

Evaluation of the Flow Characteristics in the Intake Structure and Pump Sumps Using Physical Model

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Abstract

A physical model was built at an undistorted scale of 1:8.724 tested the original design of the circulating cooling water flows to onshore intake structure and to test the flows to an inland pump house intake through four pipes. The capacity of origin water intake including circular and service pumps is 52.178 m³/s. The model was built and operated in accordance with Froude-number similitude. The aim of the model study is to test the design of the pump intake and to investigate any modifications on the design which may be needed to enhance the efficiency of the pump intake structure. Also some sensitivity tests were done at several water levels of the pump house. The model was operated at high, minimum water conditions and at different operation modes. Physical model is expected to help in evaluating the operation, to aid in design or modifying of the intake structure and to test any recommended modifications, if needed.

The results of the model test is used to determine if the initial design of the pump sump structure would be susceptible to surface and sub-surface vortices, pre-swirl entering pumps and excessive fluctuation in the velocities at the pump bell throat according to Hydraulic Institute(HI) specifications

The results of the tests showed that the rotations of the roto-meters are within the allowable limits specified by the HI criteria in all operation modes. No vortices more than type 2 was observed near the bell mouths of the circular and service water pumps at minimum water level conditions. In the high water level conditions, it was observed that vortices of type 3 or 4 appeared upstream of the curtain wall and move downstream near the bell mouth of circular water pumps. Those vortices disappeared after modifying the top of the baffle wall from elevation of minimum water to high water level. It was found that vortex type 6 was appeared when submergence above suction bell inside the pump house was about 1.5 times the pump column diameter, 2.2 of the pump impeller throat diameter and 1.05 of the suction bell diameter. Continuous type 5 or 6 surface vortices were observed upstream of all four intake pipe inlets for minimum water level cases and the vortices disappeared by closing the flow entrance between the intake pipe inlet cap slab and the stop logs slots. The velocity measurements taken inside the pump suction pipes showed that the flow velocity at the impeller location is uniform in magnitude, within $\pm 10\%$ of the mean velocity.

Key words: Intake, Vortices, Pump sump, Flow velocity, Swirl, Pre-rotation, Baffle Columns, Curtain wall.

1. INTRODUCTION

The intake's primary function is to provide the required flow to the pump. This flow should be uniform with a minimum of rotational wakes, free of harmful debris, has enough depth to prevent the formation of free surface vortices, and has an approach speed that avoids flow separation at boundaries. The design objective from a cost perspective is to keep the depth and footprint size of this substructure to the minimum necessary satisfying the hydraulic criteria, as mentioned in the hydraulic institute standard [1].

Physical sump models are frequently required to assist in the design of the pump intake structure of cooling-water pumping stations and to test any proposed modifications, if any. The problems inherent in this type of structures cannot be handled analytically or from previous experience. Numerous pump problems can be encountered by model tests such as: cavitations, vibrations, bearings and impellers damage.

The intake structure should be designed to allow the pumps to achieve their optimum hydraulic performance for all operating conditions. A good design ensures that the adverse flow phenomena are within the limits outlined in ANSI/HI Section 9.8.5.6 [1]. The hydraulic conditions that can adversely affect the pump performance and should not be present to an excessive degree are:

- Submerged vortices cause rapid changes in the local pressure on the pump propeller as a vortex core is ingested. This will result in severe vibration and cavitations.
- Free-surface vortices, also will cause rapid changes in the local pressure on the pump propeller as the vortex core is ingested, resulting in reduction of the pump discharge and a loss of efficiency. This, and any other air ingestion, can cause fluctuations of impeller load which result in noise and vibration which may lead to physical damage.
- Swirl of flow entering the pump exists if the tangential component of velocity is present in addition to the axial component. Therefore, swirl in the pump intake can cause a significant change in the operating conditions for a pump resulting in changes in the flow capacity, power requirements and efficiency. It can also result in local vortex-type pressure reductions that induce air cores extending into the pump.
- Severe swirling flow, when centered on the pump axis has an additional effect on the pump performance that can either enhance or reduce the pump's performance depending on the direction of the rotation.
- Non-uniform spatial distribution of velocity at the impeller eye results unsteady flow which causes the load on the impeller to fluctuate, which can lead to noise, vibration and bearing problems.
- Entrained air or gas bubbles because of air gulping or aerated flow will reduce pump discharge and loss of efficiency. Small quantities of air can result in significant efficiency drop.

