

# **Cyclonic circulation created by water jets in reservoirs allowing the release of fine sediments through intakes**

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## **ABSTRACT**

The release of sediment laden water through power intakes and turbines is a promising possibility to manage the long term problem of the sedimentation process in reservoirs. In order to get the suspended sediments entrained into the power intake, they need to be in suspension right in front of the water intake. Therefore an upward flow to lift the sediments and to maintain them in suspension is required. The present research study provides attractive methods which allow these processes using a minimum of external energy by making use of the affluxes of water transfer tunnels feeding the reservoir. The water of the transfer tunnels is caught and introduced into jet nozzles fixed at a definite position in the reservoir close to the power intake.

Physical laboratory test configurations of such water jets creating a cyclonic circulation show that the induced flow velocities are strong enough to transport fine sediments to the required level in order to be drawn into the water intake. A sensitivity analysis regarding the jet Froude number has been performed in order to evaluate which jet diameter and jet velocity give the optimal combination with respect to the suspended sediment release.

## **PROBLEMATIC OF THE RESERVOIR SEDIMENTATION**

In most natural river reaches sediment inflow and outflow are approximately balanced. Dam construction dramatically alters this balance creating a reservoir characterized by extremely low flow velocities and efficient sediment trapping. The continuity of sediment transport is interrupted and the sediments are captured in the reservoir in front of the dam. As the accumulating sediments successively reduce the water storage capacity, at long-term the reservoir operates only at reduced functional efficiency. Declining storage volume reduces and eventually eliminates the capacity for flow regulation and therefore all water supply, energy and flood control benefits. This process can even lead to a perturbation of the water intake for power generation. Depending on the degree of sediment accumulation, the outlet works may be clogged by the sediments. A clogged bottom outlet device is also a severe security problem.

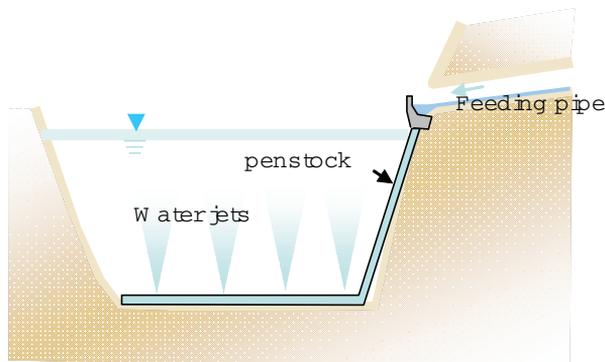
Until today there have been several methods practised to prevent the sedimentation problem in reservoirs. Nevertheless, most of them are not considered to be sustainable (Jenzer et al. 2008).

## SCOPE OF THE PRESENT STUDY

As mentioned above, the balance between sediment inflow and outflow of a natural river is altered by dam construction. Therefore, the most efficient method consists in nearly restoring this balance by creating a sediment transfer through the reservoir. Thus, the concept of the study focuses on a transfer of fine sediment through the headrace tunnel and the turbines in the case of deep reservoirs.

To entrain the sediments into the headrace tunnel, they have to be put in suspension in front of the water intake. Therefore, a way to maintain or to get the sediments in suspension has to be found.

The present study focuses on a rotational flow creating the desired uplift movement and sediment entrainment. Depending on the available water head and the discharge, rotational and upward flow can be induced by feeding pipes coming from water transfer tunnels. The momentum fluxes of these water transfer tunnels, introduced by a pipe system into jets (Figure 1), can be used to create an artificial turbulence, if arranged in an adequate configuration.



