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Weir aeration - part I: Single free fall

1. Introduction

In several Dutch water works aeration of ground-water deficient in dissolved oxygen is provided by cascades or weirs. In the Amsterdam Works viz. ground-water is passed over a series of step weirs, the number of which depends on the drop of head allowed in each step. A drop varying from 0.2 to 0.4 m has been adopted allowing of adequate aeration, as suggested by practical experience. The head requirement provided by pumping and the simple layout of the weir structure, involving low operating costs, would make weirs interesting for aeration of flowing water not requiring a detention time like for instance a mixed liquor in the purification of sewage. A further advantage is that weirs enable us to treat relatively large quantities of water in a comparatively small area. According to Huisman [1] the area required is in the order of 15—30 m^2 per 1000 $m^3.hr^{-1}$ capacity. It is further mentioned by him that the flow rate may vary from 20 to 100 $m^3.hr^{-1}$ per m weir crest without influencing the aeration efficiency.

Much research has been carried out in Great Britain in recent years on the oxygen economy of rivers by the Water Pollution Research Laboratory. During surveys it became clear that weirs may provide supplemental aeration of rivers into which waste water is discharged. The location of existing weirs, however, is seldom related to the oxygen sag curve so that their importance in the control of water quality is incidental. It is mentioned by Thackston and Speece [2] that reaeration, although no substitute for proper waste treatment at the source of pollution, can be a valuable tool in the protection of stream life for emergency cases. It is noted that in some small Dutch streams the nuisance resulting from pollution has occasionally been relieved by provision of reaeration facilities [4] and the improvement of an existing weir [3]. In the latter case Van Selm has studied whether weirs may be adapted to fulfil a multipurpose task.

It is evident that the extension of knowledge about weir aeration is desirable both in the field of drinking water supply and waste water disposal. In structural design of weirs, engineers are obliged to rely on practical experience. This is an unsatisfactory situation as they are accustomed to arrive at the allowable drop of head from the view-point of capital and operating costs. By the laboratory of Sanitary Engineering at Delft the effect of different parameters on the aeration at a single weir has been studied. Furthermore it has been investigated to what extent a structural modification may improve the efficiency. The research was carried out in an experimental weir system at 0.75 m width and 55 $m^3.hr^{-1}$ capacity.

2. Theoretical considerations

Water deficient in oxygen being passed over a weir is capable of absorbing much oxygen from the ambient atmosphere. In studying dissolved oxygen contents during surveys of rivers Gameson found that the raise of oxygen affected at weirs depends on the level of oxygenation of the water arriving at the weir. The aeration capacity is expressed by him in terms of the deficit ratio r given by:

$$r = \frac{c_s - c_a}{c_s - c_b} \quad (1)$$

where c_a and c_b represent the dissolved oxygen content of samples taken upstream and downstream from the weir respectively and c_s the oxygen saturation value. In this study the representation of measuring results is different from Gameson's in that the aeration capacity is expressed in terms of the raise of dissolved oxygen content, the water arriving at the weir being free of oxygen. This approach involves an expression of the aeration capacity being directly applicable to the general equation dealing with the rate of oxygen absorption, as will be discussed below.

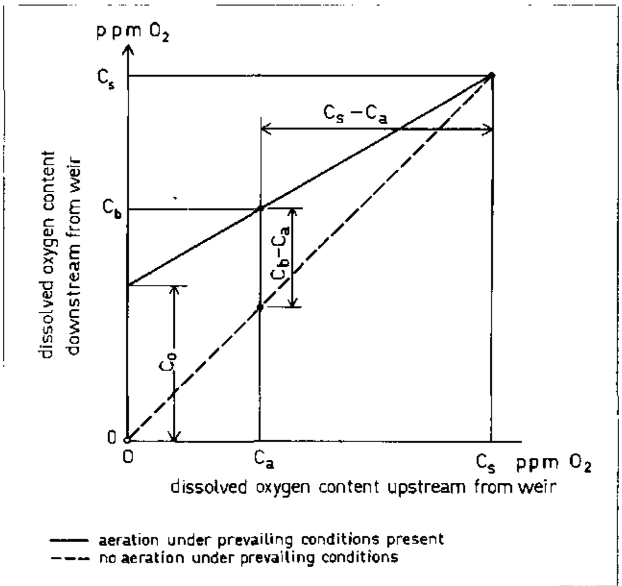
It has been found by Gameson [5] and Zweegman [6] that under steady state conditions the raise of the dissolved oxygen content $c_b—c_a$ is proportional to the oxygen deficit $(c_s—c_a)$ of the water arriving at the weir. This relationship may be expressed by:

$$c_b - c_a = K(c_s - c_a) \quad (2a)$$

Multiplying terms on both sides of equation 2a by Q, being the rate of flow passed over the weir, will yield an expression for the amount of oxygen absorbed per unit time:

$$Q(c_b - c_a) = K \, . \, Q(c_s - c_a) \quad (2b)$$

Fig. 1 - Established relationship between dissolved oxygen contents upstream and downstream from weir.



Or in other words this expression states that the rate of oxygen absorption is directly proportional to the oxygen deficit, being the relationship which has been established by Lewis [8] and Adeney [7] for sparingly soluble gases, including oxygen. Under prevailing conditions the maximum raise of dissolved oxygen, c_o, will be obtained when c_a equals zero. The relationship to be obtained then between c_a and c_b is indicated in fig. 1. It may be expressed by:

$$c_b = c_a + c_o \left(1 - \frac{c_a}{c_s}\right) \qquad (2)$$

The value of c_o, representing the aeration capacity of a particular system, has to be determined from experiment. It may be seen from equation 2 that for a given value of c_o the oxygen content downstream from the weir c_b can be readily computed when the oxygen content arriving at the weir c_a and the saturation content c_s are known. The saturation content being function primarily of barometric pressure and temperature [9, 10] causes the raise of the dissolved oxygen content and hence the value of c_o to be related to these two variables, in accordance with equation 2a. With regard to the influence of temperature it is generally known that the increase in diffusivity, for example, may offset the depression of the oxygen saturation value.

2.1. *The aeration capacity* (a convenient measure)

The effect of temperature on aeration at weirs has been investigated by Gameson et al [11], using an experimental system. In their paper temperature was correlated with the deficit ratio r for a series of single free falls over a range of 40°C. From their data obtained on clean water falling through 2 ft into a collecting tray with a depth of 3½ in. the present authors have attempted to find a new correlation between temperature and the aeration capacity c_o as defined above. Applying the oxygen solubility values obtained by Truesdale et al. [10] and assuming that the barometric pressure was invariably 760 mm Hg during the fore-mentioned experiments we arrived at the relationship indicated in fig. 2. From this it appears that c_o within a range of 12 to 18°C, being the range involved in the present experiments, varies to such a small extent that the influence of temperature in this particular range may practically be ignored.