2. DESIGN CRITERIA

Traditionally sump design has relied upon Hydraulic Institute pump standards [2] for obtaining the sump dimensions and pump position relative to the sump walls. These design guides originated and are extrapolated from experience with smaller pumps where approach flow conditions especially subsurface vortices are not as critical as they are for large capacity pumps employed today. A more comprehensive guide to pump design given by Prosser [3] is based upon research performed at British Hydromechanics Research Association (BHRA). This guide gives sump dimensions and relative position of the pump in terms of the dimensionless ratios of the distance in question to the pump bell diameter.

Application of BHRA guidelines or Hydraulic Institute standards to design a major sump does not generate a problem free sump but provides only a basis for the initial design. As there are no specific guidelines or criteria for design of trouble free intakes, the most common solution to potential problems in new designs and rectification of problems observed in existing designs is to construct a scaled model in a laboratory, observe and investigate the flow therein and propose modifications to the intake geometry. Further additional devices in the form of floor splitters or cones, back wall splitters, fillets, surface beams, guide vanes etc, aimed at controlling the vortex and swirl formation may be required to achieve a design which meets the performance criteria. Considerable prior experience and ingenuity are required to solve the problems by this method and the cost and time required are also significant [4].

In designing an intake structure, the following points must be considered:

- Flow from the fore bay should be directed toward the pump inlets in such a way that the flow reaches the inlets with a minimum of swirl.
- In order to prevent the formation of air-entraining surface vortices in the sump, the walls must be designed to avoid stagnation regions in the flow. A properly placed wall close to the inlet can reduce the tendency toward localized swirl and vortices. The liquid depth also must be great enough to suppress surface vortices.
- Although excessive turbulence or large eddies should be avoided, some turbulence does help to prevent the formation and growth of vortices.
- The sump should be as small and as simple as feasible to minimize construction costs. However, the required sump volume may be specified for other reasons, such as to provide for a minimum or maximum retention time.
- Large scale turbulence within the intake will cause uneven blade loading resulting in pump vibration and noise.
- Boundaries between stagnant regions and the main flow tend to be unstable and fluctuate on position. These regions promote unsteadiness in the main flow and increase the chances of the formation of air entraining vortices.

3. THE PHYSICAL MODEL

The model was built to test the original design of one of Abu Qir Thermal Power Plant, Gas/Oil Fired Units. It is located at the coast Mediterranean Sea east of Alexandria city, Egypt. Two Units A and B with a power capacity of 650 MW each are being constructed. The cooling system of the power plant is designed as once through circulating cooling water system. Water is withdrawn from the Sea and is discharged back to it. The circulating cooling water approaches a shoreline intake structure and flows to an inland pump house intake through four pipes. Shoreline intake has a settling basin protected by sixteen separate bar screen bays and four pipes as shown in Fig. 1. The inland pump house intake has four impact baffles, concrete vertical columns baffles, eight separate drum screen bays and four separate pump bays for vertical wet pit circulating water (CW) pumps and service water (SW) pumps.

The main aim of this study is to evaluate the flow characteristics in the intake structure and pump sumps of Units A and B. This will help to ensure a satisfactory performance of pumps in the prototype. Based on the performance criteria as defined by the Hydraulic Institute (HI) 1998 Pump Intake Design Standard, an undistorted physical model simulating the two proposed units was constructed.

3.1. Model Similitude

The model was designed using an undistorted geometric similarity in order to simulate the kinematics and dynamics of the fluid flow field. The free surface flow in the present model is dominated by gravitational and inertial forces; therefore, the model is evaluated using the Froude similarity law. The Froude number Fr , must be the same in both the model and prototype. The Froude ratio Fr is given by equations (1), (2) as follows:

$$F_r = F_m / F_p \dots\dots\dots(1)$$

$$\left[(V_m / \sqrt{gL_m}) / (V_p / \sqrt{gL_p}) \right] = 1 \dots\dots\dots(2)$$

Where V is the velocity, L is the characteristic length; g is the acceleration due to gravity and the subscripts m, p represents respectively the model and the prototype. If the length scale (L_r) is given by $L_r = L_m / L_p$, where L_m and L_p are the length in the model and prototype respectively, then the velocity scale V_r and discharge scale Q_r can be expressed, equations (3), (4), as follows:

$$V_r = V_m / V_p = L_r^{0.5} \dots\dots\dots(3)$$

$$Q_r = Q_m / Q_p = L_r^{2.5} \dots\dots\dots(4)$$

Where Q_m and Q_p are the discharge in the model and prototype respectively

3.2. Model Scale

The length scale ratio L_r was selected to be 1:8.724 to have acceptable Froude number and Weber number in the model. Using that length scale, the model scales are as follows:

Length scale $L_r = 1:8.724$, velocity scale $V_r = 1:2.954$, discharge scale $Q_r = 1:224.796$

According to the prototype dimensions of the CW pumps, the corresponding model characteristics are obtained.