**Figure 1. Schematic view of the water jets supplied by the feeding pipe coming from water transfer tunnels**

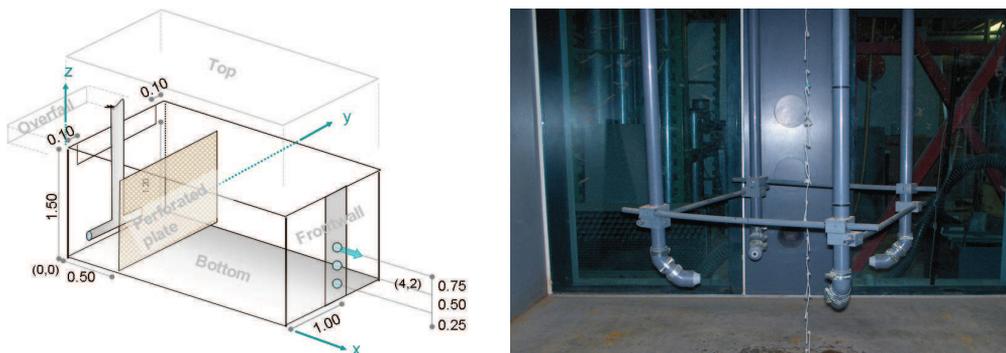
**Limitation.** Because of decreasing flow velocities when the afflux is flowing into a reservoir, a grain sorting process along the thalweg occurs such that close to the dam the deposition of the finest particles takes place. That means that the bigger a reservoir is the smaller is the grain size spectrum and the finer are the sediments encountered in front of the dam (70 to 90 % in smaller and 90 to 100 % in bigger reservoirs consist usually of finest grains in the range of clay and silt). The finer the sediments are the easier is the production of uplift entrainment forces, considering non cohesive material. Therefore, the present study is focused on big reservoirs where in front of the dam the exclusivity of very fine sediments is guaranteed.

## EXPERIMENTAL SET-UP

The details of the experimental set-up used in the current study is described in Jenzer (2009), a brief summary is given below.

In the physical experiments a suspension generating system consisting on four water jets acting on the water volume in front of the water intake is tested. Since it is assumed that the influence on the flow of such a system is locally limited, the physical model is reduced to the reservoir section in front of the dam. The experimental model is an elongated basin in a cuboid form, with a total basin length of 4 m and a width of 1.97 m. The basin height is 1.50 m. The front wall of the basin is considered to represent the dam, and the two lateral vertical walls confine the reservoir volume. In case of a locally limited circulation in front of the dam, the elongated basin form guarantees with its water body in the upper part a boundary condition as it exists in nature.

A scale factor of 1:50 has been adopted.



**Figure 2 left: Schematic view of the physical model, right: a configuration with the four stiff sanitary pipes, the jets and the water intake in the background.**

The water intake is integrated in the vertical axis of the front wall, and its elevation can be varied between 0.25, 0.50 and 0.75 m above the basin bottom (Figure 2 left).

A 50.8 mm (2 inches) diameter pipe connects the water intake to an energy dissipating basin, where the flow rate is monitored and controlled with a thin 30° angle V-notched weir plate. Turbidity of the out flowing water is measured in the dissipating basin.

The feeders are reproduced by rigid sanitary pipes (Figure 2 right), each controlled by an individual rotameter. The nozzles are fixed at their down end piece. The jet angle can be freely varied. For afflux simulation, tap water is used. In order to maintain a constant water level during the experiments, the water volume flowing out through the water intake equalizes the total jet discharge.

In the present study ground walnut shell powder has been chosen for the physical experiments. This material is almost cohesionless, light weight (specific density is  $\rho_s = 1480 \text{ kg/m}^3$ ) and homogeneous. The particle size distribution is relatively narrow and the settling velocity is small (according to Stokes' theory:

approx. 0.8 mm/s in water at 15°C). The particles have a median diameter of  $d_m = d_{60} = 0.06$  mm.

Three flat irrigation pipes with tiny holes on their upper surface, lying equally distanced on the basin bottom, give the possibility to let rise pressurized air through these holes provoking a whirling pool. This allows setting up a homogenous sediment-water mixture providing the initial conditions of the experiments.

**Experimental procedure.** The experiment starts as soon as a homogeneous mixture is reached in the whole basin. The homogenised sediment-water mixture represents the simplified situation existing in the reservoir close to the dam, right before turbidity current starts settling its sediments after having reached the dam area.

