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INCREASE COOLING WATER SYSTEM CAPACITY WITHOUT INTRODUCING PROBLEMS AND MAINTENANCE: A CASE STUDY – PROBLEM IDENTIFICATION, SOLUTION SELECTION, AND MODELING

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ABSTRACT

Increasing the capacity of a cooling water system requires more than just upgrading the cooling water pumps. The intake system needs to be evaluated as well to ensure it is capable of handling the upgraded pumps without introducing problems such as increased vortex activities. Even slight increase in pump capacity can create or increase vortex activity. Free surface and subsurface vortices can be extremely damaging to a pump and can cause major problems such as cavitation to the pump's impeller and casing, vibration, and decreased performance. The challenge here is to modify the existing cooling water intake system without major reconstruction that would be both costly and schedule intense.

This paper presents a case study of an existing South Texas petrochemical plant where a turnaround upgrade required an increase in cooling water flow through the existing sump basin and the associated engineering work for a physical hydraulic model study. The main purpose of the physical hydraulic model study was to ascertain simple and low cost modifications to the pump intake bays that allow the required flow increase through the existing pump intake system without flow disruptions from

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the higher flow volume. The hydraulic model replicated the fundamental flow parameters in the sump's pump intake bays and led to an inexpensive, timely, and easy to implement solution that did not require major construction changes to the intake system. With physical modeling, the intricate interaction between cooling water and air can be analyzed and tested, a task that computational fluid dynamics cannot achieve to the required degree of precision. The physical model identified increased air entraining vortex activity and was used to develop remedial vortex suppression pipe modules that are in the process of being designed, constructed, and mounted on each pump intake bay. A follow up paper will cover the modification, implementation, and commissioning as a continuation of this paper.

INTRODUCTION

The turnaround upgrade of the existing plant required new cooling water pumps to be bought and installed in order to meet the new cooling water capacity demand. Since it was first built a few decades ago, the cooling water system has operated without problems. There are frequent Type 1 and Type 2 vortices with sporadic Type 3 vortices that would appear on the water surface in each pump bay. During the bid clarification meeting with the cooling water pump manufacturer, the Client mentioned that the impellers were coated with an epoxy wear/impact resistant coating to prevent damage from occasional vortex ingestion and subsequent cavitation and was aware that the coating would no longer be able to provide adequate protection against the increased vortex activity as a result of increased cooling water flowrate. The Client had previously conducted a computational fluid dynamics (CFD) study but the scope of that study only investigated the flow behavior of the water in the pump intake bays. There was no focus on air entrainment and as a result did not provide any data on vortex activity nor surface phenomena.

The Engineering Contractor took the initiative to contact a CFD specialist in order to ascertain the limitations of CFD and to determine whether modeling the dynamics between water and air would yield dependable results with CFD. Ultimately, the CFD Specialist informed the Contractor that modeling the complex interaction between water and air with CFD would be time consuming and cost prohibitive as it would be a project in and of itself. In addition, the Hydraulic Institute Standard 9.8-2012 requires physical modeling for intakes that deviate from the recommended design guidelines, for pumps over 40,000 gpm or for total station flows over 100,000 gpm. In this light, the Client and Engineering Contractor reached the conclusion that physical hydraulic modeling would be the best path going forward.

