THE HYDRAULIC PERFORMANCE OF A VORTEX TUBE EJECTOR

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Abstract

The vortex tube silt extractor consists of a pipe, the crest of which has a slit and lies flush across the canal bed.
With minimal water loss, the bedload is extracted through the slit to a settling pond or a side canal back to the river, thus reducing or eliminating the bedload transported in the main canal. The resulting swirling flow phenomena is of complex nature and depends on several control parameters, as a result of which previous empirical design approaches have yielded conflicting guidelines.

By means of a simplified hydraulic system, the flow mechanism and energy in the structure can be determined.

Symbols used.

V = velocity at a distance y from wall

V_p = Potential flow velocity (not influenced by the wall)

V_0^* = Shear velocity

δ = Thickness of the turbulent boundary layer

K = von Karman's turbulence constant ($K \approx 0.4$)

k = Vortex intensity parameter

V_t = horizontal velocity component (X axis)

V_n = vertical velocity component (Y axis)

k_s = vortex parameter

w = angular velocity

r = radial distance measured from the pipe axis

V_R = axial velocity in the pipe.

1.0 Introduction:

The problems brought about by sediment transported in canals make the life of irrigation engineers difficult. Unwanted depositions reduce the widths of canals thereby reducing the conveyance capacity due to higher hydraulic losses. Seasonal cleaning up creates extra expenditure for the canal owners, besides unwanted depositions on irrigated farms. For hydropower plants, sands transported to the turbines can create huge machine losses. It is therefore recommendable to extract the sediments at the intake before they reach the canals. With the aid of modern intake design methods, [1] the amount of sediment reaching the canals can be reduced considerably although not totally. It is of interest therefore, that the sediment remaining in the canal be regulated before it reaches the power plants or irrigation farms. The extent of regulation depends on the final use of the water:

- for power plants - total removal is required
- for irrigation canals, deposition in the canal should be avoided.

For the latter case, a dynamic equilibrium of the sediment transported at any cross section should be strived for. In order to achieve the equilibrium situation, it may be necessary to remove the surplus sediment from the canal artificially, the exact amount depending on whether the canal is lined or unlined.

One of the earliest practised methods for removing surplus sediment from canals is by providing hydraulic structures. The structures are two fold:

- those which have to be stopped from time to time to allow for cleaning etc. and
- those which are hydraulically self cleaning when they are in operation

The vortex sediment ejector is one of the latter type. It has however not been very popular due to lack of enough knowledge on

its functioning principles and thus the cause for its frequent clogging.

With the aid of experimental results, the hydraulics of the principles of a vortex tube is described.

2.0 REMOVAL OF SEDIMENTS FROM CANALS

2.1 Sediment Transport.

The complex nature of transport of erodible sediments posses considerable difficulties in determining the movement of sediment particles in open channels.

The movement in open channels taken places in two major forms i.e near or on the bottom of the canal and in a suspended form.

While the former is referred to as bedload, the latter is termed suspended load. The movement of bedload depends very much on the discharge in the canal while the amount of suspended load depends on turbulence and several particle parameters. [2, 3, 4].

The position of particle at any moment - whether suspended or at the bed depends on the flow intensity and particle parameters especially the particle size. The removal of bedload is done through hydraulic structures while suspended load can only be removed by means of settling basins.

2.2 The vortex Tube Sediment Ejector.

2.2.1 Historical Development and Performance of the Tube

The recorded application of the vortex tube was an accidental result of a process, during the rehabilitation of the upper Jhelum canal in Pakistan around 1903. [5]

The canal had frequent silting problems especially in the rainy season who large volumes of sediments were washed into it.

A tunnel with holes protruding to the bottom of the canal removed most of the large particles, alleviating the silting problems. The same principle is applied today in constructing a vortex tube ejector; whereby a pipe with a slit on top is laid at an angle between 45° and 90° to the flow direction, the crown of the pipe lying flat with the canal bottom.