3.3. Check for Other Similarity Laws Effect

To achieve similar velocity profiles inside the pump column in the model as in the prototype, a high enough turbulence level in the model suction pipe should be produced. This can be assured with a Reynolds number (Re)_s inside the suction pipe greater than 1×10^5 , equation (5):

$$(Re)_s = \frac{Q_m}{(\pi D_m^2 / 4)} \frac{D_m}{\nu} = 29.16 * 10^4 > 1 * 10^5 \dots\dots\dots(5)$$

It can be seen that the model Reynolds number is very high so there is a negligible influence of the viscous effect. It is shown below that the surface tension effect is also negligible, because the model Weber number, W_{em} is higher than 240, equation (6).

$$W_{em} = \frac{Q_m^2 \rho D_m}{\sigma (\pi \frac{D_m^2}{4})^2} = 1.849 * 10^3 \dots\dots\dots(6)$$

3.4. Model Description

The overall intake model general arrangement is shown in Fig. 1. Section details of the modelled pump bay are presented in Fig. 2. The model is constructed from cement-sand mortar, while the water intake part is constructed from wood and Plexiglas to permit flow visualization. All pumps, screens, trash racks and the pump sump are modelled. The screens and trash racks are simulated by their head losses effects. Pumps are modelled by their bell-mouths, bowl external shape and suction pipes. The inflow of the water intake is withdrawn from the pumping station model structure by means of four separate pumps representing the four (CW) pumps and the two service water (SW) pumps. These pumps have enough length of suction pipe to minimize the effect of their impellers on the flow characteristics at their bell mouths. Ultra Sonic flow meter is installed on the pipe system of each pump in order to accurately measure the total flow of the pump station. The drum screen is presented by its supporting walls as well as its head loss effect on the water level. Photos 1 to 3 show general view of the model, inland pump house intake and pump bay for circulating water pump.