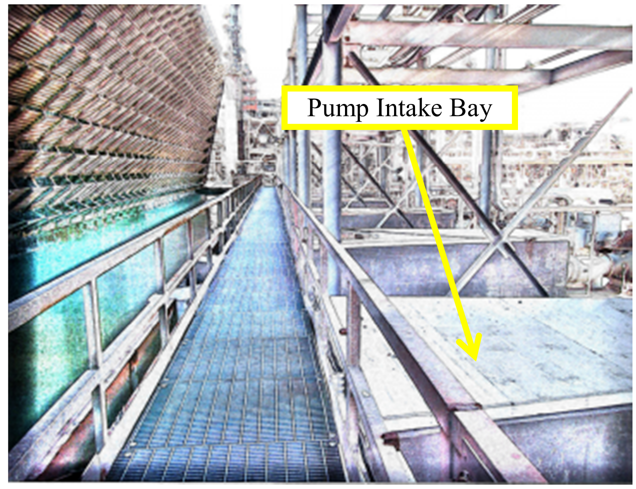

Figure 1. Existing Cooling Water Sump Intake System

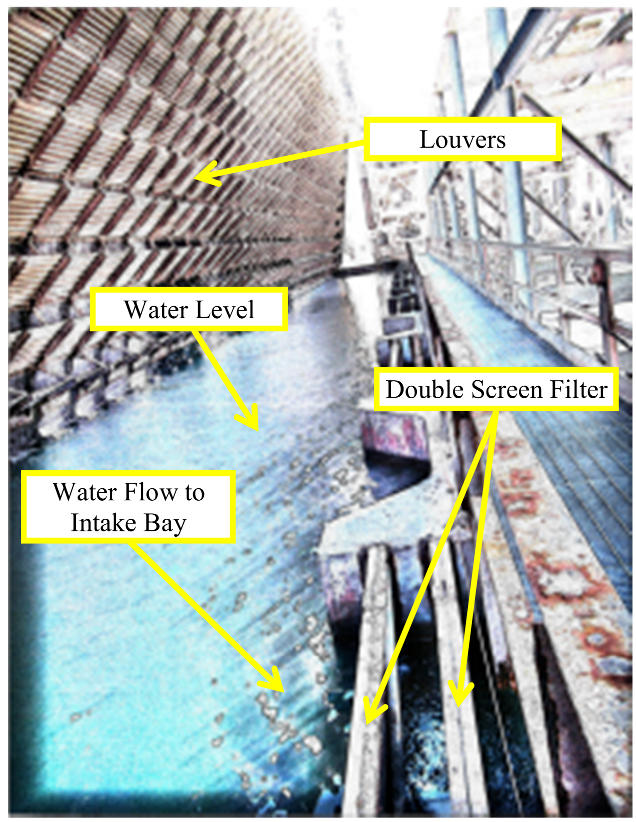

Figure 2. Existing Cooling Water Sump Intake System (Louvers and Double Screen Filter)

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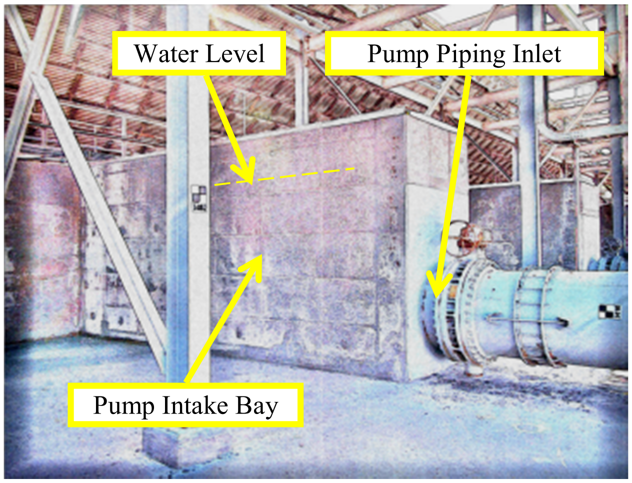

Figure 3. Existing Cooling Water Sump Intake System (Pump Bay and Pump Piping Inlet)

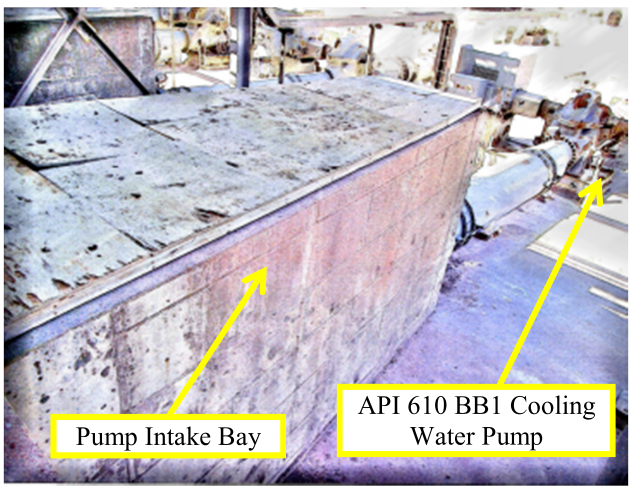

Figure 4. Existing Cooling Water Sump Intake System (Pump Bay and API 610 BB1 Cooling Water Pump)

The existing cooling water sump pump intake system layout, shown in Figure 1, consists of 8 pump intake bays (7 open, 1 closed) connecting to 7 API 610 BB1 cooling water horizontal pumps (6 operating, 1 spare). The pump bays are trapezoidally shaped and the pump piping inlet is on the short parallel side a few feet above the ground. Cooling water from the tower louvers drops into the sump and proceeds to flow through the double screen filters as shown in Figure 2. Water then travels into each pump intake bay, exits through the pump piping inlet, flows through an eccentric reducer, and then enters the horizontal cooling water pump suction as shown in Figure 3 and 4.