It is interesting to note that in the equation of the oxygenation capacity (OC) of an aeration tank Pasveer [12] has introduced the factor $\sqrt{\frac{k_{10}}{k_t}}$. In this, k represents the diffusion constant being dependent on temperature. Though theoretically unobjectionable, as oxygen absorption is governed by molecular diffusion in the liquid boundary layer, it remains to be seen whether the introduction of a diffusion constant is of practical significance. In the computation of $\sqrt{\frac{k_{10}}{k_t}}$ use was made of results obtained by Adeney and Becker [13]. The latter have determined the effect of temperature on oxygen being absorbed from a large bubble ascending in a narrow tube filled with water. Strictly speaking this circumstance cannot be compared with aeration provided at a weir. The allowance made for the results obtained by Adeney et al is thought to be justified, however, as it appeared that water passing over a weir is capable of entraining substantial amounts of air bubbles into the receiving body of water. From results obtained by Adeney et al it follows then that the initial rate of oxygen absorption in oxygen-free water is practically constant within a temperature range of 3 to 35°C. The above mentioned references would imply that in the present investigations, in which aeration provided is also expressed in terms of oxygen absorption in oxygen-free water, the influence of temperature may safely be neglected.

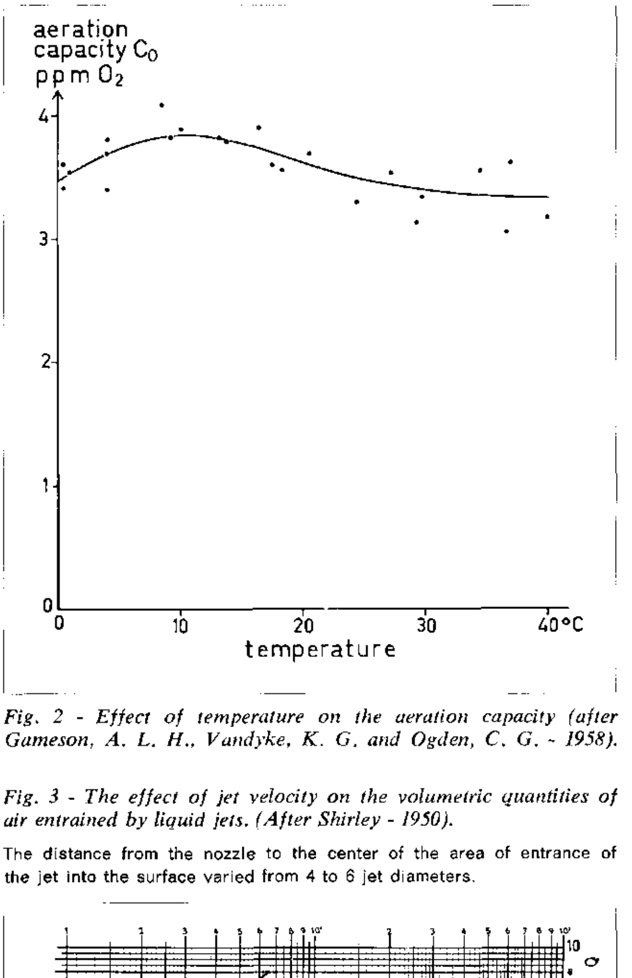
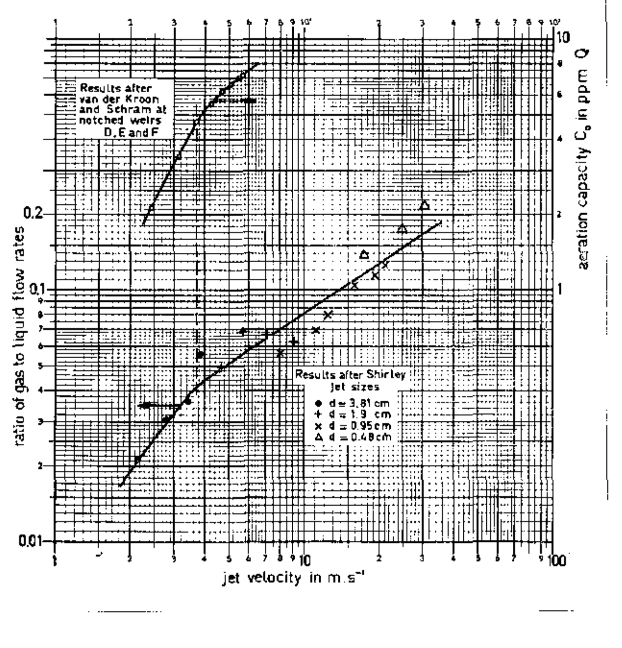


Fig. 2 - Effect of temperature on the aeration capacity (after Gameson, A. L. H., Vandyke, K. G. and Ogden, C. G. - 1958).

Fig. 3 - The effect of jet velocity on the volumetric quantities of air entrained by liquid jets. (After Shirley - 1950).

The distance from the nozzle to the center of the area of entrance of the jet into the surface varied from 4 to 6 jet diameters.



2.2. *Air entrainment*

It is known from visual observation that nappes discharging from the crest of a weir are capable of air entrainment when they pass the water surface of the receiving body of water. It is assumed that the dispersion of air occurs at the perimeter of the submerged nappe, resulting in air bubbles being brought deeply below the water surface due to the action of the nappe. When it is further assumed that aeration is promoted by an increase of the nappe perimeter, partition of the water at the crest of the weir by providing notches seems evident. Partition results in jets having a more or less circular cross-section. About the volumetric quantities of air being entrained due to the action of liquid jets has been reported by Shirley [14]. The experiments conducted by him concern jets of 0.24 to 3.8 cm nominal diameter issued from smooth converging nozzles and entering the surface at angles from 45° to 67° with the horizontal plane. The reason of dwelling on the work done by Shirley is due to the fact that jets do not absorb any significant amount of oxygen until they have been submerged into the receiving body of water. It would thus follow that emphasis should be given to the dispersion of air as a mechanism of oxygen supply. Shirley then presented his results as applicable to jets entering the water at a vertical angle (see fig. 3). From this study it appeared that the ratio of air to liquid flow rates depends on the velocity of the jet. Shirley supposed a separate relationship for each nominal diameter. The present authors are inclined to represent data obtained at different nominal diameters by one single function on the basis of results from this study, as will be discussed later.