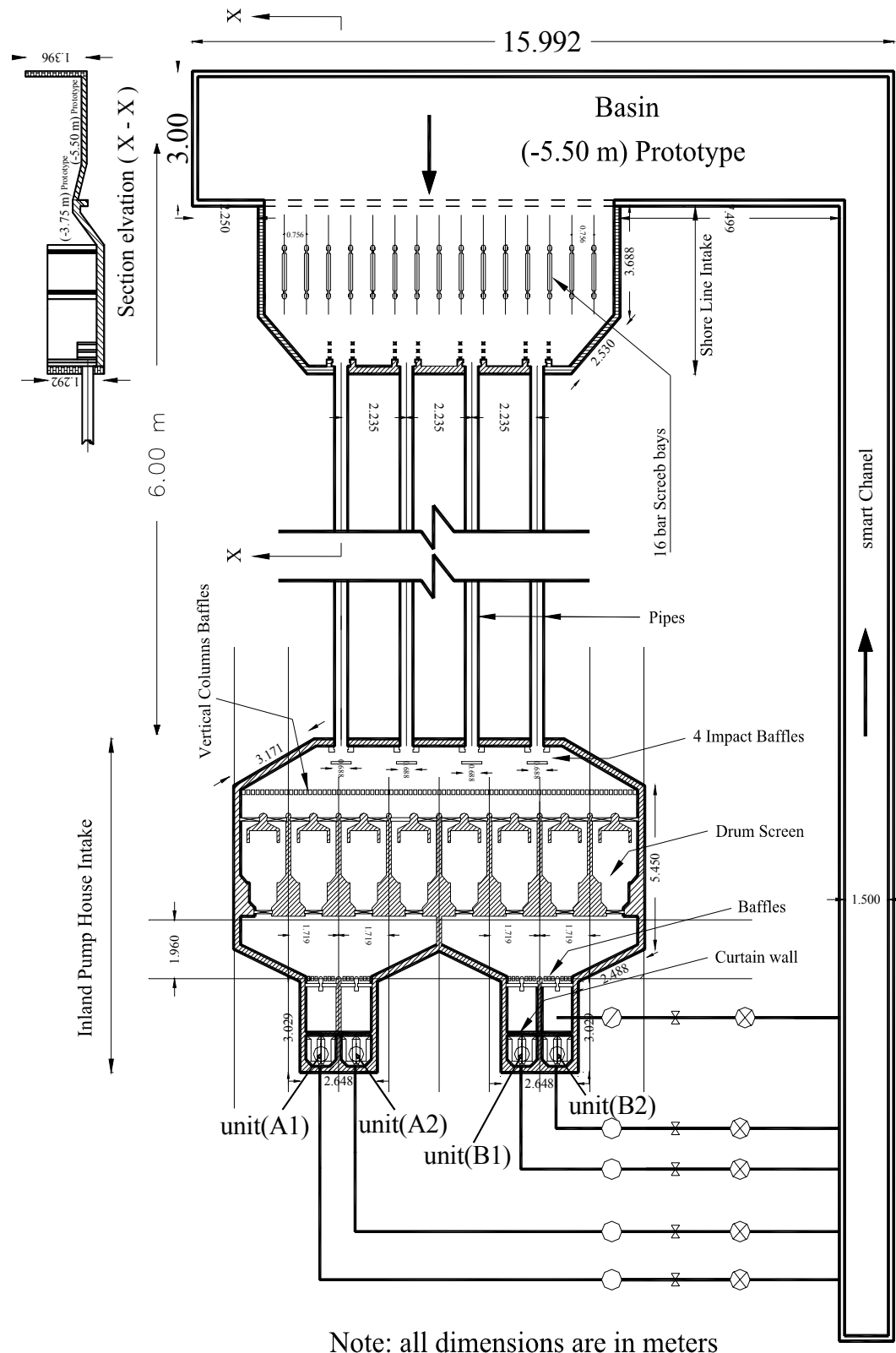
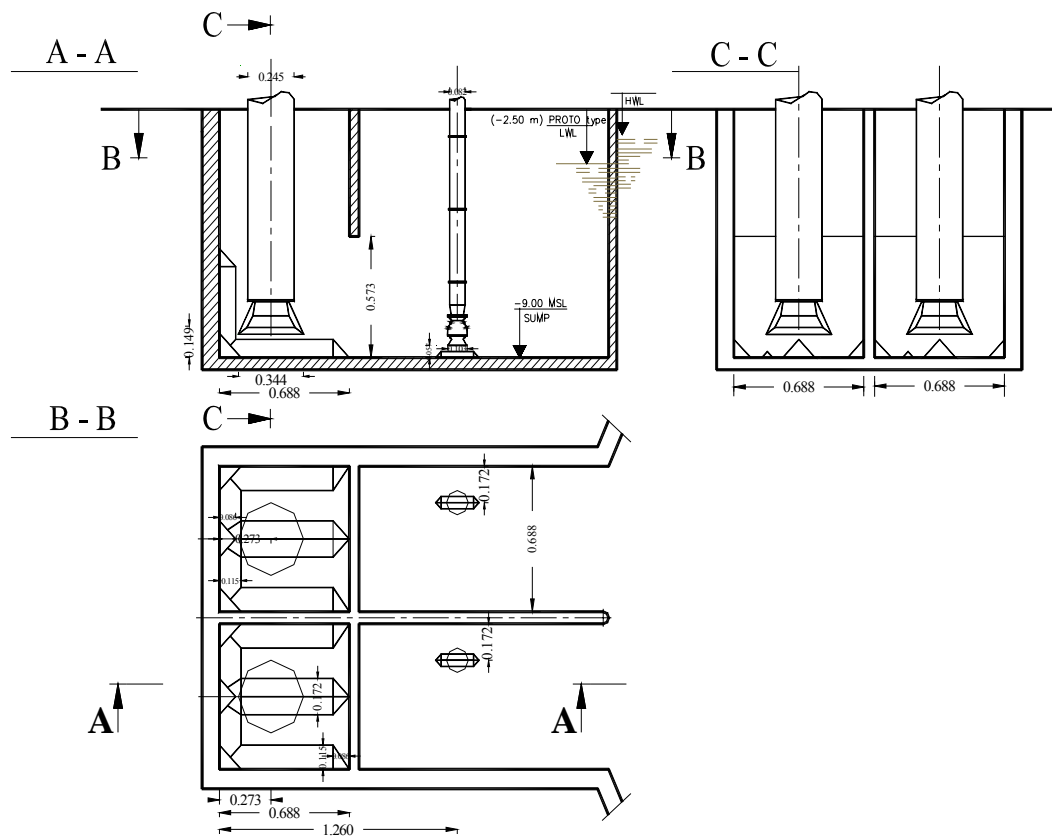


Figure 1: Overall intake model general arrangement



Note: All dimensions are in meters

Figure 2: Model pump house details – plan and sections



Photo1: General View of the model



Photo 2: Inland pump house intake



Photo 3: Pump bay for circulating water pump

Internal structural details, geometries of all CW pump bell/column including outside geometry of the bowl assembly including bowl shape, any fins, other external appurtenances and all service pumps bell/columns are modelled. Four impact baffles are located downstream of four transfer pipes which transfer the water from the shoreline intake to the pump house intake are simulated. Energy dissipating columns (vertical concrete columns with tie beam) upstream the drum screens for the eight drum screen bays and upstream the CW pumps for four CW pump bays are modelled. Also splitters, fillets, curtain wall and other details in modelled bays are simulated [5], as shown in Photos 4, 5 and 6

