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Air Entrainment by the Water Jet Flowing over Flap Gate with Recirculation Effect

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Abstract

This paper presents the phenomenon of water flow through a flap gate and the associated air entrainment from the subjet space by water jet. Air entrainment results in a temporary pressure drop in subjet space which subsequently might result in flap gate vibration, additional loads, change of the trajectory jet and coefficient of discharge. The paper, of an experimental character, submits an analysis of the conditions for recirculation occurrence, the parameters affecting its development and the empirical formula worked-out which renders it possible to calculate the amount of the air entrainment from the subjet space by a water jet, recirculation included.

Notations

a_i – parameters of the models,
b – jet width,
B – weir or flap gate width,
C – discharge coefficient,
c_{pe} – pressure coefficient,
C_T – coefficient of turbulence,
D – jet thickness,
d_n – nozzle diameter,
E_o – energy head above the tailwater,
Fr – Froude Number,
g – acceleration of gravity,
H, h – head above the weir crest,
H_o, h_o – energy head above the weir crest,
H_p – air penetration depth,

h_c – height of fall,
h_p – tailwater depth,
K – entrainment coefficient,
L_o – jet break-up length,
l_k – bottom view of flap gate length,
l_p – drop length,
Q_a – total rate of entrained air,
Q_w – water discharge,
q_a, q_w – air and water discharge per unit width of spillway,
R – radius of flap gate curvature, $r = 0.42$ m,
R^2 – R-squared,
Re – Reynolds Number; $Re = \upsilon d/\nu$,
Re_t – minimum Reynolds Number for fully turbulent flow,
s – sill height,
s_e – standard error,
Tu – turbulence characteristics,
w – flap gate height,
We – Weber Number,
X, Y – Cartesian coordinates,
Y – dependent variable,
X_i – independant variable,
y, z – elevation of the flap gate above tailwater level,
Z – liquid parameter, for constant water quality and temperature, $Z \approx 10^{-11}$,
α – inclination angle of flap gate,
β – relative air entrainment, $\beta = q_a/q_w$,
γ – glancing angle of water jet,
Δp – pressure difference,
ε – random error, increment by which any individual Y may fall off the regression line,
μ – dynamic viscosity of the water,
ν – kinematic viscosity of the water,
π_i – dimensionless Π-term,
ρ_w – density of the water,
σ_{wa} – surface tension at the air-water interface,
υ – jet velocity,

υ' – velocity fluctuation,
υ_c – critical velocity for air entrainment,
υ_o – approach velocity,
υ_w – water velocity.

1. Introduction

The role of hydraulic structures, such as weirs and dams, is essential for appropriate water resources management. The elements of these structures which render it possible to keep back water and control water flow are steal gates. Currently, one of the most commonly applied in hydraulic structures are flap gates. The popularity of this solution results from such advantages as light weight of the structure, high stiffness, assembly simplicity and the possibility of controling water discharge accurately.

During the design process of flap gates one should pay special attention to sufficient aeration under the flap (Petrikat 1958, Čábelka & Kunštatsky 1966), the reason for this is that the water jet overflowing the flap gate entrains a substantial amount of air and introduces it to tailwater (Fig. 1).

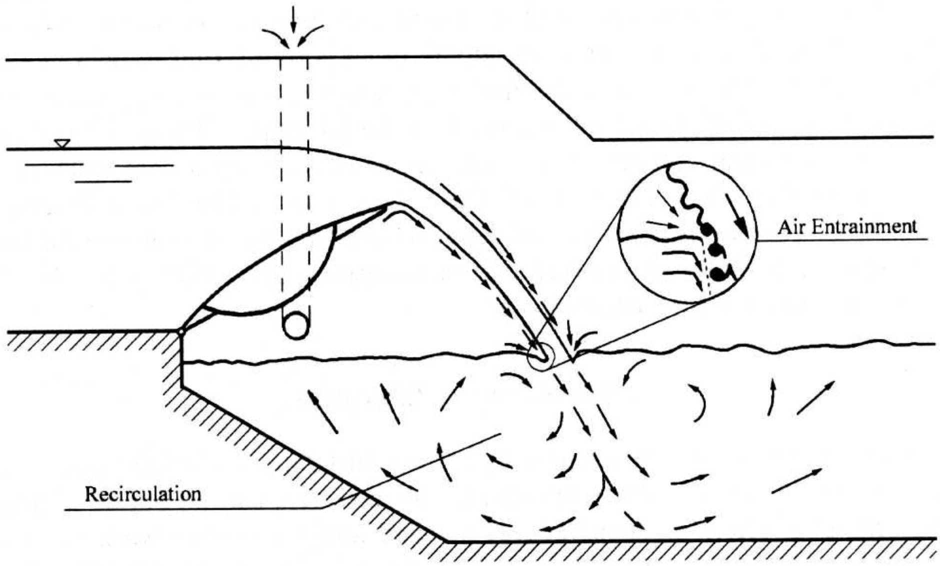

Fig. 1. Scheme of water flow through a flap gate

A certain amount of air, entrained from the subjet space by the bottom surface of the nappe, recirculates under the jet, thanks to the created return roll. The remaining air is carried to the tailwater with air entrained by the top surface of the nappe. Thus, if compact jet is restrcited by lateral faces, pressure in subjet space drops. Numerous researchers engaged in the study of this negative phenomenon observed some such undesirable effects as: additional loads on flap gates (Hickox 1944, Rogala 1968), change of the trajectory jet (Schwartz 1965, Treiber 1972), gate vibration (Partenscky 1971, Fanti et al. 1972, Rogala & Winter 1985) and coefficient of discharge (Rogala 1970). It is possible to maintain atmospheric pressure in the space under a flap gate only when the deficiency of air entrained by the water jet is compensated completely. This can be accomplished if one feeds the required amount of air through a system of air vents or interrupts a water jet and thus makes self-aeration possible. A nappe can be interrupted by nappe spoilers placed on a flap gate edge, the height of nappe spoilers is limited (about 0.3 m) as they are exposed to damage caused by ice or any other floating objects. As a result, nappe spoilers work only when the nappe layer is thin. With the increase of nappe layer thickness the broken jets are connected and consequently the phenomenon of pressure drop takes place again. For this reason air vents are commonly used; this results in generation of weak subatmospheric pressure which is necessary to overcome hydraulic losses made during airflow. Subatmospheric pressure leads to deviation of the falling water jet. While considering the problem of aeration, within the framework of this job and the experiments carried out on an existing object (Rogala et al. 1986), it was found out that when the jet glancing angle and subatmospheric pressure grow, the recirculation conditions change, i.e. a smaller amount of air is transferred to tailwater and a larger amount returns under the flap gate, which results in a subatmospheric pressure drop and the water jet returns to its initial shape. This cyclical process was observed by the authors when taking measurements on a dam spillway. In specific conditions the column caused flap gate vibration. Thus the definition of recirculation conditions and their influence on the amount of air entrained from subjet space constitutes an essential part in the explanation of flap-gate vibration generation and air vents dimensioning.