2.3. *Submerged jets*

In connection with the above mentioned picture it would seem expedient to discuss briefly some flow characteristics of a single jet after it has passed the water surface. Referring to Prandtl's model of momentum transfer it may be expected that for the vigourous interaction of the liquid jet and the water surrounding it the velocity of the jet will decrease on its way down through the receiving body of water. As a consequence the water surrounding the jet is mixed with the water supplied by it resulting in a spreading of the jet. This is illustrated in fig. 4. Due to the inflow of water surrounding the jet air bubbles being introduced by action of the jet are brought deeply below the water surface. This phenomenon is demonstrated in fig. 5, giving a view of the submerged part of the jet as it may be inferred from the air being entrained. The escape of air bubbles from the jet probably occurs at a depth at which the liquid velocity has decreased to such an extent as to allow bubbles to rise to the surface. The concept of the jet spreading itself over the depth of the basin has been verified by Häusler [15] who studied the pressure distribution at a false bottom plate struck by a jet. In his study jets were allowed to enter the water at a vertical angle and were being deflected by an adjustable plate fitted with pressuregauges. By way of example the authors have computed on the basis of Häusler's results the mean velocity distribution over the path of a jet, having a nominal diameter of about 2.4 cm and falling through 0.7 and 1.4 m respectively (see fig. 6a). The value of 2.4 represents the average size of jet encountered in this study. From fig. 6a it is apparent that the downward velocity decreases to about 0.2 and 0.3 m.s.$^{-1}$ respectively at a depth of 0.6 m. The latter values correspond with the velocities of rise of air bubbles in the range of 2 to 20 mm diameter. It must be noted that partition results in a series of smaller jets which enter the water so closely that interference is likely to occur. Although practical conditions may render the computational approach doubtful the above mentioned picture clearly illustrates that provision should be taken to allow of sufficient water depth in the receiving basin.

3. **Experimental**

During two years of laboratory investigations, including six months of preliminary tests, numerous runs were made under various conditions to determine the aeration capacity c_0 of an experimental weir system with a single

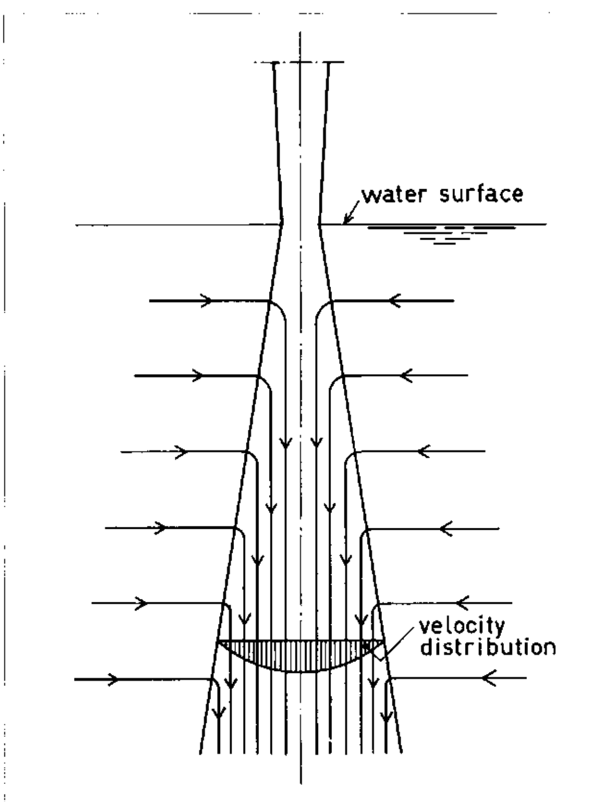
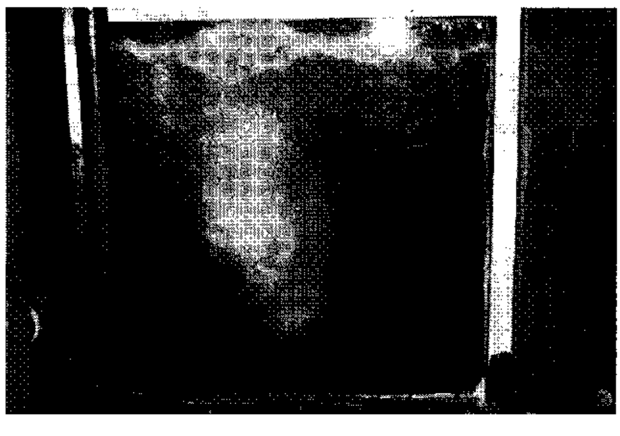


Fig. 4 - Spreading of the submerged jet over the depth of the receiving basin. (After Häusler - 1961).

Fig. 5 - View of the submerged part of the jet as inferable from air entrainment.



fall. The experiments were carried out with tap water having a temperature of 12°C to 18°C.
In this investigation the following aspects were studied:

3.1. Evaluation of the basic concepts regarding oxygen absorption.
Related to the aeration capacity:
3.2. Weir configuration
3.3. Height of the weir
3.4. Flow rate
3.5. Size of the receiving basin

Experimental weir system (see fig. 7).
The water entered the weir chamber (f) from a storage tank of about 100 m^3 capacity from which it was raised by a pump (a). The supply pipe was fitted with a valve (b) for flow adjustment and a magnetic flow meter (c). The flow rate was in the range of about 20 to 55 $m^3.hr^{-1}$. This rate could be read from a flow indicator (d). In the weir chamber screens (e) consisting of gravel packs were provided to allow water to be distributed evenly over the cross-section of the chamber. Downstream from the chamber was a detachable weir allowing of different weir configurations to be practised. The water was dropped into a receiving basin (g) the position of which could be adjusted either by lowering or lifting it. The height of the weir following from the difference in water level between the weir chamber and the receiving basin was 1.6 m at a maximum. The width of the chamber and the basin was 0.75 m. The side walls of the basin had slots in the event of only part of the basin being used and a partition wall being erected. By this measure both the length and the depth of the receiving body of water could be reduced to 0.5 m and 0.4 m respectively. Downstream from the basin there was an adjustable weir over which the water was passed to the effluent pipe for delivery to the storage tank.
To obtain a substantial change in dissolved oxygen content in the system the water was deoxygenated by addition of a solution of sodium sulfite. The solution was dosed continuously into the supply pipe at some distance upstream from the installation together with a small quantity of cobalt chloride as a catalyst to permit sulfite to be oxidized completely before reaching the weir. An oxygen sensor was available for continuous monitoring of the dissolved oxygen content of the water arriving at the weir. Fig. 7 shows the sensor assembly (h), consisting of a cell in which the sensor was mounted, an oxygen indicator and a flow indicator. The cell was being supplied at a rate of about 100 $l.hr^{-1}$ from tubing leading out of the weir chamber. After conditions had become steady samples were taken from this tube as well as from the tube leading out of the receiving basin. Analyses were made to determine the dissolved oxygen content.
The dissolved oxygen content was determined by the Winkler method. Samples were checked for the presence of sulfite with iodine.