Through the cooling water pump manufacturer, the Client contacted a consultant that specialized in creating large scale size physical models of cooling intake systems to investigate flow problems and propose solutions. A dimensionally accurate scaled physical model of the existing cooling water intake system would provide valuable information such as:

- The water flow behavior and magnitude of increased vortex activities under the new increased capacity of the intake system
- Development of alternative modifications that would alleviate the vortices

Using physical observations of the vortices, critical dimension measurement data, and the Client's site drawings of the existing cooling water intake system, the Consultant was able to construct a 1 : 9.3 scale model of the sump intake system. The scale was chosen based on the Hydraulic Institute Standard 9.8-2012 requirements for model scaling.

Vortex classification as defined by the Consultant with a scale of Type 1 to 5 is shown in Figure 5 which differs slightly (combining trash and air bubbles into the same Type 4) from the definition within the Hydraulic Institute Standards which utilizes a scale of Type 1 to 6.

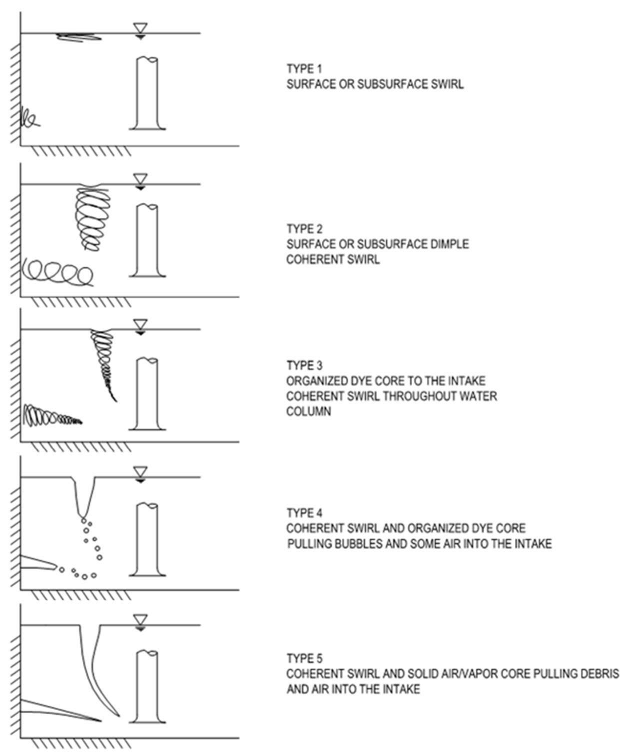

Figure 5. Consultant's Surface and Subsurface Vortex Classification

PHYSICAL SUMP INTAKE SYSTEM MODEL

The basin of the physical intake model measured about 30 feet long and 5 feet wide as shown in Figure 6 and 7. The floor and walls were constructed out of waterproof wood. The pump bay walls and inlet piping were created out of clear acrylic

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plastic as shown in Figure 8 and 9.

Water was introduced and flowed through a sparger that distributed the water across the width of the basin and then through a baffle which straightened out the flow as shown in Figure 10. Water flow then made a 90 degree turn into each of the 8 pump bays. The pump bays are routed to a single test lab pump which recirculated the water back to the intake basin.

In the model, water is coming entirely from the leftmost side which differs slightly from than the existing cooling water tower basin where a percentage of the water is coming from the cooling towers above to immediately in front of the pump intake bays. The model is slightly conservative because it allows for a slightly higher velocity at the upstream corner of the sump which can increase flow separation. If vortices can be eliminated with the higher circulation and flow separation in the model, then there is a high probability that they will be eliminated in the prototype.

Purple dye was utilized in order to visualize flow behavior of the water at specific location points in the model.