**Measurements.** The out flowing turbidity is measured continuously. Turbidity on the horizontal axis of the water intake and on the rotational (vertical) axis of the jets configuration is measured punctually and periodically. Flow velocity measurements are performed with a rack of 5 x 5 UVP-sensors in the area of the jets arrangement and close to the water intake. They provide on the one hand horizontal 2D flow patterns on four different levels (10, 30, 50 and 70 cm from the bottom) covering a plane of 2 x 2 m<sup>2</sup>. On the other hand vertical 2D flow patterns on the longitudinal middle axis corresponding to the water intake axis, as well as on the transversal axis, crossing the rotational axis are recorded.

**Basic experiments.** The basic experiments, their results, findings and consequences drawn are described in Jenzer Althaus et al. (2009).

**Jet experiments.** As soon as the water level of 1.20 m and the homogeneity of the sediment concentration are achieved, the water jets and the measurements get started. The jet configuration consists of four water jets with equivalent nozzle diameter and jet velocity arranged in a circle lying on a horizontal plane. Each jet is pointing horizontally in a 90°-angle to the position, where its neighboring jet passes from the transition phase to the fully developed jet (Figure 3). In this way a rotational flow is introduced, sucking water vertically from below and from above, and spreading water horizontally out of the jets circle.

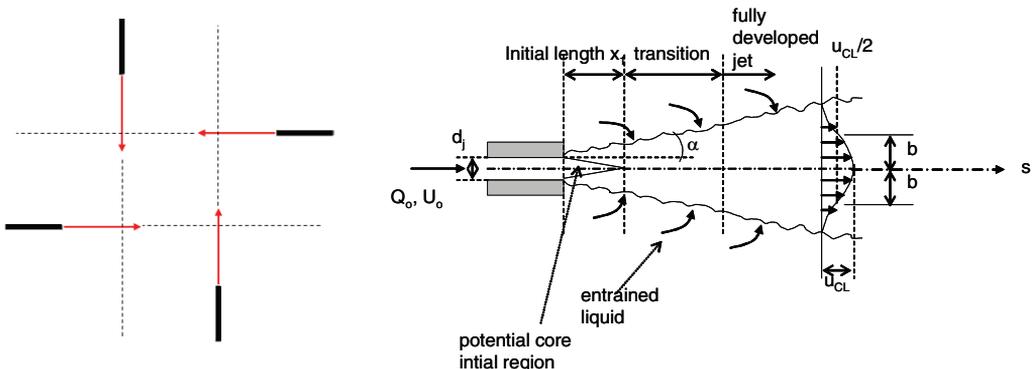


Figure 3 Left: Top view of a jet configuration with in black the nozzles and in red the middle axis of a starting jet's trajectory in an idealized case of no influence of the neighboring jets. Right: submerged turbulent jet.

**Parameter study.** The parameters influencing the efficiency of the jets arrangement are: jet velocity, jet diameter, jet Froude Number, and the following geometrical parameters (Figure 4): *s*, *H*, *D*, and *B*. A sensitivity analysis studying the influence of each mentioned parameter is effectuated.

- s* the horizontal distance between two neighboring jets
- H* the vertical distance of the jets plane to the bottom
- D* the horizontal distance from the rotational axis to the front wall
- B* the width of the basin characterizing one of the boundary conditions

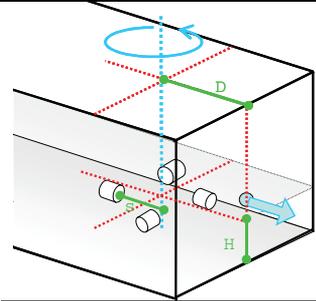


Figure 4. Geometrical parameters

### JET FROUDE NUMBER AS AN INDICATOR OF EFFICIENCY

It follows from the analysis of the turbidity measurements at the power intake, that the jet Froude number, defined in Equation 1, has an influence on the efficiency of the jet's suspension method: the higher the jet Froude number, the more sediment is evacuated. This observation arises from the comparison of the normalized instantaneous sediment concentration at the power intake in function of time (Figure 5) and from the normalized cumulated sediment output through the water intake in function of time (Figure 6) measured in experiments each with a different jet Froude number. From the experiments can be drawn, that the normalized instantaneous sediment concentration (defined in Equation 2) is linearly dependent on the jet Froude number, and that the normalized cumulated sediment output through the water intake (defined in Equation 3) is exponentially dependent on the jet Froude number.