3.1. *Evaluation of the basic concept*

The basic concept of oxygen absorption at weirs was verified by dosing of sodium sulfite and cobalt chloride at a rate to obtain a low level of dissolved oxygen in the weir chamber under conditions of constant flow, height of the weir, temperature, etc. After conditions had become steady the water arriving at the weir and in the receiving basin were analysed for dissolved oxygen. The

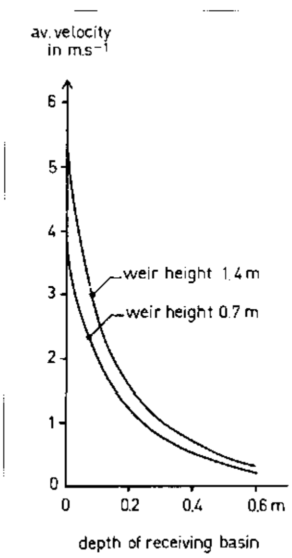


Fig. 6a - Relationship between av. downward velocity of submerged jet and depth of receiving basin for jets at 2.6 cm diameter (after Häusler).

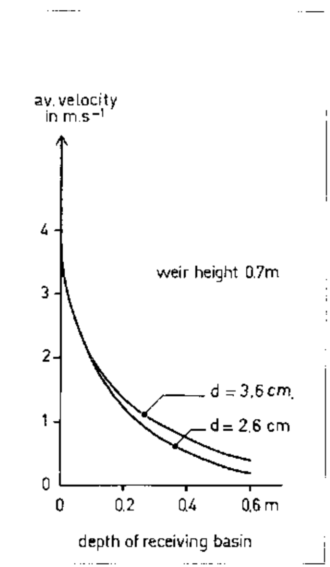


Fig. 6b - Relationship between av. downward velocity of submerged jet and depth of receiving basin for different jet diameters d at 0.7 m of weir height (after Häusler).

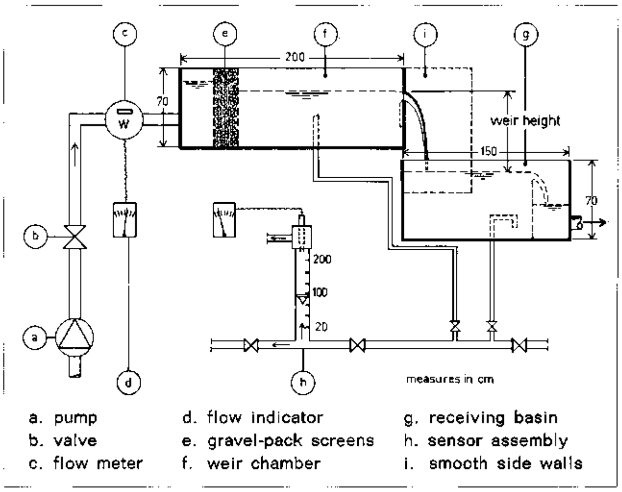
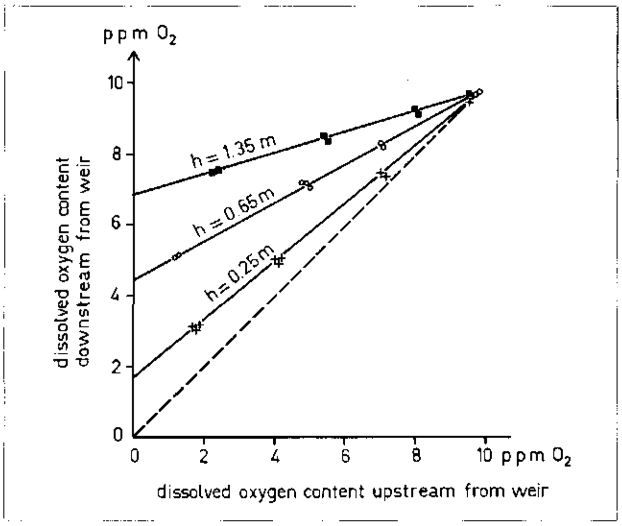


Fig. 7 - Experimental installation.

Fig. 8 - Relationship between dissolved oxygen contents upstream and downstream from weir C at a flow rate of 40 $m^3.hr^{-1}.m^{-1}$, 0.6 m depth of receiving basin and different heights of the weir.



values to be obtained were respectively c_{a1} and c_{b1}. Analysing was resumed after the supply of the reagents had been lowered resulting in values c_{a2} and c_{b2}. The final analyses were made after the supply of sodium sulfite and cobalt chloride had been stopped to allow oxygen in both the chamber and the basin to reach saturation level. On plotting values of c_{a1}, c_{a2}, etc. versus the corresponding values of c_{b1}, c_{b2}, etc. as indicated in fig. 8, a linear proportionality is apparent which may be expressed by equation 2. It will be seen that this equation contains the aeration capacity c_o, which may be regarded as an absolute measure of the aeration provided at a weir. The slight influence of temperature also makes it a convenient one as it has been argued on the basis of results obtained by Gameson. The authors must admit that this aspect should have been studied, were it not for the fact that the experimental installation is too coarse a research tool to test it exquisitely. Results of experiments carried out under constant conditions within a temperature range of 12 to 18°C indicate that it may be advanced if departures of 0.2 p.p.m from the average value of the aeration capacity are considered to be insignificant (see fig. 9).

3.2. *Weir configuration*

It has previously been argued that partition of the nappe discharging from the weir is probably of influence on the aeration capacity. In order to verify this question a variety of weirs have been tested under constant conditions of flow rate (30 $m^3.hr^{-1}$), height of the weir (0.9 m) and depth of the receiving basin (0.6 m). The weirs are represented in fig. 10. In this study provision has been taken to prevent the nappe from clinging to the face of the weir, so that the region beneath it was freely ventilated. In the investigation of weirs K and L the nappe was prevented from contracting in the plane parallel to the face of the weir by allowing it to cling to smooth side walls. The results of these tests are given in table 1. When contraction was allowed in testing weir M it appeared that a nappe discharging from it exhibits a bigger aeration capacity than nappes from weirs K and L did. It further appeared that c_o was favoured by notches provided at the crest of the weir (see A, B, C, D, E, F and J in table 1) resulting in parting the nappe. The effect of parting is shown in fig. 11, in which the front side of weir D is viewed under operating conditions. When results obtained at notched weirs are compared it is apparent that weirs discharging more than 4 separate jets yielded optimal aeration. Judging from data obtained at weirs J and E it may be concluded that the effect of the shape of the notch on aeration can safely be neglected. It was further found that partition could also be obtained by placing weirs having notches cut in them horizontally (see fig. 10 weirs G, H and I). These weirs have the advantage of offering no obstruction against floating matter in the stream. Regarding their influence on aeration data in table 1 indicate that weirs of this kind work as satisfactorily as the vertical type. This result suggests that the efficiency at notched weirs is merely obtained by the creation of splitted flows emerging from the weir or a modulation of the nappe in such a way as to distribute the water unevenly over the width of the weir. Owing to the notches the flows will be congested and issued as jets which will undergo a natural shaping during the free fall. With respect to shaping it is noted that jets will converge during the free fall as a consequence of the gravitational force causing the velocity of the water to increase. Next to this, nappes having an oblique cross-section tend to contract due to surface tension. Both actions have a similar effect and is was perceived that any of the jets tended to a more or less circular cross-section. Further investigations regarding the influence of the height of the weir concern weirs B, C, D, E, F, G and M.