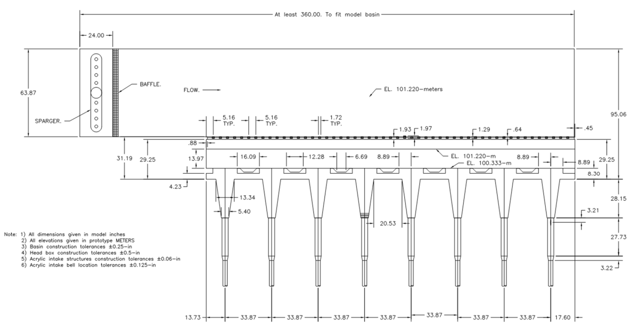

Figure 6. Layout Details of Hydraulic Model

Figure 7. Physical Hydraulic Model of Cooling Water Intake System

Figure 8. Pump Bays of Physical Hydraulic Model

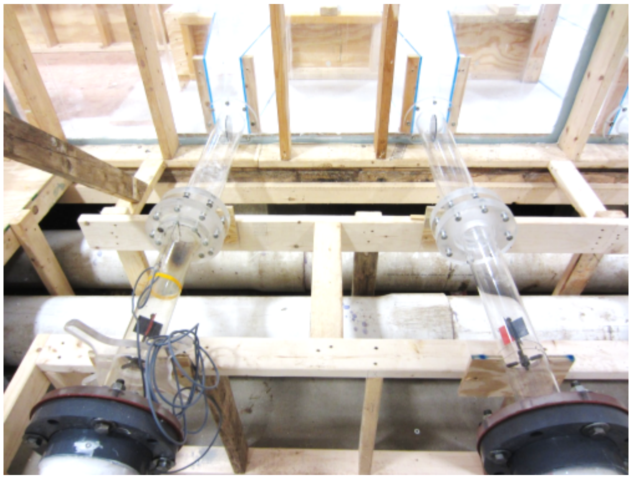

Figure 9. Pump Inlet Suction Piping of Physical Hydraulic Model

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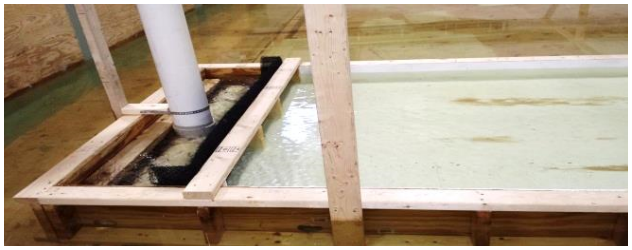

Figure 10. Water Supply, Sparger, and Baffle of Physical Hydraulic Model

Most of the measuring and testing instruments were on the inlet suction piping of each pump intake bay. There were dye injectors installed on the inlet piping near the pump intake bay entrance as well as immediately downstream of the eccentric reducer on the inlet piping. Further downstream, there is a single swirl meter that measures pre-swirl. Only one of the seven inlet piping contains a velocity probe downstream that is utilized to obtain a cross-sectional area average velocity.

A flexible pipe dye injector was another tool that was employed to see the flow behavior on the water surface and as well as the subsurface.

To ensure that the physical model can accurately simulate full-scale flow phenomena, it was validated by modeling the flow behaviors and vortex activities of the existing cooling water intake system under the same operating conditions, with the cooling pump prototype capacity of 26,000 gpm. These tests closely replicated field observations.

MODELING BASICS

For a model to be an accurate representation of a prototype, there must be dynamic similitude as well as geometric similitude. Geometric similitude is easily accomplished. In order to satisfy the dynamic similitude requirement, a 1:1 scale model is required. This requirement can be bypassed by having the model either match the major flow parameters applicable to the water flow or operate in the same flow regime: Reynolds number [Re], for inertia and friction effects, and Froude number [Fr], for gravity and water / air surface dynamic effects.

Fr is the governing parameter for prediction and modeling of water / air free surface dynamics and both surface and sub-surface vortex formation, therefore the model Fr matches that of the full-scale pump intake piping diameter. See Eq. (1).

The model scale yields sufficiently high Re, based on pump intake piping diameter, to provide fully-turbulent flow, where sub-surface viscous forces are negligible compared to inertial and gravity forces. In the fully-turbulent flow regime, the friction factors in the model will be nearly equal to those in the full-scale pump intake bays and piping.