Already Reville (1992), Fox and Gex (1956) and Lane and Rice (1982) express mixing time in chemical mixing processes effectuated in cylindrical tanks as a function of the jet Froude number. According to Jirka and Harleman (1979) we can expect recirculating cells for vertical axisymmetric jets for certain combinations of depth to jet-diameter ratio and jet Froude number.

$$Fr = \frac{v_{jet}}{\sqrt{g \cdot d_{jet}}} \tag{Equation 1}$$

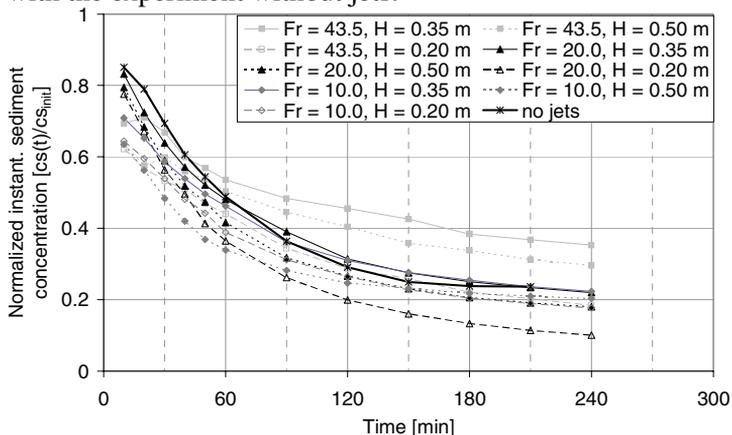
$$Cs = \frac{cs(t)}{cs_{init}} \tag{Equation 2}$$

$$P_{acc} = \frac{P_{acc}(t)}{cs_{init} \cdot d_{jet}^3} \tag{Equation 3}$$

As it can be observed in figure 5 and 6, the jet's plane level turns out to be a parameter influencing the efficiency of the method as well, even if its importance is less than the one of the jet Froude number. Among the three investigated levels (0.35 m with six different jet Froude numbers, 0.50 m and 0.20 m with 3 different jet Froude numbers), the most promising one lies on 0.35 m. This conclusion has been drawn without yet taking into account neither the influence of the power intake level nor the influence of the water level. From the observation of the flow pattern (see below), it follows, that the suction effect of the cyclonic circulation on the bottom of the basin should be highest, the lower the jet's plane is located. But, as the sediments need to be lifted up to the power intake level, the jet's level should be close to this as well. This explains why the primary as most favorable expected jet's plane level of 0.20 m doesn't perform as such.

In Figure 5, the "no jets"-line shows the normalized instantaneous sediment concentration evacuated through the water intake, in case of no jets. The evacuated discharge is compensated by a uniform current coming from the back wall of the basin. In case of no jets, concentration starts high, decreases rapidly and stagnates more or less on a normalized concentration in the range of 0.23 and 0.30.

**Long-term aspect.** Figure 2 in Jenzer Althaus et al. (2009) shows the long term basic experiment with no current. As described in the dedicated section, after 4 hours the temporal sediment concentration decrease is very low. That was the reason why the duration of the experiments with the jets was chosen to be 4 hours. Within this period, no significant changes in the curves describing the evacuated sediment concentration respectively the cumulated sediment output in function of time occur (Figure 5 and 6). Nevertheless, it is interesting to observe how these two parameters behave in this short time period. If a certain evacuated sediment concentration could be maintained over a longer time, the method would be very promising. Therefore, a long-term experiment needs to be performed, allowing a temporal extrapolation and a comparison with the experiment without jets.