TABLE 1 - *The aeration capacity as a function of weir configuration.*

Height of weirs: 0.9 m
Depth of receiving basin: 0.6 m
Rate of flow: 40 $m^3.hr^{-1}.m^{-1}$

Type of weir	A	B	C	D	E	F	G	H	I	J	K	L	M
Aeration capacity c_o in p p m O_2	4.4	5.25	5.6	5.7	5.6	5.45	5.5	4.9	4.0	5.4	2.5	2.4	3.5

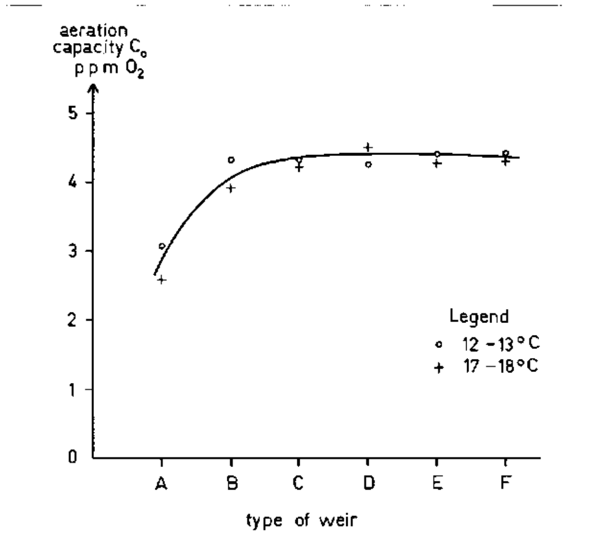
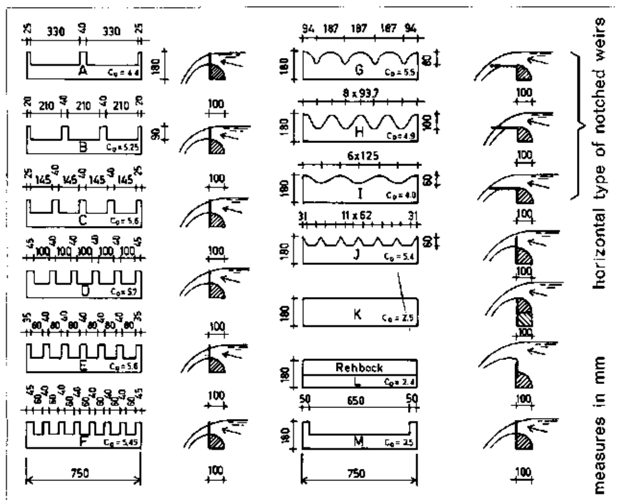


Fig. 9 - Effect of temperature on the aeration capacity at different types of weirs measured at a weir height of 0.65 m, a flow rate of 40 $m^3.hr^{-1}.m^{-1}$ and at 0.6 m depth of receiving basin.

Fig. 10 - Weir configurations.



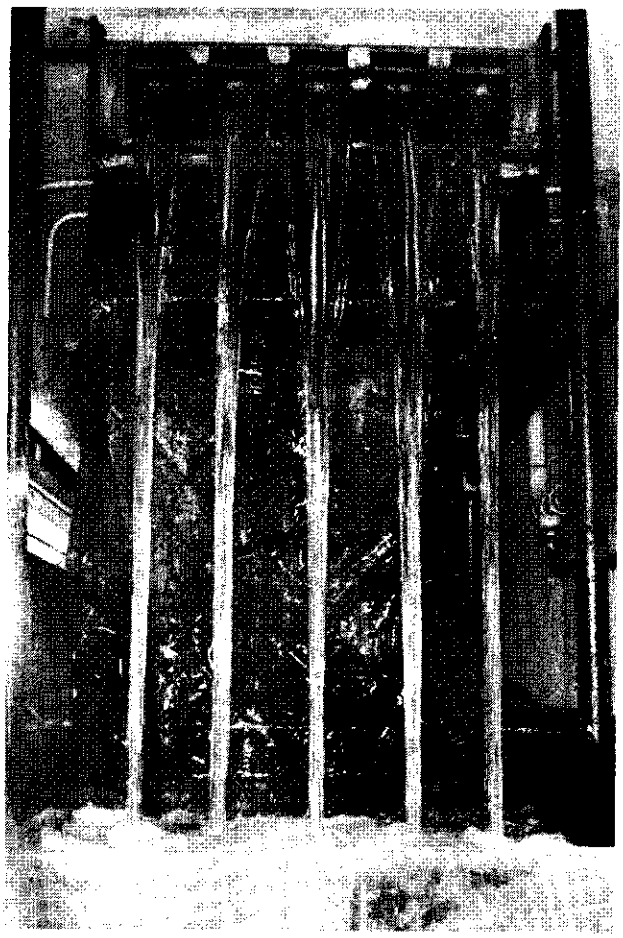


Fig. 11 - View of the front side of weir D under operating conditions.

3.3. *Height of the weir*

The precise influence of height on the aeration efficiency is still unknown. Barrett et al [16] have reported about aeration studies under natural conditions in which they arrived at an empirical relationship between the height of the weir and the deficit ratio. For lack of knowledge of the aeration mechanism the aeration capacity advanced in this connection is likely to be considered as an alternative, whilst the relationship proposed herein must be empirical too. In spite of the different weir configurations the height h will result in a velocity v of the water which may be solved from Torricelli's theorem:

$$v = \sqrt{2gh} \qquad (3)$$

It is reasonable to suppose that the height will affect the aeration capacity so far as the velocity of the jet is concerned, the more so as it has been shown by Shirley that bigger velocities will cause more air to be introduced relative to the rate of liquid flow. Experiments have been carried out to determine the aeration capacity at different weir configurations over a range of 1.6 m. From results obtained in the investigation on weir C at a flow rate of 40 $m^3.hr^{-1}.m^{-1}$, for instance, it appeared that c_0 increases with increasing height of the weir (see fig. 8). Collected data regarding c_0 at weirs M, B and C reveal that it is true of each of the systems (see fig. 12), whereas the plottings also substantiate the effect of parting being valid over the total range of weir height. It may be seen that an improvement of about 80 per cent was obtained at a height of 0.9 m in changing weir M for weir C.