3.5. Operating Conditions (prototype)

Each circulating water pump has flow rate/pump and in runout condition of 12.51 and 16 m³/s, respectively, Pump impeller throat diameter, bell mouth diameter (D_p), pump chamber width (W_p) and floor clearance (bp) are 1.424, 3.00, 6.00 and 0.995 m respectively. Each service water pump has flow rate of 1.069 m³/s, pump column external diameter of 0.711 m, pump impeller throat diameter of 0.502 m and bell mouth diameter of 0.90 m. Operating water levels of Sea HWL and LWL are 0.93 and -0.43 m MSL respectively. Upstream Intake basin HWL is 0.63 m MSL and in LWL is -0.73 m MSL. Pump pit HWL, LWL and minimum W.L. are -0.8, -2.1 and -2.5 m MSL respectively. Maximum and minimum available submergence above suction bell inside the pump house for CW pump are 7.245 and 5.545 m, respectively.



Photo 4: One of the drum screen



Photo 5: Original design baffle wall



Photo 6: Bell-mouth of CW pump

3.6. Model Measurements

The discharge is measured with an accuracy of $\pm 2\%$ by Ultra sonic flow-meters. Water levels in all locations in the model are measured using point gauges with an accuracy of ± 0.1 mm. Two

perpendicular Pitot tubes are installed and used for measuring the velocity distribution inside the suction pipe of CW pumps. The Pitot tubes are calibrated before considering their readings. Swirl in each CW pump column and SW pump column is measured by vane-type swirl meter installed at a location of $4d$ (d = diameter of the suction pipe) from the bell-mouth as shown in Fig. 3. Rotations of the swirl meter are counted manually. The revolutions per unit time of the swirl meter are used to calculate the swirl angle, θ , which is an indicative of the intensity of the flow rotation.

To evaluate the strength of vortices at pump intakes systematically, the vortex strength scale varying from a surface swirl or dimple to an air core vortex, shown in Fig. 4, are used. Vortex types are identified in the model by visual observations with the help of dye. Sub-surface vortices usually terminate at the sump floor and walls, and may be visible only when dye is injected near the vortex core. The classification of sub-surface vortices, given in Fig. 4 will be used. The approach flow condition to drum screen is observed by injecting dye and following it by eyes and pictures.