2. Survey of the Literature

The phenomenon of air entrainment by a water jet falling to a water region from the atmosphere was the subject of considerable research, carried out by scientists representing a variety of disciplines. A detailed analysis of such work has been presented in the earlier works of the authors (Rogala 1981, Rędowicz 1994). They bring one to the conclusion that they concentrated mainly on the explanation of the phenomenon mechanism, stating the amount of air entrained, examination of limiting conditions and the possibility of modelling the phenomenon. Most of the research refers to the water jet discharged under pressure from a variety of nozzles to a deep water basin. The remaining part of the research concerns water jet flowing through water engineering and measuring weirs. For the purpose of presenting the complexity of the phenomenon in question, we will present substantial research results obtained earlier.

2.1. Air Entrainment Mechanism

The mechanism of air entrainment by a sharp-crested weir in a water basin is a very complex process and depends largely on turbulence intensity of the jet itself, defined by the following formula:

$$C_T = \frac{\sqrt{\overline{v'^2}}}{v} 100\%. \tag{1}$$

Most of the research concerning this problem was carried out on jets discharged from vertical, round nozzles (Ervine et al. 1980). The increase of turbulence intensity is accompanied by the increase of the amount of air entrained by the jet.

Our own observations, made for a rectangular jet, revealed that with the increase of velocity the jet becomes unstable and the section of its side surface assumes a sinusoid shape. The amplitude of a sinusoidal wave grows with the increase of jet fall height. Most air entrained by such a jet rests in surface hollows (Fig. 1), the remainder rests in a boundary layer surrounding the jet. Air, introduced to water in the form of a pocket, is disintegrated into small bubbles and transferred with the jet; at the same time a distinct diffusion boundary, divides the non-aerated water jet from the water-air mixture is marked.

2.2. Formula Defining the Amount of Air Entrained

The initiator of the research on the problem of air entrainment of a water jet in a sharp-crested weir over a hydraulic structures flap gate was Hickox (1949). He conducted his research on large models and on a dam weir with vertical gates. On the basis of the results obtained and an earlier work by Johnson (1935) he developed an empirical formula which allows to calculate the amount of air needed to maintain subatmospheric pressure in the space created by two water jets, one of which flows over and the other under a vertical gate:

$$q_a = \frac{(C H_o)^{3.64} g^{0.5}}{\Delta p^{1.14}}. \tag{2}$$

The formula indicates that (2) Hickox makes the amount of air entrained dependent on the thickness of weir layer and thus indirectly dependent on water discharge and the value of subatmospheric pressure created in subjet space. He did not take jet fall height into consideration; this was probably the reason why his formula did not find its way into world literature, apart from few exceptions (Chow 1956, Čábelka & Kunštatsky 1966).

Wisner and Mitric (1961) carried out research on similar weir, excluding the water jet under the vertical gate. They arrived at the empirical formula:

$$\beta = k Fr^2. \tag{3}$$

Formula (3) is valid for a narrow variability range of Froude numbers ($3.5 \leq Fr \leq 5$) and when the subjet space is completely aerated. The necessity to satisfy this condition and a few measurements, taken by the author to determine the formula, contributed to the fact that it did not become common.

Another method of air flow rate calculation for a flap gate was developed by Levin (1965), who used Kamieniew's measurements results (Kamieniew 1964), he examined the influence of jet aeration on the size of scour in the bottom. Kamieniew measured the section shape of a free falling water jet at various heights and aeration degrees. He demonstrated that just beyond the flume outlet, the initially rectangular water jet narrows and takes the shape of a horseshoe then along with velocity increase it disintegrates into separate jets and drops. In effect, Kamieniew developed a function graph of aeration degree and Levin proposed its application in the calculation of amount of air absorbed, at the same time he suggested dividing the values by two to take into account that only the bottom jet surface absorbs air from the subjet space. The case examined by Kamieniew refers to a dissipated jet and thus the amount of entrained air calculated by this method are substantially underrated as a compact jet absorbs much more air than the dissipated one (Ervine et al. 1980).

Yet another researcher who dealt with the aeration problem was Pontoni (1967); on the basis of the results of research on a flap gate model, he worked out a graph form of the dependence of absorbed air rate on subatmospheric pressure in the subjet space and on water discharge. The obtained results are valid only for the examined conditions and in the range of flow variation realised by Pontoni. As a result one cannot use them to determine spillway aeration of other dimensions and flows.