Below, Eq. (1) states that the full-scale pump intake system [subscript "p"] and the model [subscript "m"] have equal Fr.

$$Fr_p = Fr_m \qquad (1)$$

Eq. (2) presents Fr_p and Fr_m as functions of flow velocity [U], gravity [g], and a characteristic length [L] that is the linear base of Fr. In this particular model study, L is the entrance suction diameter and U is referenced at the entrance suction. The unknowns here are the model parameters U_m and L_m.

$$\frac{U_p}{\sqrt{gL_p}} = \frac{U_m}{\sqrt{gL_m}} \qquad (2)$$

Eq. (3) describes the volumetric flowrate [Q] as a function of velocity and a characteristic cross-sectional area [A] that is further represented by L. This relationship will be used to link U_p and L_p, and U_m and L_m.

$$Q = UA = UL^2 \qquad (3)$$

The model scale can be derived by re-working Eq. (2) with the relationships from Eq. (3), thus leaving only Q and L.

$$\frac{Q_p}{Q_m} = \left(\frac{L_p}{L_m}\right)^{5/2} \qquad (4)$$

The model scale, L_p/L_m, can be computed to accommodate the Q_m values that the test pump can deliver, while at the same time yielding fully-turbulent Re_m, per Eq. (5), where ν is the kinematic viscosity of water.

$$Re_m = \frac{U_m L_m}{\nu} \qquad (5)$$

Once the value of L_m is set, the Q_m for each test condition can be computed from Eq. (4).

MODEL TESTING

When model testing sump intake modifications for the prevention of vortex formation, in order to provide reliable and accurate results, the testing is required to fulfill these five criteria:

- No free surface or submerged vortices greater than Type 1.
- Pre-swirl need to be less than five degrees at pump impeller location.
- Time averaged velocities within the pump reference plane should deviate less than ten percent.
- Time-varying velocity fluctuations at a pump within the pump reference plane should be less than ten percent.

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- These criteria will meet ANSI/HI 9.8-2012 test specifications.

Since the criteria condition at the pump suction and impeller area cannot be fulfilled due to the nature of the model, measurements of pre-swirl and time averaged velocities are taken at "pump reference plane" corresponding with the pump suction flange.

The first phase in the testing process is Baseline Testing of the model at the two different operating prototype capacities, 26,000 gpm (existing capacity) and 37,000 gpm (new capacity required for plant upgrade), without any intake modifications. The purpose of this testing is to first ensure that the model simulates actual observed flow phenomena and secondly to view/analyze the flow behaviors of the water in all of the different areas of the intake system. The intake system was operated in different pump configurations as seen in Table 1 and 2.

The letters represent each of seven different pumps. The only velocity probe is located on the downstream inlet piping of the "A" pump.

Baseline Testing

Test 1			Test 2		
Pump	Prototype Capacity (gpm)	Pre-Swirl Max (deg.)	Pump	Prototype Capacity (gpm)	Pre-Swirl Max (deg.)
A	26000	0.2	A	26000	0.2
B	26000	0.2	B	26000	0.2
C	26000	0.2	C	0	-
D	26000	0.2	D	0	-
E	26000	0.2	E	0	-
F	26000	0.2	F	26000	0.2
G	26000	0.2	G	26000	0.2
Velocity and Turbulence			Velocity and Turbulence		
Min Vel.	-8.7%		Min Vel.	-6.7%	
Max Vel.	9.6%		Max Vel.	3.8%	
Max Turb. %	8.4%		Max Turb. %	2.5%	

Test 3			Test 4		
Pump	Prototype Capacity (gpm)	Pre-Swirl Max (deg.)	Pump	Prototype Capacity (gpm)	Pre-Swirl Max (deg.)
A	31500	0.2	A	37000	0.6
B	0	-	B	37000	0.2
C	0	-	C	37000	0.2
D	0	-	D	37000	0.2
E	0	-	E	37000	0.2
F	0	-	F	37000	0.2
G	31500	0.2	G	37000	0.2
Velocity and Turbulence			Velocity and Turbulence		
Min Vel.	-2.5%		Min Vel.	-9.7%	
Max Vel.	2.4%		Max Vel.	5.4%	
Max Turb. %	3.7%		Max Turb. %	2.9%	

Table 1: Baseline Testing Pump Configurations (Test 1 - 4)

Baseline Testing

Test 5			Test 6		
Pump	Prototype Capacity (gpm)	Pre-Swirl Max (deg.)	Pump	Prototype Capacity (gpm)	Pre-Swirl Max (deg.)
A	37000	0.4	A	37000	0.4
B	37000	0.2	B	37000	0.4
C	0	-	C	37000	0.2
D	0	-	D	37000	0.2
E	37000	0.2	E	37000	0.2
F	37000	0.2	F	0	-
G	37000	0.2	G	0	-
Velocity and Turbulence			Velocity and Turbulence		
Min Vel.	-8.1%		Min Vel.	-8.1%	
Max Vel.	4.5%		Max Vel.	4.5%	
Max Turb. %	1.7%		Max Turb. %	1.7%	