The upstream and downstream edges of the slit can lie at the same or different levels, (see fig. 1) The continuation of the pipe forms an open end of the tube which drains in a basin or into a smaller canal back to the river. The flow through the vortex tube can be regulated by means of a gate valve. By using the vortex but, up to 50% of the bedload transported in the canal can be removed while losing only 5 to 10 percent of the discharge from the canal.

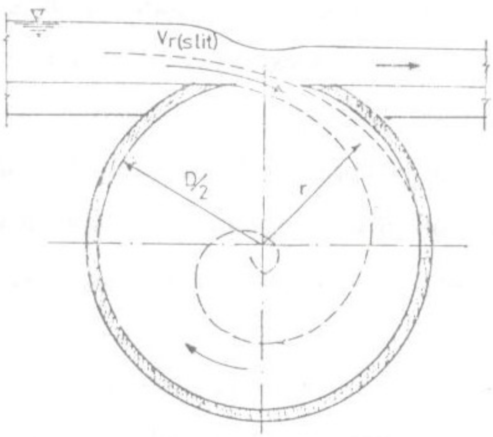

Fig. 1: A cross section through a vortex tube

Advantages of the vortex tube.

The major advantages of using the vortex tube are:

(i) easiness of construction. Neither complicated technology nor expensive equipment is required.

(ii) small amounts of water needed for its optimum operation.

(iii) does not hinder or interfere with the flow in the canal.

Performance of a Vortex Tube.

The water flowing close to the bottom of the canal directs the bedload into the tube through the slit. The entry creates a spiral motion (vortex) which holds the particles in suspension. Due to the head difference between the water levels in the canal the basin at the end of the tube, the swirling flow effect will be pushed in a lateral direction parallel to the pipe axis.

2.2.2 Functional problems of the vortex tube.

Like many other types of sediment ejector, the vortex tube is rated best at extracting bedload while exhibiting poorer performances as far as suspended load is concerned.

The major prerequisites for its good performance are:

- particles entering the slit should not be thrown out back into the canal.
- deposition and therefore clogging of the pipe should not occur.
- high removal of sediments with minimum loss of water from canal

Past experience had shown, that the no-deposition condition was difficult to achieve and thus jeopardised the popularization of the structure. [6], [7].

To solve the problem of deposition in the tube, a better understanding of the hydraulics of the flow was necessary. Experiments were carried out in the hydraulics laboratory [8]. where the flow was studied in a simplified model. The two phase flow phenomenon was reduced into two single phase phenomena and studied independently; i.e the flow of water only in the canal and tube as well as movement (transport) of particles in the tube. The first case included the entrance through the slit and the development of the vortex flow in the pipe including the velocity and pressure distribution.

3. EXPERIMENTS AND MEASUREMENTS

3.1 Experimental set up.

The laboratory experiments were carried out on plexiglass flume which had a downstream gate with the help of which the water level in the canal could be regulated. A slit across the bottom of the flume was joined to a pipe i.e. the vortex tube, which ended in a basin with a water level regulator. The flume was 0.50 m wide, 0.65 m deep with a length 7 m . The water pumps in the laboratory could supply up to 60 L/s.

Different diameter plexiglass pipes i.e. 50mm , 80mm and 100mm with slit openings of 10 mm, 15 mm 20mm were used at different angles $45^0 < O^\circ <, 90^\circ$ to the flow direction in the canal.

3.2 Instrumentation and Measurements.

Discharges were measured using an automatic electrical discharge measuring equipment (edm) as well as V-notch weirs.

The flow depth in the canal was determined by stationery manometers installed 40 cm apart on the bottom of the canal, with two at each cross section. The average value between the two is taken as depth at the cross-section. Ott-current meters were used for velocity measurement, while the pressures inside the plexiglass pipes were made by a combination of manometers and pitot tubes.

For measuring the velocity head in the radial direction (vortex effect) a special pitot tube was installed as shown in figure 2. The head difference between the pitot tube and the pressure manometer was taken as velocity head i.e. the kinetic energy in the radial flow.