A detailed analysis of the above formula for the amount of air absorbed by a water jet overfalling gates, was conducted by Rogala (Rogala 1981). He found out that the results obtained with the application of the formula differ considerably from each other. The reason why was either failure to take into consideration the scale effect, or the omission of some factors influencing the phenomenon, or maybe improper interpretation of measurement results. With regard to the above, Rogala carried out complex research on three large size hydraulic models and in effect established an empirical dependence enabling the maximum amount of air entrained by a falling water jet in the conditions of total aeration of subjet space to be defined:

$$\beta = 0.78 \cdot 10^{-9} Fr^{1.51} Re^{1.1}, \tag{4}$$

where:

$$Fr = \frac{v}{\sqrt{gd}} = \left(\frac{8g h_c^3}{q_w^3}\right)^{0.25}, \tag{5}$$

$$Re = \frac{v h_o}{\nu} = \frac{\sqrt{2g h_c} h_o}{\nu}, \tag{6}$$

$$h_c = z + 0.643 h_o, \tag{7}$$

it is important in nondimensional variation interval for the following parameters: $3.12 \leq Fr \leq 12.5$ and $3.4 \cdot 10^5 \leq Re \leq 16.6 \cdot 10^5$. Taking into account that air vents should be so designed as to suit the least favourable conditions, the author assumed that the total volume of air entrained by a water jet is taken out of the subjet space. Rogala justified this assumption by the construction of the stilling basin in which there is a downstream face of spillway acting similarly to a deflector used in the described research.

A more general analysis of the aeration problem in the water flow through water engineering was put forward by Kobus (1985). He divided the practically occurring cases of water jet aeration, taking place during the flow of water through various types of water engineering, into two groups:

- structures in which the lack of flow continuity occurs such as: sharp-crested weirs, siphon spillways, morning glory spillways, bottom outlets of dams, synclines for energy dissipation;
- structures in which the velocity of the flow is very high, such as chutes and overflow structures.

While dealing with the first group, Kobus made a unitary air flow q_a dependent on independent variables describing: system geometry expressed by a reference length and other characteristic lengths, water flow expressed by velocity v_w and turbulence (Tu), an air feeding system expressed by differential pressure Δp, unitary body force expressed by gravitational acceleration g and fluid physical properties such as: density ρ_w, viscosity μ_w, surface tension σ_w. Employing the principles of dimensional analysis he submitted the following equation:

$$\beta = f(geometry\ coefficient, (Tu), c_{pe}, Fr, Re, Z), \tag{8}$$

where parameter

$$Z = \frac{g\,\mu_w^4}{\rho_w\,\sigma_{wa}^3}, \tag{9}$$

substitutes the classical Weber's number, which describes the influence of surface tension. The parameter offers one advantage over Weber's number, namely, it includes neither the length dimension, nor the relative velocity. It is the function of the physical properties of liquid exclusively, and these do not depend on scale, geometry and flow velocity. For pure water $Z \approx 10^{-11}$ and it remains constant for constant temperature and water quality.

It should be mentioned that Tu parameter represents flow turbulence characteristics, i.e. it defines all conditions which influence the mechanism of the air entrainment process. One can include in this group turbulence intensity described by formula (1), velocity distribution in jet cross-section, flow curvature effect.

Once he conducted the analysis of aeration phenomenon, Kobus presented the method by which to calculate the volume of air entrained by a jet overfalling a sharp-crested weir and falling into a deep pool. Kobus suggested the application of the research results of Ervin & Elsawy (1975) for wide sharp-crested weirs, they have introduced the following formula:

$$\beta = 0.13 \left(\frac{h}{d}\right)^{0.446} \left(1 - \frac{v_c}{v}\right), \tag{10}$$

where the initial air entrainment velocity $v_c = 1.1$ m/s.

Formula (10) was derived for a rectangular jet discharged from a nozzle at high velocity, thus, from the point of view of initial turbulence degree, he describes a different physical phenomenon. Yet another problem is the fact that nozzle diameter d_n and jet thickness d, at the point where they reach the basin, are treated interchangeably. Quantity h also has a slightly different meaning in both cases. In Ervin's research it refers to the height of jet fall after it is discharged from the nozzle and it was not the only parameter producing jet velocity v. The jet discharged from the nozzle already reached a certain velocity which depended on the water level in the upper pool, as well as the shape and length of a nozzle.

2.3. Possibilities of Air Entrainment Phenomenon Modelling

Model research of water engineering is most often reduced to measurements taken on physical models constructed on a small scale, which is connected with the so-called scale effect. One can trace the problem of scale effect on the basis of dimensional analysis. To obtain complete similitude between the model and nature, equation (8) must be satisfied. In research models, the same fluids, i.e. water and air, are usually used, consequently complete geometric and dynamic similitude cannot be satisfied. This results from the fact that dimensions of bubbles, produced during air entrainment, always have the same size, which means that the geometric scale is not maintained, the velocity quotient of bubble outflow to water velocity on the model and in nature is not constant. Moreover, even if one disregards this fact and reduces further considerations to geometric similitude, when the water used is the same as in the prototype, i.e. Z = const, and examines air entrainment from the atmosphere, i.e. $c_{pe} = 0$, equation (8) will be reduced to:

$$\beta = f\left(Fr, Re, (Tu)\right). \tag{11}$$

If, following Froude law, the flow is modelled by appropriate velocity scale selection, then the scale effect will result from the incorrect modelling of *Re* number and turbulence characteristics. Usually *Re* number on a model is smaller than the one on a prototype, consequently the viscosity effect is more significant on a model in a small scale. However, if a completely turbulent flow is acquired on a model, then the mean characteristics of flow and macroscopic turbulence structure become independent of the *Re* number. This is due to the fact that the energy exchange between mean motion and the greatest vortices is controlled by the inertia effect. Viscosity dominates only in the energy dissipation of the smallest vortices. In such conditions it is sufficient if the *Re* number acquires an appropriate value to achieve a completely turbulent flow on a model, i.e. to make

$$Re_{model} > Re_t, \tag{12}$$

where: Re_t – minimum *Re* number for completely turbulent motion. Based on substantial research it is commonly agreed that $Re_t = 10^5$ or even slightly less.

2.4. Conclusions

The survey of exxtensive literature referring to the phenomenon of air entrainment by a compact water jet enabled the authors to draw a number of important conclusions, which contributed considerably to the solution of the problem of air recirculation in the tailwater of a flap gate. There are as follows:

- The air entrainment phenomenon is a physical process which is so complex that it has not been analytically solved until now.
- Most attention was devoted to the explaining of the mechanism of this phenomenon, defining the volume of air entrained and conditions of its modelling.
- It has been demonstrated that the aeration phenomenon can be modelled if one manages to achieve a completely turbulent motion on the model.
- Existing research on water engineering is scarce, its results being valid only for the specific schemes researched.