Test 7			Test 8		
Pump	Prototype Capacity (gpm)	Pre-Swirl Max (deg.)	Pump	Prototype Capacity (gpm)	Pre-Swirl Max (deg.)
A	37000	0.6	A	48100	0.7
B	0	-	B	0	-
C	37000	0.2	C	0	-
D	37000	0.2	D	0	-
E	37000	0.2	E	0	-
F	37000	0.2	F	0	-
G	37000	0.2	G	48100	0.5
Velocity and Turbulence			Velocity and Turbulence		
Min Vel.	-7.9%		Min Vel.	-9.9%	
Max Vel.	2.9%		Max Vel.	4.3%	
Max Turb. %	1.8%		Max Turb. %	3.9%	

Table 2: Baseline Testing Pump Configurations (Test 5 - 8)

For tests with pump configurations that operated below 37,000 gpm, consistent Type 3 vortices (strong dye cores) were observed as shown in Figure 11. When operating at the new flows, Type 4 vortices (air bubbles are pulled to the pump) were observed with operating capacities greater than or equal to 37,000 gpm as shown in Figure 12. Pre-swirl and velocity deviation was within the acceptance criteria.

The second phase in the testing process was Intake Modification Testing which is conducted to develop modifications that would prevent the formation of vortices or dissipate their effects prior to reaching the pumps. Modifications that would require no major structural changes were desired. Based on the labs experience, several different surface vortex suppression baffles were evaluated in the model. It was discovered that a series of horizontal suppression pipes installed submerged under the water surface towards the front of the pump bay would impede vortex formation (Figure 13). As shown in Table 3, the only pump configurations that are necessary to be tested for Intake Modification Testing involves pumps operating at 37,000 gpm and greater.

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Modification Testing					
Test 9			**Test 10**		
Pump	Prototype Capacity (gpm)	Pre-Swirl Max (deg.)	Pump	Prototype Capacity (gpm)	Pre-Swirl Max (deg.)
A	37000	0.6	A	48100	0.7
B	37000	X	B	0	-
C	37000	X	C	0	-
D	37000	X	D	0	-
E	37000	X	E	0	-
F	37000	X	F	0	-
G	37000	X	G	48100	X
Velocity and Turbulence			Velocity and Turbulence		
Min Vel.	-7.1%		Min Vel.	-6.70%	
Max Vel.	5.8%		Max Vel.	6%	
Max Turb. %	4.6%		Max Turb. %	5.4%	

Table 3: Intake Modification Testing Pump Configurations (Test 9 - 10)

Final Documentation Testing was run with the pump configurations shown in Table 4 and 5 with the horizontal vortex suppression pipes installed. The purpose of this testing was to confirm the vortex suppression pipes' effectiveness.

Final Documentation Testing					
Test 11			**Test 12**		
Pump	Prototype Capacity (gpm)	Pre-Swirl Max (deg.)	Pump	Prototype Capacity (gpm)	Pre-Swirl Max (deg.)
A	26000	0.2	A	26000	0.2
B	26000	0.2	B	26000	0.2
C	26000	0.2	C	0	-
D	26000	0.2	D	0	-
E	26000	0.2	E	0	-
F	26000	0.2	F	26000	0.2
G	26000	0.2	G	26000	0.2
Velocity and Turbulence			Velocity and Turbulence		
Min Vel.	-8.8%		Min Vel.	-5.2%	
Max Vel.	5.7%		Max Vel.	3.7%	
Max Turb. %	5.5%		Max Turb. %	5.4%	
Test 13			**Test 14**		
Pump	Prototype Capacity (gpm)	Pre-Swirl Max (deg.)	Pump	Prototype Capacity (gpm)	Pre-Swirl Max (deg.)
A	37000	0.1	A	0	-
B	37000	0.1	B	37000	0.1
C	37000	0.1	C	37000	0.1
D	37000	0.1	D	37000	0.1
E	37000	0.1	E	37000	0.1
F	37000	0.1	F	37000	0.1
G	37000	0.1	G	37000	0.1
Velocity and Turbulence			Velocity and Turbulence		
Min Vel.	-3.7%		Min Vel.	-	
Max Vel.	5.3%		Max Vel.	-	
Max Turb. %	6.8%		Max Turb. %	-	
Test 15			**Test 16**		
Pump	Prototype Capacity (gpm)	Pre-Swirl Max (deg.)	Pump	Prototype Capacity (gpm)	Pre-Swirl Max (deg.)
A	37000	0.1	A	37000	0.1
B	37000	0.1	B	37000	0.1
C	37000	0.1	C	37000	0.1
D	37000	0.1	D	37000	0.1
E	37000	0.1	E	0	-
F	0	-	F	0	-
G	0	-	G	0	-
Velocity and Turbulence			Velocity and Turbulence		
Min Vel.	-3.5%		Min Vel.	-3.4%	
Max Vel.	3.4%		Max Vel.	3.1%	
Max Turb. %	7%		Max Turb. %	6.8%	