It has been mentioned elsewhere in this report that at 0.9 m height an optimal result was obtained at weirs discharging more than 4 jets. In view of the shape of the jet being developed gradually over the height of the weir it is conceivable that the optimal aeration efficiency, as a function of weir configuration, will be affected by the height. This is illustrated in fig. 13 showing the combined effect of weir configuration and weir height. It is clear from this figure that at the smallest height an optimal result is achieved only at the maximum number of jets

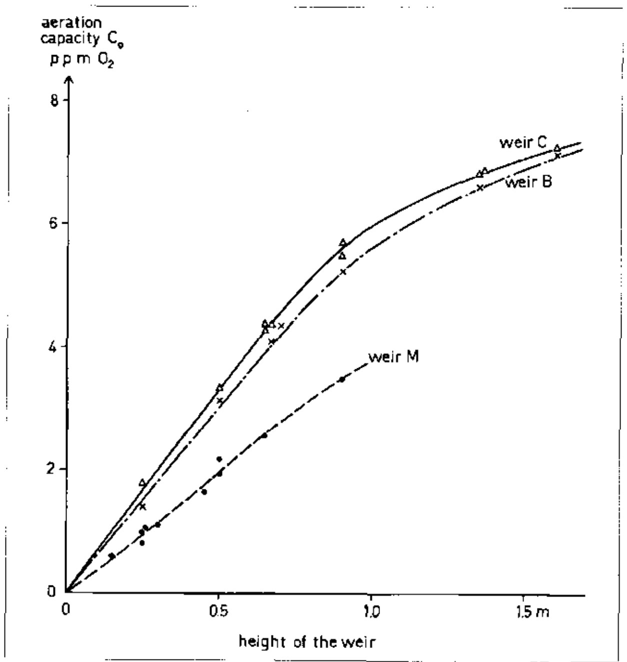
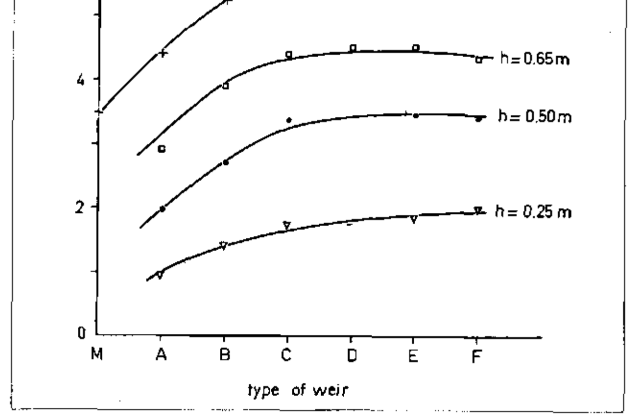


Fig. 12 - Effect of height on the aeration capacity at weirs M, B and C measured at a flow rate of 40 $m^3.hr^{-1}.m^{-1}$ and 0.6 m depth of receiving basin.

Fig. 13 - The combined effect of partition of the nappe and height of the weir on the aeration capacity at a flow rate of 40 $m^3.hr^{-1}.m^{-1}$ and 0.6 m depth of receiving basin.



practised in this study, whereas at the greatest height less parting will suffice. In order to decide on the influence of height on the aeration capacity at weirs it seems practicable to combine data obtained at weirs D, E and F, discharging more than 4 jets (see fig. 14). It may then be concluded that over a height of 0.7 m the aeration capacity is almost linearly proportional to the height in the event of parting the nappe. At a height of 0.7 to 0.8 m the aeration capacity will deviate abruptly to assume a further increase with increasing height, although at a lower rate.

3.4. *Flow rate*

The above mentioned weirs were also investigated over a flow range of 75 $m^3.hr^{-1}.m^{-1}$ to determine the influence of flow rate on the aeration capacity. Although abundant experimental data have been collected the presentation of results will be confined to those obtained at weirs which approved to be most efficient in aeration, viz. weirs D, E and F. From fig. 15 it appears that the aeration capacities at weir heights of 0.5 and 1.0 m decreased with increasing rate of flow. It is mentioned that other weirs showed a similar trend. The decrease due to the augmented flow rate is comparatively small, however, so that it would seem as if quite large quantities of water can be treated successfully. The experimental conditions did not allow more water to pass over the weir so that further research is required to investigate whether the trend as indicated in fig. 15 is likely to continue.

3.5. *Size of the receiving basin*

Results obtained so far all point to the importance of splitting the flow and the role of jets in weir aeration. When it is assumed that the velocity at which jets strike the surface of the receiving body of water may be solved from equation 3, the size of the jets at the various weir configurations and flow rates can be easily computed in the event of jets assuming a more or less circular cross-section. Under the above mentioned circumstances the diameter of jets was found to vary from 1.5 to 3.5 cm and when looking at fig. 6 it is apparent that these jets may penetrate the receiving water. As it has been argued that air bubbles are being dragged along with the flowing water it is reasonable to suppose that the allowance of depth may promote the contact time between air bubbles and water, thus affecting the aeration capacity of the weir system. This aspect was studied by allowing water to fall into 0.4 and 0.6 m depths of receiving basin. Results obtained at a height of 0.9 m and a flow rate of 40 $m^3.hr^{-1}.m^{-1}$ have been chosen to demonstrate the influence of depth on the aeration capacity (see fig. 16). From this figure it follows that weirs discharging more than 3 jets may safely be applied in combination with a receiving depth of 0.4 m, whilst the aeration capacity at weirs discharging less than 3 jets seems to be affected then. This result may be explained from fig. 6b, showing the velocity distribution over the depth at two different jet sizes. This figure suggests that jets having a greater diameter may penetrate deeper so that air bubbles being entrained may strike the bottom of the basin at this size of the jet. When it is assumed that deflection of the jet may cause air bubbles to escape from it easier, it is probable that greater jet diameters give rise to loss of contact time.

Experiments further revealed that at a height of 1.35 m, involving a greater velocity at which jets entered the receiving water, the aeration capacity at each of the weir systems was affected in the event of the smaller depth. It is a pity that there is little information available at the greatest flow rates practised in this study. Though it might seem as if weirs being efficient in aeration can successfully be combined with a receiving basin at a depth of 0.4 m over a range of weir height up to 0.9 m, a depth of 0.6 m for the time being would be preferred.