Having conducted a detailed analysis of the problem in question and reaching the above conclusions, it was found out that none of the existing formulae take into account the phenomenon of recirculation influence on the volume of air entrained by a water jet overfalling a flap gate, although this phenomenon always occurs. However, its intensity depends on stilling basin geometry and conditions in the tailwater.

As regards the fact that a flap gate has become one of the most commonly used in water engineering and also that the explanation of as many as possible if not all problems connected with the way it functions and can be safely exploited is significant from the point of view of both science and practice. Thus the decision was made to undertake a detailed analysis of the recirculation mechanism, define the parameters influencing its development and the volume of air entrained from the space under the flap to tailwater.

3. Definition of the Volume of Air Entrained with Regard to Recirculation

3.1. Air Recirculation Conditions

When we consider flow conditions through flap weirs we should distinguish the three most characteristic solutions, which depend on the height and shape of the threshold on which a flap gate is based (Rogala 1981). The first solution is a gate situated on a low threshold. The second possibility, probably the most common one, is a gate situated on the threshold with downstream face of spillway, and the third a flap gate situated on the high threshold. The feature shared by all of these solutions is the occurrence of a whirling water return roll, which makes some of the air entrained by the bottom surface of a water jet, recirculate back to tailwater. It can be assumed that the volume of returning air depends directly on the size of the roll, this in turn being influenced by the depth of stilling basin as the location of downstream face of spillway.

To sum up our considerations referring to air entrainment by a compact water jet flowing through a flap gate, we can define parameters which influence the volume of air introduced to water and its recirculation (Fig. 2). According to the authors they can be divided into two different groups.

The first group contains parameters which have a decisive impact on the volume of air entrained to water, such as jet surface velocity and a group of factors influencing jet turbulence and its roughness. A precise definition of surface velocity is impossible due to the difficulty in specifying the part of jet energy transmitted to ambient air and lost in the friction process. All researchers then operate an average jet velocity υ, which is determined from the free fall law, regardless of hydraulic losses. The resulting error is of minor importance, since hydraulic losses do not exceed 5%.

A much more complex problem is the defining of jet turbulence degree ε without measurement, and what follows the definition of critical velocity υ_c, which starts the process of air entrainment. This is especially important when υ and υ_c do not differ very much. The turbulence degree of a water jet discharged from a flap gate depends on the geometry of the upper station and flap gate inclination angle. The geometry of the upper station depends largely on weir light, shape and length of piers, height and shape of a threshold, radius of curvature and flap height. The definition of appropriate value υ_c, which changes from 0.8 to 3.0 m/s requires separate research or assuming the least advantageous value 0.8 m/s.

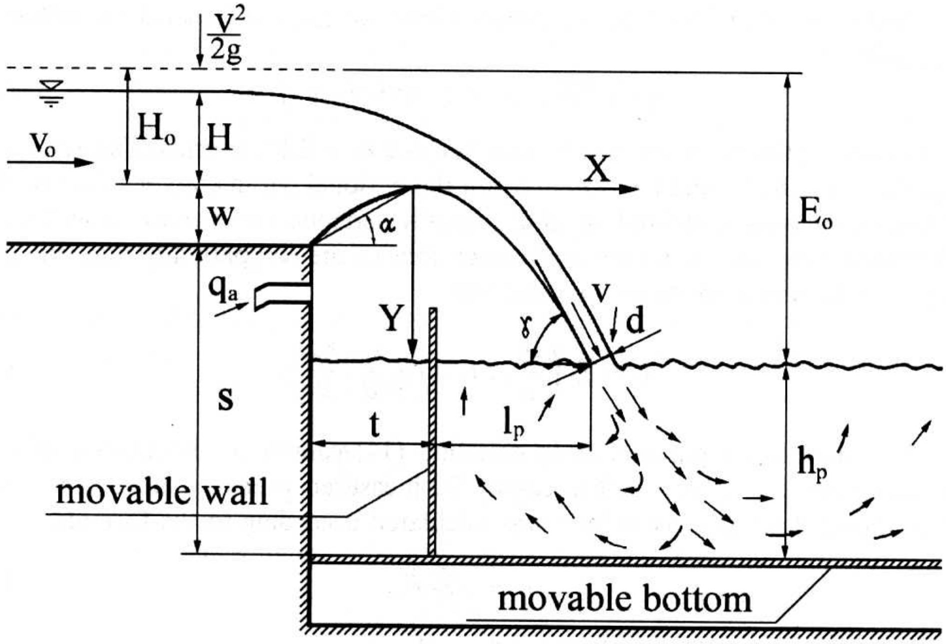

Fig. 2. Scheme of a flap gate with parameters of decisive impact on air entrainment and its recirculation

The other group contains parameters which decide as to the penetration depth of bubbles and recirculation development in a stilling basin. This group includes: jet thickness d, water depth in tailwater h_p, jet fall distance from downstream face of spillway l_p and jet glancing angle γ (Fig. 2).

3.2. Structural Formula

For the purpose of determining a general equation describing the problem in question, we used Buckingham's theorem since it constitutes the basis of dimensional analysis commonly applied in model research (Rouse 1961).

Having analysed the question of air entrainment by the bottom surface of a compact water jet of constant temperature in complete aeration conditions with the possibility of air recirculation to the space under the flap (Fig. 2.), it was assumed that the part of the entrained air which does not return under the flap and flows to the weir tailwater, is related to jet width unit q_a, which depends on initial entrainment velocity v_c, water jet velocity v, water jet thickness d at collision point, sinus of glancing angle γ, jet fall range from downstream face of spillway l_p, water depth in tailwater h_p and gravitational acceleration g. The effect of surface tension and viscosity were left out, assuming the existence of completely developed turbulent motion. Physical properties of air were also disregarded due to the significant difference in media density.