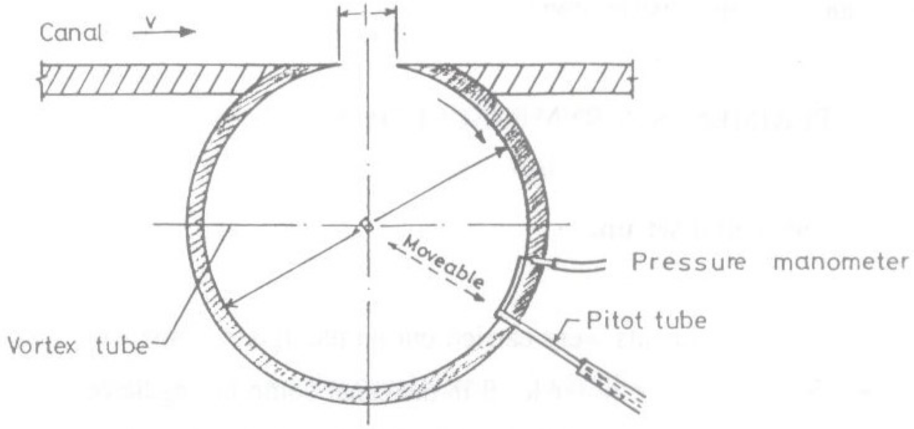

Fig. 2: Section though a Vortex Tube showing the pressure measuring instruments.

3.3 Parameters Varied

3.3.1 Geometrical Parameters

Four geometrical parameters namely, pipe diameter D, Pipe angle to canal flow direction Θ° slit width t and pipe length L were varied to study their effect on the vortex phenomenon. The parameters are summarized in Table 1.

3.3.2 Hydraulic Parameters.

The discharges in the canal Q_k, flow depth in the canal h_k as well as pipe flow Q_R were varied independently (see table 2).

Table 1: Varied Geometric Parameters

No.	Pipe Diameter D	Angle of Pipe to flow direction θ°	Slit width t	$\frac{t}{D}$	Pipe lengths L_R
	(mm)	(degrees)	(mm)	(-)	(m)
1.	100	90	20	0.20	0.90
2.	100	45	20	0.20	$0.90\sqrt{2}$
3.	100	45	15	0.15	$0.90\sqrt{2}$
4.	100	45	10	0,10	$0.90\sqrt{2}$
5.	80	90	12	0.15	0.90
6.	50	90	10	0.20	0.50
7.	50	90	10	0.20	0.90
8.	50	90	10	0.20	1.90

4.0 ANALYSIS OF THE RESULTS.

4.1 Flow in the canal.

The distribution of the flow velocity in an open channel is actually a three dimensional phenomena. In practice however, it can be approximated to a one dimensional analysis $V_k = f(h_k)$if the flow cross - section over the studied length remains constant, a condition satisfied in the above mentioned experimental set up.

The radial velocity in the tube (i.e. vortex effect) is very much influenced by the strength of the velocity at the canal bottom. The effective velocity at the canal bottom can be expressed through the vertical velocity distribution in the canal. Besides the empirical equations based on exponential laws, the logarithmic equation of PRANDTL and von KARMAN are commonly used in expressing the velocity distribution.

Table 2: Varied hydraulic parameters

Canal		Pipe Flow Q_R	Extraction rate: $E = Q_R/Q_n$
Q_k	h_k		
L/s	cm	L/s	%
20	6,32 - 7,17	3,0 - 4,4	12 - 22
25	7,12 - 8,12	3,0 - 4,8	12 - 19,2
30	6,97 - 7,92	3,0 - 5,0	10 - 16.7
40	10,42 - 11,12	3,0 - 5,0	7,5 - 12,5
45	10,32 - 11,62	3,0 - 5,0	6,7 - 11,1
50	11,62 - 12,50	3,0 - 5,0	6,0 - 10,0
55	12,12 - 13,07	3,0 - 5,0	5,5 - 9,1
60	12,67 - 13,87	3,0 - 6,3	5,0 - 10,5

PRANDTL theory expresses the velocity of a turbulent flow over a flat plate as

$$\frac{v_p - v}{v_{O*}} = -\frac{1}{\kappa} \ln \frac{y}{\delta} , \qquad \text{.......(1)}$$

where V_p = potential flow velocity
V = velocity at a distance y from wall
V_{o*} = shear velocity