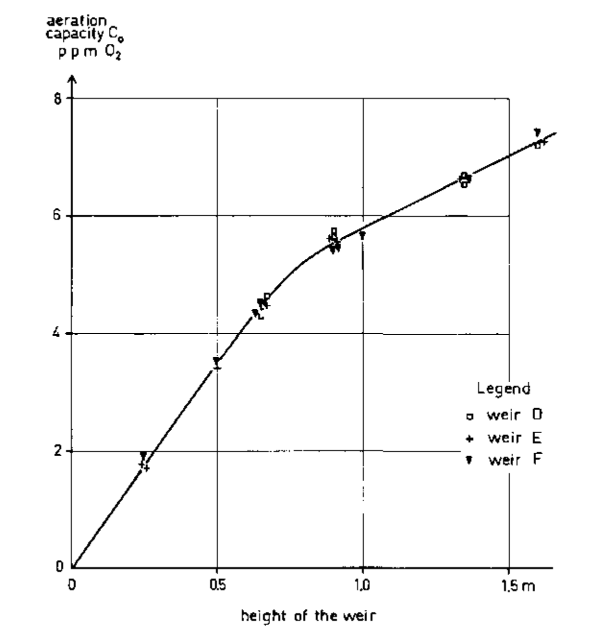
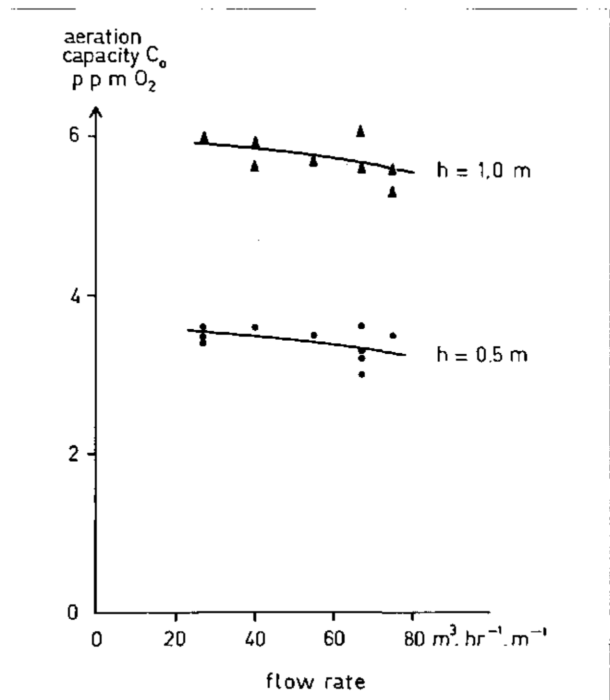


Fig. 14 - Effect of height on the aeration capacity at weirs D, E and F measured at a flow rate of 40 $m^3.hr^{-1}.m^{-1}$ and 0.6 m depth of receiving basin.

Fig. 15 - The effect of flow rate on the aeration capacity. (Weirs D, E, F).



4. Discussion

It is probable that air entrainment is not the only mechanism involved in weir aeration. Next to it the possibility of aeration during the free fall and the effect of splashing have to be considered. In fact, the influence due to falling was found to be insignificant, a result which has also been obtained by Gameson [6], whereas the effect of splashing in deep receiving basins as applied in the present study may safely be ignored. It must be noted that the effect of splashing, as it may be achieved by allowing water to fall into shallow basins, is beyond the scope of this study. This brings out the importance of air entrainment in our particular weir system justifying the ample attention being paid to it. The authors have put forward a concept to be relevant to weir aeration for the sake of conveyance and have not tried to find a basis for a physical model or whatsoever. Only the practical aspects are dealt with in this paper so that the reader will find little information regarding the physical processes involved.

Among the experimental data there are three interesting results. First of all there is the finding that the aeration capacity was increased considerably by parting the nappe discharging from the crest of the weir. An improvement of about 60 per cent was obtained at a height of 0.9 m by changing weir M, discharging one single jet, for weir D, discharging 4 jets (see table 1). The effect of parting is even more pronounced when comparing weir K, representing a sharp-crested weir of infinite length, with weir D yielding 160 per cent of improvement. This result is of primary importance as it enables sanitary engineers to achieve better aeration by structural modification at a very low cost. The nuisance arising from the presence of vertical notches may be eliminated by the application of the horizontal type of notched weir G, without influencing the aeration efficiency. This appears from a comparison of data obtained at this weir (see fig. 17) with data obtained at weirs issuing more than 4 jets (see fig. 14). Inspection of fig. 13 shows that in parting the nappe an optimal result may be obtained at 4 to 5 jets over a range of 0.5 to 1.6 m of weir height. This is equivalent to about 6 jets per meter weir crest. As a further partition did not add significantly to the aeration capacity it is reasonable to combine results obtained at more than 4 jets in the case of fig. 14. The second finding regards the influence of flow rate on the aeration. Fig. 15 provides evidence that the decrease in aeration capacity due to an augmented flow rate is comparatively small, substantiating Huisman's statement that weirs enable the treatment of relatively large quantities of water in a comparatively small area. The allowance to be made for proper treatment of water deficient in dissolved oxygen at a rate of 75 $m^3.hr^{-1}.m^{-1}$ may now be computed on the basis of the experimental data and in the event of a single fall. It has been found in this study that the length of the receiving basin may safely be reduced to 0.5 m without influencing the aeration capacity. So that in case of a length of 0.5 m to be chosen for the weir chamber and 0.5 m to be provided for supply and discharge of the water the total spacing would come to 20 m^2 per 1000 $m^3.hr^{-1}$ capacity. Last but not least comes the almost direct proportionality found to be valid between the aeration capacity and the height of the weir. Moreover it was found that the constant of proportionality decreased abruptly irrespective of the type of weir being practised when the height was within a range of 0.7 to 0.8 m (see fig. 12, 14 and 17). In this respect it is pointed out that engineers somehow prone to advocate step weirs should be cautious. A better efficiency generally claimed to warrant their application has become questionable, especially within a height range up to about 0.7 m, as for the raise of the dissolved oxygen content the effect of a second fall will be smaller. Anyhow, this question needs further study and in a following paper the authors will discuss this aspect more elaborately.

From the physical point of view it is remarkable that at a particular height the aeration capacity is almost

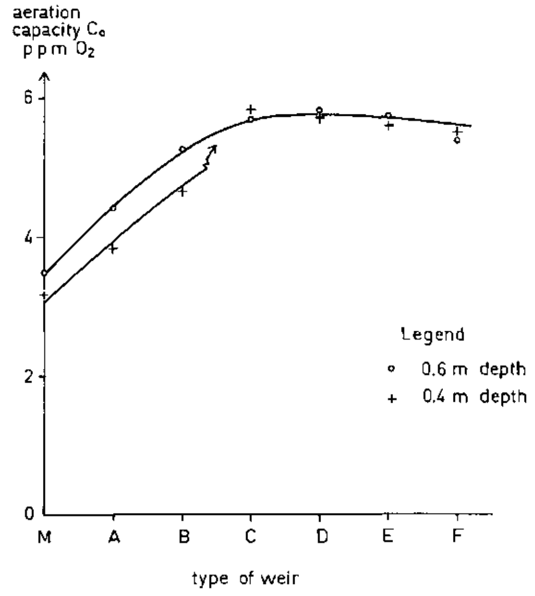
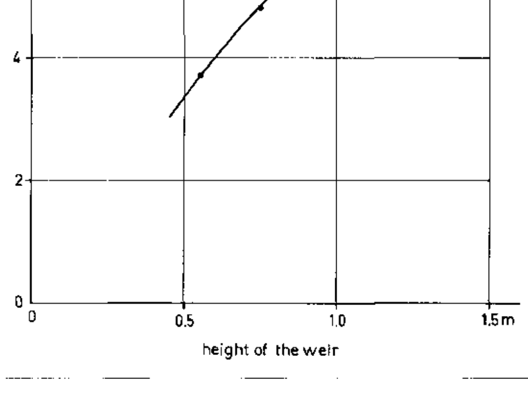


Fig. 16 - Effect of depth of the receiving basin on the aeration capacity at different weirs measured at a weir height of 0.90 m and at a flow rate of 40 $m^3.hr^{-1}.m^{-1}$.