Taking into consideration the above values, we can put forward the following equation:

$$q_a = f_1(v_c, v, d, g, \sin\gamma, l_p, h_p). \tag{13}$$

In equation (13) there are $n = 8$ variables and $m = 2$ basic units. The structural equation will then contain $n - m = 6$ non-dimensional parameters π. The selected dimensional basis consisted of dimensionally independent values: v and d. To determine product π form we used dimensions of the compatibility rule and after appropriate transformations we obtained:

$$\beta = f_2\left(\frac{v_c}{v}, Fr, \sin\gamma, \frac{l_p}{d}, \frac{h_p}{d}\right). \tag{14}$$

Non-dimesional parameters in equation (14) cannot be determined directly as such values as v, d, γ and l_p cannot be measured precisely, hence they were determined indirectly. Velocity v was calculated according to the formula:

$$v = \sqrt{2gE_o}. \tag{15}$$

Water jet thickness d was calculated from the dependence:

$$d = \frac{Q_w}{bv}. \tag{16}$$

Angle γ and fall range l_p determination will be given in part 3.3.

3.3. Definition of Range and Glancing Angle of a Water Jet

Determination of a water jet fall range in the case of a water jet overfalling various types of weirs was the subject of research for numerous scientists. The reason was that this value is indispensable for the determination of the starting point of a hydraulic jump, which takes place below a hydraulic structure and thus it is also necessary to dimension the stilling basin. The formulas applied for weirs and degrees of vertical faces can be found in both world and Polish literature.

In the case we are investigating, knowledge of the bottom surface of the water jet overfalling a flap gate, will be more useful.

This question was the subject of interest for authors who needed to know the shape of the bottom surface of a free falling water jet to design curvilinear overflow structure profiles, which ensured that the pressure on the overflow structure will be only slightly lower than atmospheric pressure. Research demonstrated that the water jet shape depends mainly on the energy line location under the overflow structure, flow in velocity and hydraulic wall shape. The curvature of the bottom jet surface, we are interested in, has been described by two equal equations: quadratic parabola and a power equation.

As we were uncertain whether the existing formula can be applied for a flap gate, we decided to conduct our own model research for the purpose of establishing an equation for the bottom surface of nape for the researched flap gate. The research was conducted on a physical model described in 3.4.1. In effect we obtained the following equation (Rędowicz 1996):

$$\frac{Y}{H_o} = 0.407 \tan^{-0.338} \left(\frac{X}{H_o} \right)^{2 \tan \alpha^{0.145}} . \tag{17}$$

This describes the shape of the bottom surface of a water jet depending on the value of the water power over flap gate edge and its inclination angle. For $\alpha = 30°$ the equation takes the following form:

$$\frac{Y}{H_o} = 0.504 \left(\frac{X}{H_o} \right)^{1.856} . \tag{18}$$

Having transformed equation (18) with regard to X we obtained:

$$X = 1.447 H_o^{0.461} Y^{0.539}. \tag{19}$$

The fall range of a water jet from the downstream face of the spillway was calculated in accordance with markings on Fig. 2, from the relation:

$$l_p = l_k + X. \tag{20}$$

Jet glancing angle γ was determined with equation (19) transformed with regard to Y and differentiated after X. We obtained:

$$Y = 0.504 H_o^{-0.856} X^{1.856} \tag{21}$$

and

$$Y' = 0.935 H_o^{-0.856} X^{0.856}. \tag{22}$$

After further transformation we obtained:

$$\gamma = \arctan \left(0.935 H_o^{-0.856} X^{0.856} \right) \tag{23}$$

and

$$\gamma = \arctan \left(1.283 H_o^{-0.461} Y^{0.461} \right). \tag{24}$$

3.4. Model Research

The purpose of the research was to determine how the variability of non-dimensional parameters of equation (14) influences the development of air recirculation and air entrainment intensity from subjet space and transferred to tailwater, which is connected with it and in effect our goal was to change from a structural equation (14) to a physical formula.

Since our intention was to achieve the utmost fidelity in representing the researched phenomenon on a model we had to minimise the so called scale effect, described in 2.3. Although it is impossible to obtain complete dynamic similitude, one can conduct model research assuming that one of the active forces on the model and in nature is dominant and the influence of the remaining forces is insignificantly small. The water flow through a weir pertains to flow in an open flume and short distance ones, they are subject to Froude criterion of numbers equality. At the same time, the flow must be completely turbulent so as to disregard the influence of viscosity, which takes place only when equation (12) is satisfied. There is one more condition, namely, accomplishing, on a model, velocity which is higher than the initial velocity of air entrainment υ_c.

3.4.1. Test Stand

Hydraulic parameters which have a decisive impact on the process of the researched phenomenon are water discharge and maximum fall obtained. In the hydrotechnics laboratory of the Department of Water Engineering at the Institute of Geotechnics and Hydrotechnics of Wrocław University of Technology it was possible to obtain $Q_{w\,\max} = 0.090$ m^3/s i.e. $q_{w\,\max} = 0.15$ m^2/s and $E_{o\,\max} = 1.30$ m, which afforded $\upsilon_{\max}$ order 5.0 m/s. The relatively high value of water flow ensured accomplishing large Reynolds's numbers' values ($Re_{\max} = 1.5 \cdot 10^5$), thus the condition referring to motion turbulence degree was easily satisfied.

The scheme of a keep-back water degree is presented in Fig. 2. Water discharge was measured by a wheel weir with up to 1% accuracy. Water levels in top pool and in tailwater were measured by piezometers with up to 0.001 m accuracy.

To maintain pressure equal to atmospheric pressure in the space under the flap, the appropriate amount of air was pumped in. The volume of pumped air was measured using rotameters with up to 1.5% accuracy. The pressure under the flap was measured with U type a liquid-column gauge of a and a Askania micro manometer, which enabled the establishing of the pressure difference with 0.01 mm H_2O accuracy.

3.4.2. The Curriculum and Scope of the Research

The measurements were taken for a flap inclined at a 30° angle, since according to earlier research (Rogala 1981), this position is the least advantageous from the point of view of air entrainment. For higher flap positions ($60° < \alpha < 45°$) the nappe is broken by nappe spoilers and for lower flap positions ($15° < \alpha < -9°$) bottom part of water floods the flap and air entrainment no longer takes place. Air entrainment is most intensive at $45° < \alpha < 15°$, hence $\alpha = 30°$ angle right in the model of the interval was selected. One more fact supporting the selection of this position is the occurrence of maximum hydrodynamic loads at this inclination angle of a flap (Fanti et al. 1972).