Based on equation (1) and similarity principles the equation for velocity distribution in the canal can be given as:

$$\frac{v_p - v}{v_{o*}} = -\frac{1}{\kappa}\left[\sqrt{1 - \frac{y}{\delta}} + \ln\left(1 - \sqrt{1 - \frac{y}{\delta}}\right)\right] \qquad \text{..........(2)}$$

Where κ = von Karman's turbulence constant
δ = thickness of a turbulence boundary layer

The two equations differ only in the fact that different values of the bottom shear stress are applied. The ratio of the measurements of the velocities at 2mm and 40 mm above the canal bottom resulted

in a linear correlation as expected, showing that eqn. (2) can be used to express the velocity distribution with depth.

4.2 Flow in the Vortex Tube.

The inflowing water from the canal bottom through the slit creates a swirling effect (vortex) which extends the whole length of the tube. The swirl intensity can be expressed by a parameter which expresses the entrance velocity into two components in the axes x and y i.e.

$$k = V_o / V_n \qquad \text{..................(3a)}$$

where V_o = horizontal bottom velocity on channels bed
V_n = vertical component at the entrance
k_s = vortex parameter

The bottom horizontal velocity can be assumed to be linearly correlated to the average flow velocity $\bar{V}$ in the canal and therefore $V_t = V_{bottom} \approx \text{constant} \cdot \bar{V}$

$$k = V_t / V_n \approxeq \text{constant}\ \bar{V} / V_n \tag{3b}$$

The circulating flow in the pipe can be expressed by a modified swirl (vortex) parameter.

$$k_s = V / V_n \qquad \text{..........(4)}$$

where V = average flow velocity in the canal.

The easily determined vortex parameter ks differs from the initial vortex intensity parameter only by a constant factor. The swirl flow in the tube can therefore be studied knowing the average flow in the canal V and the swirl parameter k_s.

4.3 Experimental Results.

From the measurements, it is shown, that the vortex (swirl flow) created by the inflowing water influences the flow pattern in the tube. (see also fig. 3)

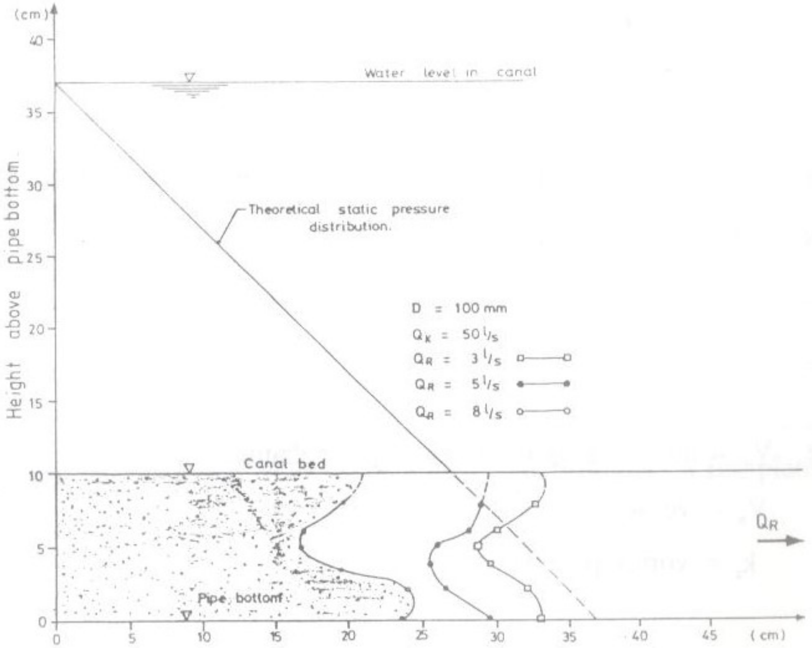

Fig. 3: Pressure distribution at a pipe cross section.