Fig. 17 - Effect of height on the aeration capacity at weir G measured at a flow rate of 40 $m^3.hr^{-1}.m^{-1}$ and 0.6 m depth of receiving basin.



constant over the total range of flow rate Q and at the different weirs, providing adequate splitting of the flow is provided and enough height is available to allow jets to obtain a more or less circular cross-section. Choosing the height h of the weir constant so that the jet velocity v at the location of entrance into the receiving basin, according to equation 3, may be assumed to be constant it would follow from the above mentioned results that the aeration capacity is independent on the diameter of the jet. When n jets are provided the jet diameter d can be computed from:

$$d = \sqrt{\frac{4}{\pi} \cdot \frac{Q}{n} \cdot \frac{1}{v}} \qquad (4)$$

It has previously been noted that Shirley's data, regarding the quantities of air being entrained, suggest that the ratio of air to liquid flows only depends on the velocity of the jet. It has been argued that the ratio is probably constant at the various diameters and at a given velocity. This argument is partly based on our own results and partly on the assumption that the aeration capacity and the quantity of air being entrained are likely to be related. From an inspection of fig. 3 it appears that the ratio r deviates abruptly at a jet velocity of about 4 $m.s^{-1}$, whereas the aeration capacity reveals this tendency at a height of 0.7 to 0.8 m, being equivalent to a jet velocity at the location of entrance of about 3.7 to 4.0 $m.s^{-1}$. This is in support of the above mentioned concept, in spite of the widely differing circumstances. In fact, Shirley issued jets at a distance of 4 to 6 jet-diameters from the location of entrance. It is reasonable to suppose that air being entrained is flowing through an annular space in the atmosphere surrounding the jet. This annular space contains either the total air boundary layer or only part of it. Due to viscosity the layer adhering to the jet and the liquid jet itself will travel with equal velocities until both will submerge. If air dragged along with the jet during its free fall would be entrained completely, the effective thickness of the air boundary layer comes into play. The thickness δ, representing the amount of air being supplied by the jet to the receiving body of water, may be deduced from results obtained by Shirley. When it is assumed that air is flowing at an average velocity v′, the ratio r of air to liquid flows may be expressed by:

$$r = \frac{v' \cdot \pi \cdot d \cdot \delta}{v \cdot \frac{1}{4} \pi d^2} = 4 \cdot \frac{v'}{v} \cdot \frac{\delta}{d} \qquad (5)$$

When it is further assumed that v′ is related to v and not related to d, it may be inferred that the thickness δ, being equivalent to the quantity of air entrained, is directly proportional to the diameter of the jet. The variation of δ with d is not understood, however, as the effective boundary layer thickness does not depend on the size of the jet [17]. It may thus be concluded that, in spite of the drag of air being relevant to air entrainment, δ does not bear any relationship to the thickness of the boundary layer. Further investigations are required to elucidate the mechanism of air entrainment.

As the air being entrained passes through a zone in which turbulent mixing prevails it may be expected that the rate of oxygen absorption is high. From a combination of results obtained by Shirley and the present authors the absorption efficiency in oxygen-free water, expressed as the aeration capacity per unit weight of oxygen supplied, appears to be rather great as will be shown now. At a height of 0.7 m, for example, the aeration capacity taken from fig. 14 will come to 4.7 g of oxygen per m^3 of water supplied to the weir. This height is equivalent to a jet velocity of about 3.7 $m.s^{-1}$, so that the quantity of air being entrained per m^3 of water supplied will come to about 0.045 m^3 according to fig. 3. When it is assumed that 1 m^3 of air contains 280 g of oxygen the supply will come to:

$280 \times 0.045 = 12.6$ g of oxygen per m^3 of water supplied.

Consequently the absorption efficiency in oxygen-free water amounts to:

$$\frac{4.7}{12.6} \times 100 = 38 \text{ per cent}$$

being a value which is unique in literature. It may be concluded that weirs provide an efficient aeration and it would seem as if full scope be given to the jet by allowing it to penetrate the receiving basin. Our results indicate that by providing 0.6 m of water depth this object will probably be achieved. The aeration efficiency, expressed in terms of net energy is given by:

$$\frac{3600}{9.81} \cdot \frac{c_0}{h} \text{ kg of oxygen per net kWh}$$

where c_0 is the aeration capacity in $kg.m^{-3}$ and h is the weir height in m. As the aeration capacity up to 0.7 m is almost doubled when twice as much height is applied it may be seen that the efficiency over this range is almost independent on the height of the weir. At weirs D, E and F, which approved to be most successful in aeration the efficiency was found to be about 2.5 kg of oxygen per net kWh.

Would it be possible to improve the aeration efficiency any further? This is an interesting question which the authors have tried to answer being conscious of results obtained by Shirley. The latter has found that a decrease of the angle of inclination of the jet resulted in the entrainment of greater quantities of air. Our attempt concerned a system in which weir H was combined with a spillway upstream from the weir as to obtain flow in the rapid state. As a result of this the deflection of the jets discharged from the weir was affected assuming a longer trajectory and striking the water at a smaller angle. It was found, however, that the increase in aeration capacity was offset by the additional head to be provided at the spillway. It may finally be asked why not aeration by jets issued from nozzles should be advocated? Though less flexible such a system would probably require a minimum of spacing.

5. Conclusions

From the study of an experimental weir system with a single free fall it appeared that:

5.1. the aeration capacity may be applied as an absolute measure of the raise of dissolved oxygen effected by a weir. It has been argued that it is also a convenient measure;

5.2. the aeration capacity is promoted by parting the nappe discharging from the crest of the weir. At the lower range of weir height up to 0.4 m an optimal result was obtained by parting into 10 jets per m weir crest. At a greater height less parting may be provided, the minimum coming up to 6 jets per m at heights in excess of 0.65 m;

5.3. due to the relatively small decrease in aeration capacity experienced in the augmentation of flow rate a capacity of 75 $m^3.hr^{-1}.m^{-1}$ seems practicable;

5.4. up to a value of 0.7 m the aeration capacity is almost linearly proportional to the height of the weir. As for the raise of the dissolved oxygen content the effect of a second fall will be inferior in the event of a step weir. This result suggests that in the practice of ground-water treatment step weirs would need to be revaluated;

5.5. oxygen is absorbed from the air being entrained due to the action of the jet. Full scope be given to the jet by providing 0.6 m of water depth in the receiving basin;

5.6. on the basis of results obtained elsewhere and at Delft it is shown that weirs provide efficient aeration. As much as 38 per cent of absorption efficiency in oxygen-free water may be obtained. The maximum aeration efficiency, expressed in terms of net energy expended, was found to be 2.5 kg of oxygen per net kWh.

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