Measurements were taken in six series which differed in the position of a movable bottom defined by s value. The value of s was changed in the $0.5 \div 1.0$ m range every 0.10 m. For $s = 0.90$ m a separate series of measurements was made to establish the influence of l_p variability on air entrainment intensity. It was accomplished by a quadruple change in the position of a boundary wall. Changes in the location of the wall are defined by parameter t, its value was subsequently 0.15 m, 0.30 m 0.45 m, 0.54 m. The values measured for each series were as follows: water discharge Q_w, volume of air fed in Q_a, elevation of water level over a flap gate edge H and water depth in tailwater h_p. The values of Q_w and Q_a were next recalculated to q_w and q_a.

Flow q_w was generated for the set position of the bottom, the value of h_p was changed several times. Measurement q_a was realised only when the volume of air fed in was sufficient to maintain the pressure level in subjet space at the level of atmospheric pressure. The number of measurements in specific series differed and depended on variability interval h_p.

3.4.3. Measurements Results

On the basis of own observation and measurements' results it has been established that parameters: υ, d, h_p and l_p have substantial influence on recirculation development and thus also on the volume of air entrained to tailwater, while it was impossible to define directly the influence of glancing angle γ. To show that specific parameters have a significant influence on the discussed process a graphic analysis was carried out to illustrate the fact. The analysis commenced with the establishing of the influence of jet velocity, which was changed at the interval of $2.86 \div 4.37$ m/s. A number of relation graphs $q_a = f(\upsilon)$ were made of various values of water flow q_w and depth h_p to achieve this purpose. The character of the influence of velocity on the volume of air entrained is presented in Fig. 3.

This shows that the value of q_a increases almost linearly with the increase of water velocity and that the influence of jet thickness is significant i.e. the thicker the jet falling to a basin at the same velocity the more air it entrains.

Next, the influence of water depth h_p was analysed, every time the constant values of υ, d and γ were selected. Figure 4 shows also that the increase of depth h_p ensues the reduction of the volume of air introduced to the space under a flap. The case discussed refers to jet velocity $\upsilon \cong 3.0$ m/s and jet thickness changing from 0.022 m to 0.049 m. A similar tendency was observed for other values of jet velocity and thickness.

To have a complete description of the influence of depth h_p on the recirculation phenomenon attention should be paid to the fact that the practically used

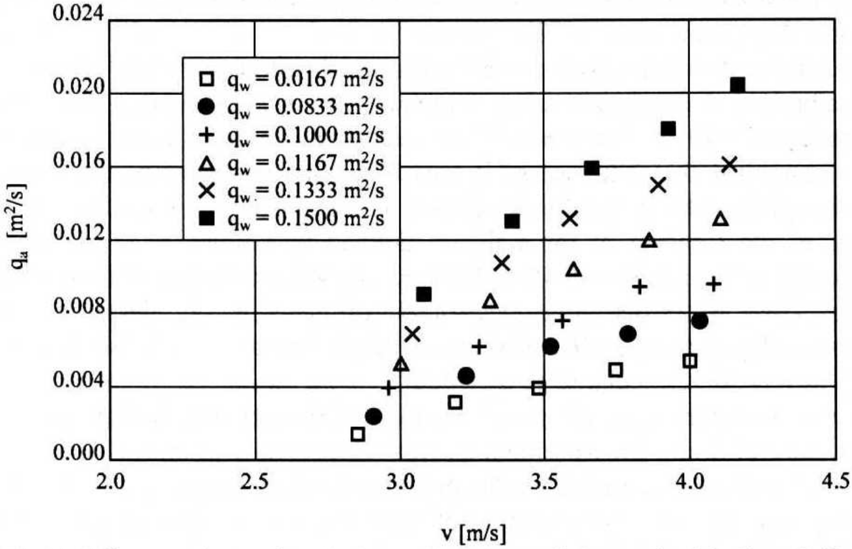

Fig. 3. Influence of water jet velocity on the volume of air entrained for $h_p = 0.38$ m

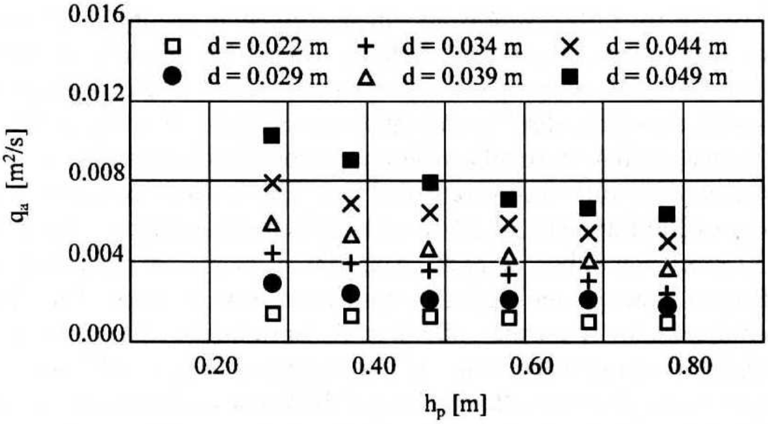

Fig. 4. Influence of water depth h_p and jet thickness d on the volume of air entrained

basins do not have depths which would be equal to or greater than the air penetration depth H_p, thus we should understand that the formula we look for will refer to cases where $h_p < H_p$.

The last parameter which influences the recirculation development is the distance between the place where the jet falls from the downstream face of spillway l_p. The measurements taken afforded explaination complete of the influence of downstream face of spillway location in relation to water on recirculation development and the volume of entrained air. Fig. 5. presents the dependence $q_a = f(l_p/h_p)$

for the minimum and maximum values of water flow. The figure shows that the influence of the downstream face of spillway location becomes insignificant for $l_p/h_p > 0.3$ and the recirculation phenomenon is fully developed. This observation gives rise to the conclusion that the l_p value can be omitted, although its influence on the volume of entrained air is significant, when we use such shape of downstream face of spillway which allows for full air recirculation development in a stilling basin. Further search for a formula to describe the volume of entrained air with regard to recirculation will refer to this case.

