** 1978. A Study of Air Entrainment Using Plunging Water Jet, Ph.D. theses, Qeen's University of Belfast, UK.
32. **Gonzales C.A.; Chanson H.** 2005. Interactions between cavity flow and main stream skimming flows: an experimental study, Can Jl of Civ. Eng. 31(1): 33-44. http://dx.doi.org/10.1139/l03-066
33. **Kucukali, S.; Chanson, H.** 2008. Turbulence measurements in the bubbly flow region of hydraulic jumps, Experimental Thermal and Fluid Science, 33(1): 41-53. http://dx.doi.org/10.1016/j.expthermflusci.2008.06.012
34. **Van Der Geld, C.W.M.; Kuerten, J.G.M.** 2009. Axisymmetric dynamics of bubble near a plane wall, J. Fluid Mech., 640: 265-303. http://dx.doi.org/10.1017/S0022112009991340
35. **Li-Hua, L.; Forterre, Y.** 2009. Drop impact of yield-stress fluids, J. Fluid Mech., 632: 301-327. http://dx.doi.org/10.1017/S0022112009007198
36. **Tsoukala, V.K.; Moutzouris, C.I.** 2008. Gas transfer under breaking waves: experiments and improved vorticity-based model, Ann. Geographys., 26: 2131-2142. http://dx.doi.org/10.5194/angeo-26-2131-2008
37. **Fuentes, E.; Coe, H.; McFiggans, G.** 2009. Laboratory-generated primary marine aerosol via bubble- bursting and atomization, Atmos. Meas. Tech. Discussions 2:2281-2320.
38. **Furuyama, S.-I.; Chanson, H.** 2010. A numerical simulation of tidal bore flow, Coastal Engineering Journal, Vol. 52, No 3: 215-234. http://dx.doi.org/10.1142/S057856341000218X
39. **Chanson, H.; Chachereau, Y.** 2011. Bubbly flow measurements in hydraulic jumps with small inflow Froude numbers, International Journal of Multiphase Flow, 37: 555-564. http://dx.doi.org/10.1016/j. ijmultiphaseflow.2011.03.012
40. **Chanson, H.; Brattberg, T.** 2000. Experimental study of the air-water shear flow in a hydraulic jump, International Journal of Multiphase Flow, 26: 583-607. http://dx.doi.org/10.1016/S0301-9322(99)00016-6
41. **Murzyn, F.; Chanson, H.** 2009. Free-surface fluctuations in hydraulic jumps: Experimental observations, Experimental Thermal and Fluid Science, 33(7): 1055-1064. http://dx.doi.org/10.1016/j.expthermflusci.2009.06.003
42. **Toombes, L.; Chanson, H.** 2008. Interfacial aeration and bubble count rate distributions in a supercritical flow past a backward-facing step, International Journal of Multiphase Flow, 34: 427-436. http://dx.doi.org/ 10.1016/j.ijmultiphaseflow.2008.01.005
43. **Chanson, H.; Gonzales, C.A.** 2005. Physical modelling and scale effects of air-water flows on stepped spillways, Journal of Zhejian Universitety SCI 6A(3): 243-250. http://dx.doi.org/10.1631/jzus.2005.A0243
44. **Gonzales, C.A.; Takahashi, M.; Chanson, H.** 2005. Effects of step roughness in skimming flows: an experimental study, Research report CE160: 1-154.

A. Vaidelienė, V. Vaidelys

ORO BURBULIUKŲ IR VANDENS LAŠELIŲ ĮTRAUKIMAS IR IŠMETIMAS TURBULENCINIUOSE VANDENS SRAUTUOSE

R e z i u m ė

Atvirų vandenų oro ir vandens sandūros sluoksniuose vyksta įvairūs fizikiniai procesai. Tarp jų išskirtinai svarbus yra deguonies aeracijos procesas, kuris yra tampriai susijęs su vandens taršos ir savivalos reiškiniais. Vandens įsotinimas deguonimi yra vienas iš svarbiausių veiksnių, lemiančių vandens savivalos spartą ir liekamąją taršą. Oro ir vandens sandūros sluoksniai šiuo požiūriu yra išskirtiniai sluoksniai. Būtent tuose sluoksniuose vyksta oro burbuliukų ir vandens lašelių įtraukimas ir išmetimas. Tai grynai fizikiniai reiškiniai, kurie yra mažai tyrinėti. Nustatyta, kad ypač atkreiptinas dėmesys į oro ir vandens burbuliukų mišinių susidarymo specifiką, sąlygojamą per užtvankas krentančio ar per hidroelektrinių turbinas išleidžiamo vandens turbulencijos. Galutinis darbo tikslas buvo aprašyti šiuos procesus matematiškai. Sudarytas matematinis modelis, leidžiantis apskaičiuoti oro burbuliukų ir vandens lašelių koncentracijos kitimą K-tąjame sluoksnyje, kai žinoma jų koncentracija pirmajame ir antrajame sluoksnyje. Apskaičiuotos priklausomybės gerai sutampa su nepriklausomų tyrėjų eksperimentiniais duomenimis. Atlikto darbo rezultatai rodo, kad krintančio vandens sraute susidarę oro burbuliukai ir vandens lašeliai skatina aeracijos procesą.

A. Vaidelienė, V. Vaidelys

AIR BUBBLES AND WATER DROPLETS ENTRAINMENT AND REMOVAL IN TURBULENT WATER FLOWS

S u m m a r y

Open reservoir's water pollution is becoming a global problem. Solution of this problem requires investigation of many phenomena that determinate degree and sustainability of the pollution. These phenomena are highly influenced on many factors. Among these factors an important role plays air bubbles and water droplets mixing in turbulent water flows. The aim of this paper was mathematical description of air bubbles and water droplets entrainment and removal process. Produced mathematical simulation allows calculating of air bubbles and water droplets concentration in several layers next to the air-water interface. The obtained results show that mixing process stimulates water aeration which on its own turn reduces water pollution. Also the results show good coincidence with experimental data obtained by independent researchers.

Keywords: air bubbles, water droplets, turbulent water flows

Received March 17, 2011
Accepted February 09, 2012