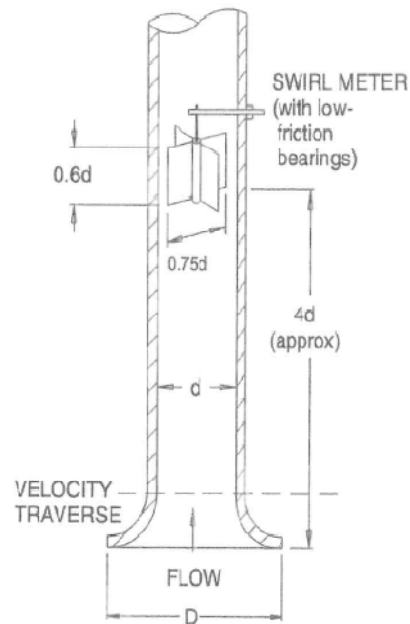


Figure 3: Diagram of swirl meter

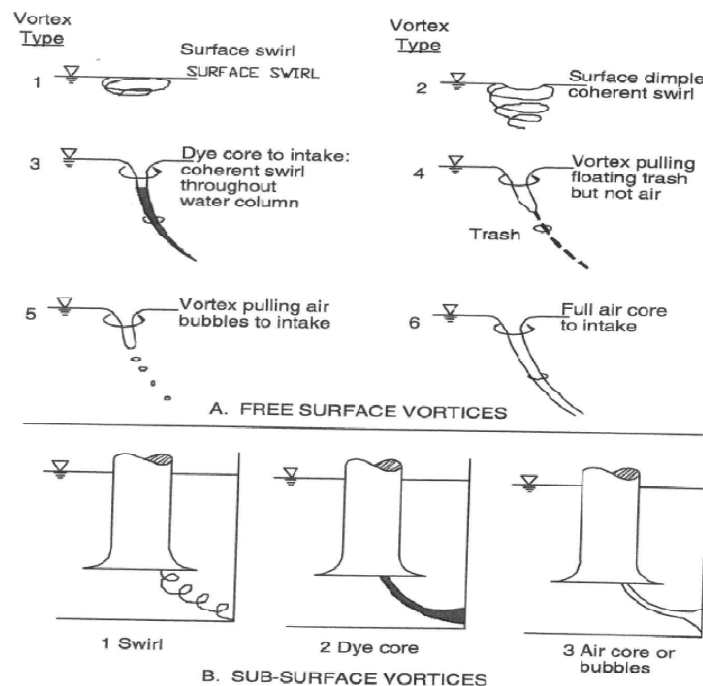


Figure 4: Free surface and sub-surface vortices classification

4. TEST RESULTS AND ANALYSIS

4.1. Pre-rotation Tests

The pre-rotation of the flow through the pump column is measured indirectly by the swirl angle. The swirl angle (θ) is defined using the pump column mean axial velocity (V_{mean}) and the tip velocity of the swirl meter (V_θ) and then, n is produced as in equations (7) to (12):

$$\tan \theta = \frac{V_\theta}{V_{mean}} \quad \dots\dots\dots(7)$$

$$\tan \theta = \frac{\pi d_p n / 60}{\frac{Q_p}{\pi d_p^2 / 4}} \quad \dots\dots\dots(8)$$

$$n = \frac{24 Q_p}{d_p^3} \cdot \tan \theta, \text{ in rpm} \quad \dots\dots\dots(9)$$

Per HI standard, a criterion for the swirl angle ($\theta = 5$ degrees) is considered to ensure flow through the pump is free from unacceptable pre rotational velocity.

$$n < 2 \frac{Q_p}{d_p^3} \quad \dots\dots\dots(10)$$

This holds for the prototype while for the model case:

$$n < 2 \frac{Q_p / Q_r}{d_p^3 / L_r^3} \quad \dots\dots\dots(11)$$

Since discharge scale $Q_r = (L_r)^{5/2}$, the criterion for maximum number of revolutions of the roto-meter becomes:

$$n < 2 \sqrt{L_r} \frac{Q_p}{d_p^3} \quad \dots\dots\dots(12)$$

Based on the above mentioned figures the number of revolutions per minute (n in rpm) of the roto-meters in case of CW pump corresponding to swirl angle of 5 degrees for $Q = 12.5$ and $16 \text{ m}^3/\text{s}$ are 33 and 50 rpm, respectively and SW pumps for $Q = 1.069 \text{ m}^3/\text{s}$ is 70 rpm.

Units A&B are set in operation. The different operating conditions are tested under minimum condition (tests from no. 1 to no. 11) and HWL condition (tests from no. 13 to no. 20) as shown in Table (1). The results showed that the swirl angles at the CW pump range between 3.93 degrees (test no 3, unit A1) and 0.19 degree (tests No 13, 14 unit A2). The rates of the roto-meters rotation are within the allowable limits. This indicates that there exists a uniform flow distribution inside the pump column.

Table 1: Test program and operation moods

Test No	Circulating Water Pumps				Service Water Pumps				Sea Water Level	Model Flow l/s	Remarks
	Unit A		Unit B		Unit A		Unit B				
	CW1	CW2	CW3	CW4	SW1	SW2	SW3	SW4			
1	on	on	on	on	on	off	on	off	Min.WL	232.113	At rated flow
2	on	on	on	on	on	off	off	off	Min.WL	227.357	At rated flow
3	on	off	on	on	on	off	on	off	Min.WL	191.987	At rated flow and runout
4	off	on	on	on	on	off	on	off	Min.WL	191.987	At rated flow and runout
5	on	off	on	off	on	off	on	off	Min.WL	151.862	runout flow for CWP
6	off	on	off	on	on	off	on	off	Min.WL	151.862	runout flow for CWP

7	on	on	off	off	on	off	off	off	Min.WL	116.056	rated flow 1 unit off
8	on	off	off	off	on	off	off	off	Min.WL	75.931	runout flow 1 unit off
9	on	on	on	on	on	off	on	off	Min.WL	232.113	50% blockage
10	on	on	on	on	on	off	on	off	Min.WL	232.113	One transfer pipe stop logged
11	on	on	off	off	on	off	on	off	Min.WL	120.812	Two transfer pipe stop logged
12	on	on	off	off	on	off	off	off	Min.WL	174.085	1.5 * Ftest
13	on	on	on	on	on	off	on	off	HWL	232.113	At rated flow
14	on	on	on	on	on	off	off	off	HWL	227.357	At rated flow
15	on	off	on	on	on	off	on	off	HWL	191.987	At rated flow and runout
16	off	on	on	on	on	off	on	off	HWL	191.987	rated flow and runout
17	on	off	on	off	on	off	on	off	HWL	151.862	runout flow for CWP
18	off	on	off	on	on	off	on	off	HWL	151.862	runout flow for CWP
19	on	on	off	off	on	off	on	off	HWL	120.812	rated flow 1 unit off
20	on	off	off	off	on	off	off	off	HWL	75.931	runout flow 1 unit off

1- For screen clogging test no 9, the screen is blocked 50%. The head lose in this case is simulated in the model.