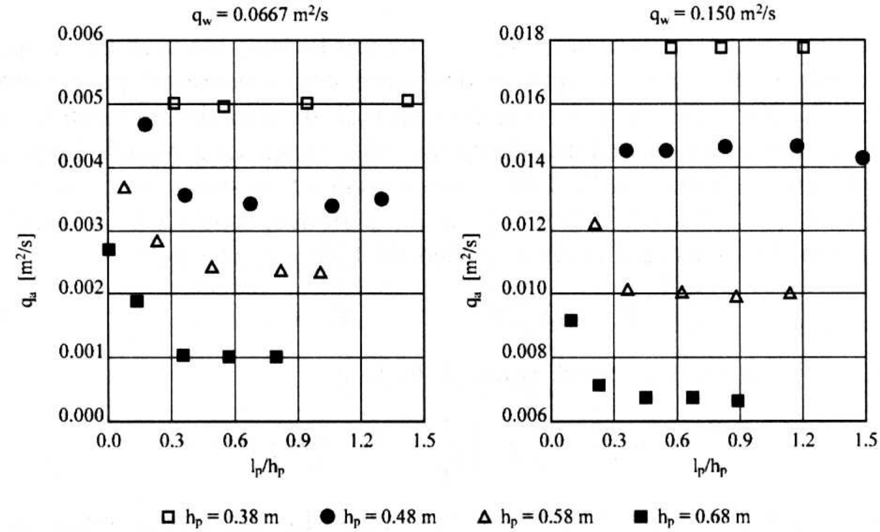

Fig. 5. Influence of l_p/h_p quotient on the volume of air entrained

The research conducted enables for a quality description of recirculation influence on the volume of air entrained from subjet space. It has been established that the intensity of the phenomenon is influenced mainly by water jet velocity and its thickness, where velocity has influence on the total amount of air entrained to water while the velocity and thickness has influence on its propagation in a basin. Limiting the development of recirculation by reduction of h_p and l_p values results in an increase in the amount of air transferred to tailwater and thus also a decrease of air returning under the flap. In an extreme case, as a result of recirculation elimination, the return of air to the space under a flap does not take place at all. Both l_p and h_p have significant influence on recirculation development and the volume of returning air, however, the influence of l_p in relation to h_p is reduced faster.

Yet another problem was the definition of the initial air entrainment velocity v_c. A precise and direct determination of this value proved to be very difficult. The only possibility of value determination during the research was the observation of the air entrainment phenomenon and grasping the moment when it appears or disappears. Numerous observations for all changed water flows formed the basis for assuming that velocity v_c in the condition of the researched carried out was encompassed by a 2.5 ÷ 2.8 m/s interval. Fig. 3 confirms this as it shows that air entrainment stops when a jet reaches the velocity encompassed by the said interval. However, since we have no certainty that accepting an average value is the best solution, we decided to determine v_c by way of estimation, treating it as one of the model parameters describing the discussed phenomenon.

3.4.4. Determination of the Precise Form of the Aeration Coefficient Formula

To transform structural formula (14) to a physical formula we used the measurement results of the values needed to determine non-dimensional parameters in the formula. Formula (10) was treated as an indication of the probable form of the physical formula, as well as information about regressive models from literature (Draper & Smith 1981). Taking into consideration structural formula (14) and what was established in reference to l_p, a product model was accepted for further considerations as it is often applied for hydraulic research:

$$Y = a_0 X_1^{a_1} X_2^{a_2} \ldots\ldots\ldots X_i^{a_i} + \varepsilon. \tag{25}$$

In the case discussed the model assumed the form:

$$\frac{q_a}{q_w} = a_0 \left(1 - \frac{v_c}{v}\right)^{a_1} \left(\frac{d}{h_p}\right)^{a_2} Fr^{a_3} (\sin\gamma)^{a_4} + \varepsilon. \tag{26}$$

For the purpose of determining number values of model unknown parameters the least squares method was used. Due to the fact that the model in question is significantly non-linear, the iteration procedure was used. Numerical calculations were made by means of Statgraphics Plus v. 6,0 software, with the application of non-linear regression procedure based on the numerical algorithm developed by Marquardt. This method is a compromise between the linearyzation method and the steepest descent method and is considered one of the most effective and economic methods of function minimizing currently available.

Before numerical calculations were started, equation (26) was partly modified, bearing in mind that the v_c value only initially estimated, was not uniquely accepted. Thus an additional parameter was introduced to substitute v_c. Calculation results are compiled in Table 1. This shows that a_1, a_2 and v_c parameters have relatively small standard deviations while a_3 and a_4 parameters show larger deviations, equivalent to calculated coefficients. Moreover, parameter a_3 is close to zero which suggests that the Fr variable has insignificant influence on coefficient β variability. It should also be mentioned that parameter a_1 does not differ much from a unit. Consequently, the model expressed by equation (26) was simplified to the following form:

$$\frac{q_a}{q_w} = a_0 \left(1 - \frac{v_c}{v}\right) \left(\frac{d}{h_p}\right)^{a_1} + \varepsilon. \tag{27}$$

Table 1. Calculation results for equation (26) parameters

Coefficient	Estimate	Standard error	Ratio	R^2
a_0	1.0003	0.16332	6.125	
a_1	1.0271	0.03120	32.919	
a_2	0.5103	0.00888	57,673	0,980
a_3	0.0677	0,06093	1.113	
a_4	−0.6725	0.56786	−1.184	
v_c	2.6656	0.00728	365.920	

Results of recalculation are compiled in table 2.