Table 4: Final Documentation Testing Pump Configurations with Intake Modifications (Test 11 - 16)

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Final Documentation Testing					
Test 17			**Test 18**		
Pump	Prototype Capacity (gpm)	Pre-Swirl Max (deg.)	Pump	Prototype Capacity (gpm)	Pre-Swirl Max (deg.)
A	37000	0.1	A	0	-
B	37000	0.1	B	0	-
C	0	-	C	0	-
D	0	-	D	0	-
E	0	-	E	0	-
F	37000	0.1	F	37000	0.1
G	37000	0.1	G	37000	0.1
Velocity and Turbulence			Velocity and Turbulence		
Min Vel.	-3.7%		Min Vel.	-	
Max Vel.	5.3%		Max Vel.	-	
Max Turb. %	6.8%		Max Turb. %	-	
Test 19			**Test 20**		
Pump	Prototype Capacity (gpm)	Pre-Swirl Max (deg.)	Pump	Prototype Capacity (gpm)	Pre-Swirl Max (deg.)
A	48100	0.1	A	0	-
B	0	-	B	0	-
C	0	-	C	0	-
D	0	-	D	0	-
E	0	-	E	0	-
F	0	-	F	48100	0.1
G	48100	0.1	G	0	-
Velocity and Turbulence			Velocity and Turbulence		
Min Vel.	-4.4%		Min Vel.	-	
Max Vel.	4.1%		Max Vel.	-	
Max Turb. %	3.7%		Max Turb. %	-	

Table 5: Final Documentation Testing Pump Configurations with Intake Modifications (Test 17 - 20)

The vortex suppression pipes completely eliminated the vortex activity for all test scenarios as shown in Figure 14. Pre-swirl and velocity deviation was within the acceptance criteria.