**Figure 5. Normalized instantaneous sediment concentration in function of time. The dependency on the jet Froude number as well as the influence on the level of the jet's plane becomes visible. "no jets"-line: experiment with no jets, but with an evacuating discharge equivalent to the experiment with jets Froude number 10, the evacuated water compensated from the back wall.**

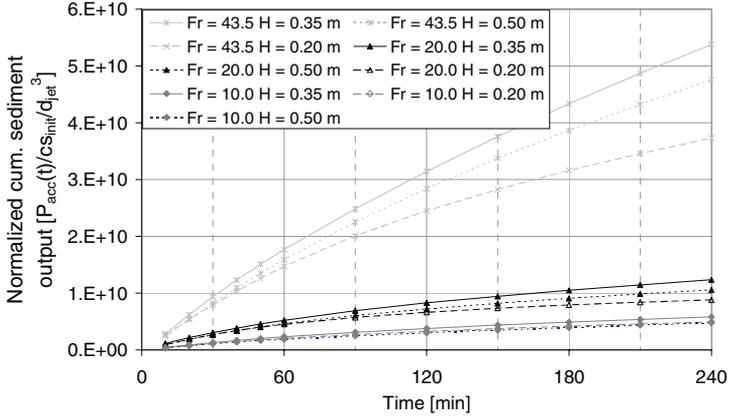


Figure 6. Normalized cumulated sediment output through the power intake in function of time. The dependency on the jet Froude Number and on the jet's plane level becomes visible.

The normalized cumulated sediment output  $S_{cum}$  is in an exponential relationship with the jet Froude number:

$$S_{cum} = a \cdot e^{bFr}$$

where the variables  $a$  and  $b$  are dependent on the jet's plane level and on time.

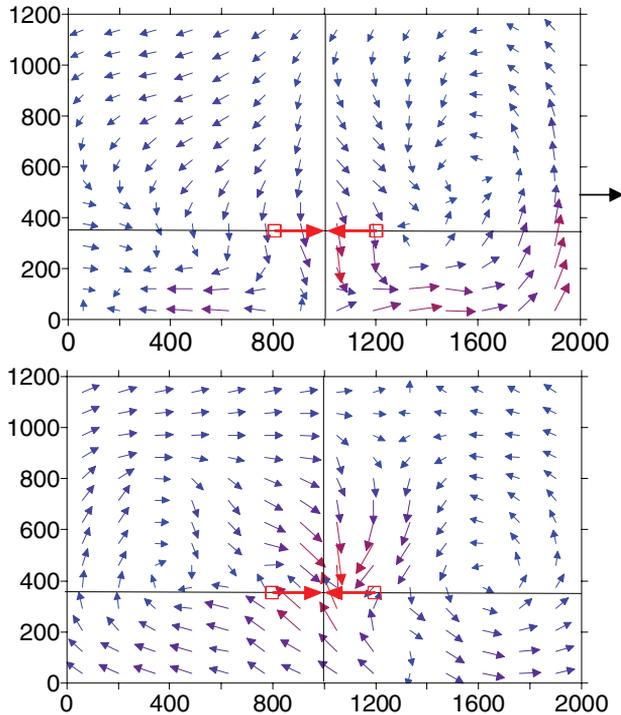


Figure 7. Above: Measured flow pattern in the longitudinal axis with the water intake at the right edge (level 500 mm, arrow). Below: Measured flow pattern in the transversal sense through the rotation axis of the jets. Units in mm. jet configuration with  $d = 8$  mm,  $v = 2.8$  m/s.

**Flow pattern analysis.** It can be observed that water is sucked vertically from the reservoir bottom up and from above down to the level of the jet's plane, from where the water is spread out horizontally (Figure 7). Because of its very complex 3-dimensional flow pattern, it is difficult to draw any conclusions explaining the findings respective to the efficiency of the jet Froude number.

## CONCLUSION

A new promising measure to evacuate fine sediments through the turbines out of a reservoir, consisting of a jet arrangement comprising four equivalent jets lying in a circle on a horizontal plane, is being developed. Herein, the jet Froude number appears to be an indicator of the efficiency regarding the evacuated sediment quantity. The performed experiments show, that the geometrical aspects of the jet's arrangement have an influence on the efficiency as well. Long-term observations will be performed to assess the persistence of the method during the settling process of the sediments. More parameters will be examined in order to optimize the measure as well.

The work done on different jet Froude numbers with jets lying on three different levels is a first step in developing a new measure to evacuate fine sediments out of the reservoir and therefore reducing reservoir sedimentation.

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