Table 2. Calculation results for equation (27) parameters

Coefficient	Estimate	Standard error	Ratio	R^2
a_0	1.20474	0.02386	50,489	
a_1	0.51160	0.00770	66.464	0.978
v_c	2.66094	0.00449	592.872	

After substitution of calculated parameters the final formula has acquired the following form:

$$\frac{q_a}{q_w} = 1.205 \left(1 - \frac{2.66}{v}\right) \left(\frac{d}{h_p}\right)^{0.512}. \tag{28}$$

Table 2 shows that standard errors of particular parameters constitute only a minor percentage. This refers especially to air entrainment initial velocity.

As the measure of model correctness multiple correlation coefficient $R^2 = 0.978$ was accepted, its value means that 97.8 % of the observed aeration coefficient β variability depends on v_c/v and d/h_p variables and only 2.2 % descends from other sources not taken into account during the model research. The multiple correlation coefficient was calculated from the formula:

$$R^2 = \frac{\sum\left(\hat{Y}_i - \bar{Y}\right)^2}{\sum\left(Y_i - \bar{Y}\right)^2}, \tag{29}$$

where $\hat{Y}_i$ is the predicted value of dependent variable Y, $\bar{Y}$ is its average value and Y_i the observed value.

4. Summary

The work analyses recirculation phenomenon in a stilling basin of a weir, as well as its influence on the volume of air entrained form subjet space and transferred to tailwater, which has never been taken into consideration before. The assumed basis was the phenomenon of water jet overflow of a flap gate inclined at angle of $\alpha = 30\circ$, since according to earlier research, at this inclination the air entrainment is most intensive and hydrodynamic structure load reaches its maximum values.

Dimensional analysis, observations and measurements of a physical model enabled the introduction of formula (**??**), which gives the relation of aeration coefficient to the velocity and thickness of a jet and water depth in tailwater, valid for $0.0299 < d/h_p < 0.1089$.

It was found that air entrainment is also significantly influenced by the water jet collision range from the downstream face of spillway. Although in extreme cases the volume of entrained air is doubled, when l_p is close to zero, for $l_p/h_p > 0.3$ it becomes insignificant.

On the basis of the research, formula (**??**) was developed, it enables defining of the range of water jet fall from a flap gate, the initial velocity was also determined and is equal to 2.66 m/s, which is the velocity which starts air entrainment.

Bearing in mind that our purpose is to introduce only the minimum volume of air to subjet space, one should design stilling basins in such a way as to make the development of recirculation possible and thus increase the volume of air returned under the flap, this will allow us to produce air vents of smaller diameters.

References

Chow V. T. (1959), *Open Channel Hydraulics*, McGraw-Hill,

Čábelka J., Kunštatsky J. (1966), *Jezy*, Slowenské vydatelstwo technickej literatury, Praha.

Draper N., Smith H. (1981), *Applied Regression Analysis*, second edition, Wiley, New York.

Ervine D. A., Mc Keogh E., Elsavy E. M. (1980), Effect of Turbulence Intensity on the Rate of Air Entrainment by Plunging Water Jets, *Proc. Inst. Civil Engr*, Part 2, June, 425–455.

Fanti K., Fiedler K., Kowalewski J., Wójcicki S. (1972), *Hydraulic structures*, Arkady, Warszawa (in Polish).

Hickox G. H. (1944), Aeration of spillways, *Transactions American Society of Civil Engineers*, Vol. 109, 537–566.

Johnson J. (1935), The aeration of sharp-crested weirs, *Civil Engineering*, March, 177–178.

Kamenev J. A. (1964), Aeracja potoka podajuščego s konsolnogo vodosbrosa, *Gidrotechničeskoe Stroitelstwo*, No. 8, 45–49.

Kobus H. (1985), *An Introduction to Air-Water Flows in Hydraulics*, ISBN 3-921694-61-2 Stuttgart.

Levin L. (1965), Calcul hydrauliqe des conduit d'aération des vidanges de fond et dispositifs deversants, *La Houille Blanche*, No. 2, 121–126.

Partenscky H. W. (1971), Theoretical Study of Flap Gate Oscillation, *XIV Congress IAHR*, Paris.

Pontoni K. J. (1966), Entraîement d'air par une nappe déversante sur une vanne, Trav. 3.31, *II^e Congrès des Hydrauliciens d'Amérique Latine*, Julliet, Caracas.

Petrikat K. (1958), Vibration Tests on Weirs and Bottom Gates, *Water Power*, February-May.

Rędowicz W. (1994), *Influence of recirculation on the volume of entrained air from subjet space*, doctoral thesis, Raport Ser. PRE nr 554, Wrocław University of Technology, Institute of Geotechnics and Hydrotechnics (in Polish).

Rędowicz W. (1996), Shape of water jet overfalling a flap gate, *Materials for the 16^th National Hydraulic School*, Grodno near Międzyzdroje, 16–20.09.1996 (in Polish).

Rogala R. (1968), Increase of loads on a flap gate induced by lack of aeration in space under the flap, *3rd Scientific Session of Civil Engineering Department*, Wrocław University of Technology (in Polish).

Rogala R. (1981), *Aeration of nappe*, Scientific Works of Geotechnics Institute, Wrocław University of Technology, series: Monografie, Wrocław (in Polish).

Rogala R. (1981), Entrainement d'air par lame deversante, *La Houille Blanche*, No. 1.

Rogala R., Kostecki S. (1985), Vibration of flap gates, *Archives of Hydroengineering*, Vol. 1 (in Polish).

Rogala R., Kostecki S., Rędowicz W. (1986), Vibration elimination in flap gates of dams column, *III TKZ Conference*, Warszawa, K 4.11 (in Polish).

Rogala R., Winter J. (1985), Hydrodynamic Pressures Acting Upon Hinged-Arc Gates, *Journal of Hydraulic Engineering*, Vol. 111, No. 4, April.

Rouse H. (1961), *Fluid Mechanics for Hydraulics Engineers*, Dover Publications, Inc. New York.

Schwartz H. I. (1965), Nappe Oscillation, *Journal of the Hydraulic Division, Proceedings ASCE*, HY3, May.

Treiber B. (1974), Theoretical Study of Nappe Oscillation, *IAHR IUTAM Symposium*, Karlsruhe, Springer Verlag, Berlin.