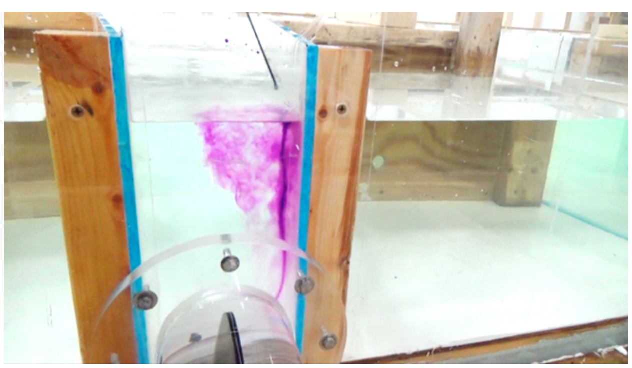

Figure 11. Model Flow Behavior at 26,000 gpm Displaying Type 3 Vortex Activity

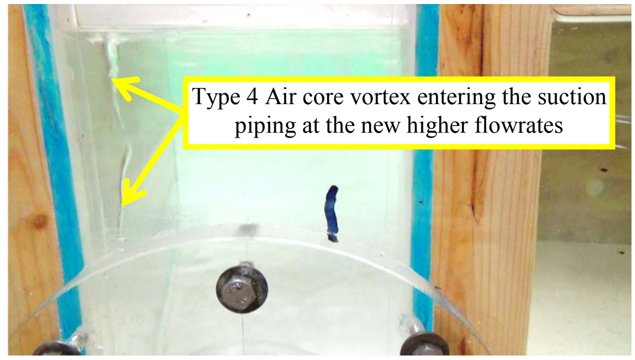

Figure 12. Model Flow Behavior at 37,000 gpm Displaying Type 4 Vortex Activity

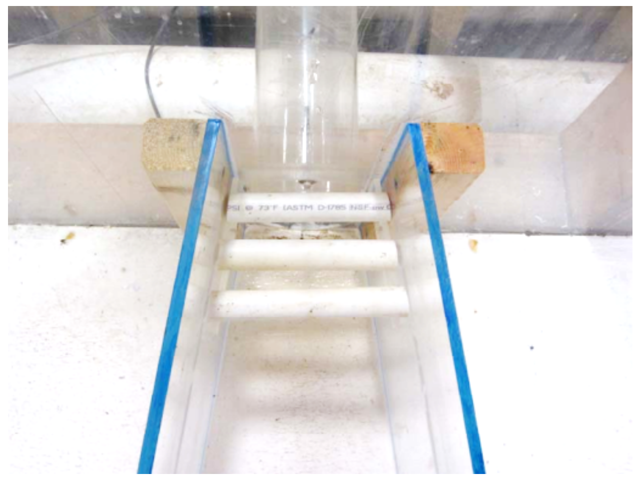

Figure 13. Vortex Suppression Pipes Modification Installed on Model

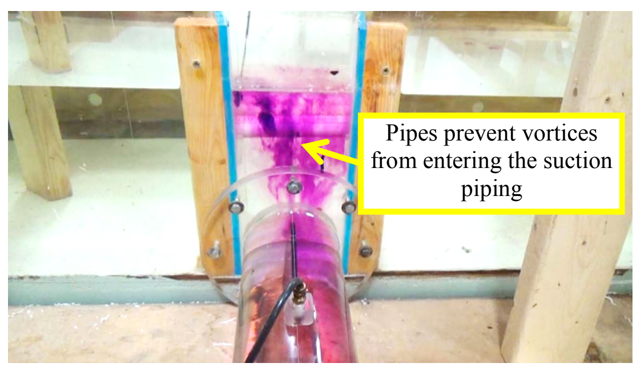

Figure 14. Model Flow Behavior at 37,000 gpm with Vortex Suppression Pipes Modification Displaying No Vortex Activity

PROPOSED SOLUTION

From the results of the intake model testing, the Consultant's recommended solution was retrofit installation of horizontal vortex suppression pipes in each of the pump bays. The pipes break up the vortices before they were able to form. Since the pipes are attached from end to end to the convergent

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pump intake bay walls and laid out horizontally, they are varied in length.

The Consultant originally proposed three 10 inch diameter pipes submerged in each of the pump intake bays and verified this proposed solution through model testing. Based on the Consultant's previous experience, a four 8 inch diameter pipes solution also eliminated the vortices and was equally as effective as the three 10 inch diameter solution. The two solutions have similar pipe spacing and positioning with the second recommended solution stretching further due to the additional pipe. The Client was given the option and ultimately decided on utilizing four 8 inch diameter pipes. All relevant model figures presented in this paper are with three 10 inch diameter pipes.

The next course of action is for the Engineering Contractor's civil design team to complete their design drawings and to hire a construction contractor to create modification modules with mounting brackets that would easily fit on top of the side walls of each of the pump bay. The suppression pipes can be made of inexpensive materials such as PVC and there would be no need for changing the existing sump/intake foundation. The modification module installation shall be completed before the turnaround date and before the new cooling water pumps are installed.

CONCLUSION

The cooling tower sump pump intake modification work is still in the progress of being completed by the Engineering Contractor. Initially, CFD was considered but given that it could not be used to meet the Hydraulic Institute Standards, the physical model option was selected. Not only was the physical model able to provide a thorough analysis of the existing intake system, it served as a control for the baseline and modification testing. As a result, the absoluteness of the suppression pipes modification preventing vortex activity was confirmed. The savings for the Client is evident when comparing the total cost of the model study, the engineering work, the construction and installation of the modification modules versus the price to lay out new foundation to expand or modify the existing cooling water intake system. More details and information in a follow-up paper will be available that will outline the modification implementation and commissioning process.

NOMENCLATURE

Fr	Froude Number
Re	Reynolds Number
U	Velocity
g	Acceleration of gravity
Q	Flowrate
A	Dimensional area
L	Dimensional length
ν	Kinematic viscosity

Subscripts:

m	model
p	prototype

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