2- During one CW pump running for a unit, the operating pump will run out at a flow of 16 m³/s.

4.2. The Effect of Baffle Columns

- Unite A was operated at minimum water level (test no 7), the rate of roto-meter rotation of the pump in Unit A1 was 13 rpm (2.42 degree). The same operation was carried out with 2 baffle columns removed in front of Unit A1 bay, the rate of roto-meter rotation of the above mentioned Unit was 16 rpm (2.93 degree). This means that the baffle columns did not influence much the pump impeller.
- An operation with condition as the above mentioned was carried out with baffle column drum screen closed, it was found that, it did not affect the pump impeller.
- An operation as the above mentioned was carried out with baffle column bay closed, the rate of roto-meter rotation of the pump in Unit A1 was 30 rpm (5.58 degree). This means that closing the baffle columns bay can affect much the pump impeller.

4.3. Vortex Formation Investigation

The results, of the observation of the surface and subsurface vortices near the CW pumps and SW pumps in all tests in cases of minimum and high WL, can be concluded as the following:

1) In the case of minimum water levels:

- 1- No surface or subsurface vortex appeared down stream the curtain wall near the CW pumps in all tests.
- 2- Surface vortices types 1 and 2 appeared upstream the curtain wall of Units A&B.
- 3- Test case no 12, which is Unit A in operation in case of flow at 1.5 Froude number. Type I surface vortex in Unit A1 and A2 pumps was observed from time to time. Type I sub surface vortex in Unit B1 pump was also observed from time to time.
- 4- Continuous type 5 surface vortices have been observed upstream all the four intake pipe inlets for minimum WL cases. Even though these vortices do not affect the pumps performance, it will adversely affect pipe inlet performance. Photo 7 shows surface vortex type 6 upstream the intake pipe. Vortices totally disappeared after closing the flow entrance between the intake pipe inlet cap slab and the stop logs slots.

2) In the case of high water level:

Surface vortices type 3 and 4 appeared at different times (infrequent duration) near the SW pump column, upstream the curtain wall of Units A&B in all high water case tests. These vortices appeared even when the SW pumps were off. These vortices go down to the curtain wall and infrequently move near to the bell mouth of the circulating water (CW) pump as shown in Photo 8. To eliminate the surface vortices upstream of the curtain wall, it was proposed to extend the baffle walls above HWL. All high water case tests were repeated after increasing the baffles height as mentioned above. With this trial, all surface vortices higher than type I previously observed upstream the curtain walls have been eliminated. In addition, the swirl meter readings for the pumps are much less than before modification in all the above mentioned cases.



Photo7: Surface vortex type 6 U. S. the intake pipe Photo 8 Surface vortex type 3 or 4 U.S the curtain wall

3) Additional tests

The results of the above mentioned tests showed that the appeared vortices were type 1 or type 2 which they are acceptable. Some tests were carried out to predict the water level which produce unallowable vortex. The results showed that surface vortex type 6 was appeared at water level of -4.9 m MSL, Photo 9. This was done under the condition of the depth in the pump house was about 1.5 times the pump column diameter, 2.2 of the pump impeller throat diameter and 1.05 of the suction bell diameter.

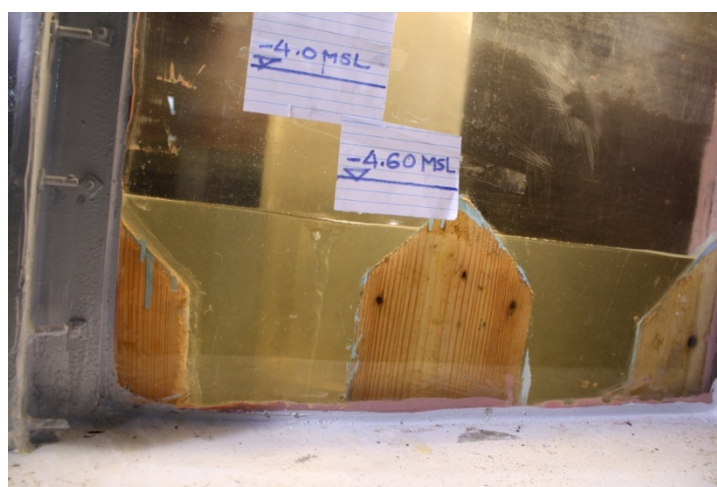


Photo 9: Surface vortex type 6 close to CW pump

4.4. Velocity Distribution in the Suction Pipe

To check the flow uniformity inside the pump column, velocity measurements were taken inside the pump column. Velocity distributions in the suction pipe were measured in a cross section where the impeller inlet is situated in reality. The measurements were taken along two perpendicular cross sections at 7 different measuring locations using Pitot tubes. Fig. 5 shows the cross sections location and the distance of the point velocity from the pipe edge. The following criterion is used for every measuring point:

$$absolute [V_n - V_{mean}] \leq 10 \% \cdot V_{mean}$$

$$absolute \left[\frac{V_n}{V_{mean}} - 1 \right] \leq 0.1$$

Where V_n is the point measured mean velocity and V_{mean} is the overall mean velocity in the measuring section { $V_{mean} = Q_m / (\pi \cdot D_m^2)$ }. The measurements were taken for run no. 1, 3, 5 and 9. These runs were the highest roto-meter rates which mean at the least favourable flow condition runs. The results showed that the value of absolute $[V_n / V_{mean} - 1]$ does not exceed 10% and it ranges between -3.9 to +4.37% which are within the allowable limits according to HI criteria.

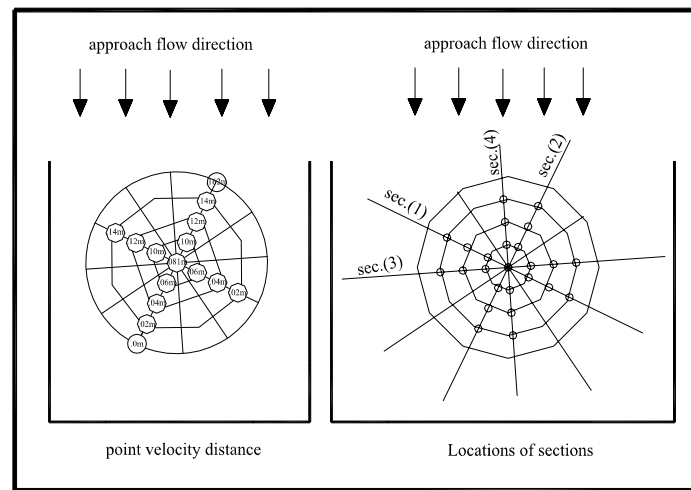


Figure 5: Velocity measurements at Bell-throat

4.5. Check of Stagnation Areas

Dye observation to identify low flow area suspecting for siltation was carried out at expected stagnation areas such as the corners of the pump chambers. It was found that no stagnation areas exist. The approach flow condition to drum screen was observed by injecting dye and it was followed by visual observation. It was found that the flow pattern is regular.

5. CONCLUSIONS AND RECOMMENDATIONS

Based on the above mentioned tests in table 1, the following conclusions can be formulated:

1. A uniform pump approaching flow existed in the pump chambers of Units A&B. This was indicated from the results of pre-rotation tests.
2. The swirl angle was not influenced, when 2 baffle columns removed or baffle column drum screen closed, while closing the baffle columns bay can affect much the pump impeller.
3. An acceptable sump design that will ensure a safe operation of the pumps in case of minimum and high water level conditions. This was indicated because no vortices more than type II were observed near the bell mouths of the pumps. Vortices of type 3 or type 4 were observed upstream from the curtain wall and moved downstream near the bell mouth of CW pumps. Those vortices disappeared after changing the top of the baffle wall from minimum water level to high water level.

4. It was found that vortex type 6 was appeared when submergence above suction bell inside the pump house was about 1.5 the pump column diameter, 2.2 of the pump impeller throat diameter and 1.05 of the suction bell diameter, so the above mentioned ratios should be cared during the pump operation.
5. Closing the flow entrance between the intake pipe inlet cap slab and the stop logs slots of all four intake pipe inlets helped for disappearing continuous type 5 or type 6 surface vortices in minimum WL cases.
6. Velocity measurements were taken inside the pump suction pipes. The velocity at the impeller location was found uniform in magnitude within $\pm 10\%$ of the mean velocity as HI standard criteria.

The results obtained in the present model study indicated the following recommendations:

- 1- The top of the baffle wall should be changed from minimum water level elevation to high water elevation.
- 2- The flow entrance between the cap slab for the four intake pipe inlets and the stop logs slots should be closed using curtain walls.

Except the above two modifications, it is recommended that the original pump intake design to be used as the final design.

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