The flow is a is a forced vortex type where tangential velocity is a function of the angular velocity w.

$$V_t = w.r \qquad ....(5)$$

The vortex flows can be explained by the Rankine theory which is valid for a combined vortex with a circulating boundary. The circulating boundary creates the so called "free vortex" zone with the inner core forming the forced vortex. [9]

For the free vortex the tangential velocity can be expressed as

$$V_t = Z / r \qquad ....(6)$$

where Z = Circulation constant and the Circulation as used in the combined Rankine vortex can be given as:

$$\Gamma = 2 \pi r v_t$$

and substituting equation (6) $\Gamma = 2 \pi Z$

For the forced vortex, the Circulation

$$\Gamma = 2 \pi r^2 \omega \qquad ....(7)$$

5. DISCUSSIONS AND CONCLUSIONS

5.1 Discussion of the Results.

The results in eqn.(7) and the measurements as shown in fig. 3 show, that the flow in the vortex tube can be simplified and expressed using the forced vortex equations.

JULIEN studied similar flows in a vertical axis. [10]

Combining the results of the study and transposing Juliens results on a horizontal axis, the pressure distribution in a forced vortex can be shown to have a minimum of underpressure, (maximum of absolute pressure) in the pipe axis.(fig. 3.) The tangential velocity varies with radius measured from this axis.

The pressure slope between the axis and the pipe wall results in a centrifugal acceleration which can be expressed as:

$$\frac{1}{\rho_w}\frac{\partial p}{\partial r} = \frac{v_t^2}{r} = \omega^2 r \qquad \text{..................(8)}$$

If we denote the pressure in the pipe axis as P_o ($r = 0$) and neglecting friction, an integration of eqn. (8) gives:

$$p - p_o = \rho_w \cdot \omega^2 \cdot \frac{r^2}{2} = \rho_w \cdot \frac{v_t^2}{2} \qquad \text{.................(9)}$$

where $\rho_w \cdot v_t^2/2$ is the expression for the kinetic Energy.

Considering a cross-section of the pipe, the total kinetic energy per unit length of the pipe can be given:

$$E_{kin} = \int_{r=0}^{r=D/2} \rho_w \frac{\omega^2 r^2}{2} \cdot 2\pi r dr \qquad \text{................(10)}$$

$$= \rho_w \cdot \frac{\left(\Gamma^2\right)_{r=D/2}}{16\pi}$$

In practice however, the value of the kinetic energy at a cross section is less than given in eqn. (10) because it is difficult to have a pure forced vortex flow in the pipe. The lateral axial flow superimposes the swirl flow. This reduces the intensity of the flow as shown in fig. 4.

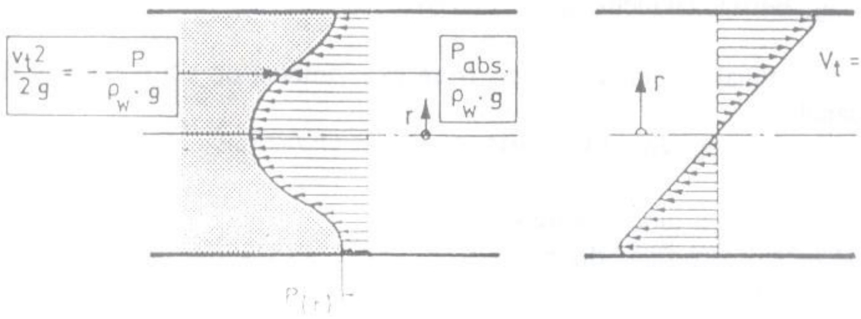

Fig. 4. Absolute pressure and velocity distribution at a cross-section.

BAKER et al in [11] showed that the swirl effect decays exponentially as a function of the flow Reynolds number Re and the initial impulse I_D the latter can be expressed as:

$$I_A = \rho_W \pi v_R^2 \frac{D^2}{4}$$

5.2 Conclusions.

The hydraulics of the flow in a vortex tube can be simplified and expressed in terms of the kinetic energy in the flow. Knowing the energy in the flow at a given pipe section enables the determination of the total energy in a flow, and hence the amount of material to be transported when the flow is used as a carrier medium, especially in conveying industrial ore (hydro transport) or in a sediment ejector in canals.

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