Improving Approach Flow Hydraulics at Pump Intakes
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Abstract— Experiments were conducted on a physical hydraulic model of a circulating water pump sump structure. The cooling water intake structure consisted of two circulating water pumps and two auxiliary water pumps withdrawing flow from one end of a cooling tower basin. The objective of the hydraulic model study was to evaluate the performance of the initial design of the pump sump and to develop modifications to eliminate flow problems such as severe vortexing, intense swirl, or uneven flow distribution at the pump bell. The initial design of the intake structure developed high levels of pre-swirl and strong vortices were observed entering the circulating pumps. Modifications were developed in the model to reduce the level of flow pre-swirl and vortex activity and to improve the flow conditions entering the circulating water pumps. Proposed modifications to the sump included the installation of sidewall fillets, back-wall fillets and center floor splitters. Modifications also included the installation of a curtain wall set at El. 1089.95 and 3.71 m from the back-wall of the sump. With these modifications installed in the model, flow pre-swirl, vortex activity and pump throat velocities were all within acceptable limits for the range of operating conditions examined in the model. The minimum recommended water level in the cooling tower basin to prevent the formation of a hydraulic jump and to avoid the potential for adverse hydraulics and degradation in pump performance in the sump was El. 1089.90 m.

Index Term— Flow Swirl, Physical modeling, Vortices, Water Pumps.

I. INTRODUCTION

ELECTRIC power generating plants utilize circulating-water cooling systems that typically require a number of large scale hydraulic pumps to withdraw water from a river or a reservoir. Cooling system pumps experience certain common operational problems such as vibrations, impeller damage due to cavitation and excessive bearing wear. These problems are associated with certain undesirable characteristics of the flow field in the vicinity of the pumps and are caused primarily by poor design of the intake channel surrounding the pump bell or insufficient pump intake submergence depth. Poor pump intake design can result in an approach flow with high swirl levels. If the level of swirl at the entrance to the pump is excessive, the flow will approach the impeller blades at an angle, which can lead to deviations in pump performance and a reduction in the minimum pressure on the impeller blades. In extreme cases, this minimum pressure can be low enough to generate cavitation and damage the impeller blades. With the level of flow swirl usually irregular, there will be a loading and unloading on the impeller that can result in vibration and fatigue [3]. An inappropriate geometrical layout near the pump bell may lead to strong subsurface vortices. These flow phenomena create a fluctuating load on the blades of the pump impeller as each blade passes through the low-pressure vortex core. This can lead to vibration, increased bearing wear and potentially fatigue failure of the pump components [6] and [2].

Given these potential impacts on pump performance, the following performance criteria have been developed from the [8] and [4], and were utilized in evaluating the performance of the circulating water pump sump design for the current study:

- Free surface and sub-surface vortices entering the pump must be less severe than vortices with diffusive dye cores (Type 2). Fig. 1 illustrates the Vortex Classification system utilized for the study.
- The average swirl angle should be less than 2.5 degrees. The swirl meter rotation should be reasonably steady, with no abrupt changes in direction when rotating near the maximum allowable rate (angle).
- Time-averaged velocities, V, at points in the throat of the bell or at the pump suction in a piping system shall be within 10 percent of the cross-sectional area average velocity.
- Time-varying fluctuations at a point shall produce a standard deviation from the time-averaged signal of less than 10 percent.

[1] reviewed flow problems at water pump-intake bays and methods for their mitigation. They mentioned that as there were no reliable guidelines or criteria of design of trouble-free intakes and added that the usual solution to suppress such pump intake vortices is to conduct a laboratory experiment on a scaled model, observe the flow, identify the source of particular problems and propose modifications to intake geometry.

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Severe free surface vortices may be broken up and effectively suppressed by arranging baffles and vanes to correct the rotational flow field due to the approach flow distribution. Relocation of pumps, using breaker pipes, introduction of horizontal grids below the water surface, changing of wall and floor clearances, improvements in approach channel configurations, and changes in lengths and spacing of piers are some of the common techniques for reducing vortex activity. Surface vortices can also be controlled by installing a curtain wall immediately upstream of the pump.

Submerged vortices are usually eliminated by installing splitter vanes or floor cones under the bell. Variations in floor and wall clearances can also be effective and should be tried in the model.

II. PROTOTYPE DESCRIPTION

The hydraulic model study was conducted to assist in developing the hydraulic design of the circulating water pump structure for the prototype. The cooling tower intake structure consists of two circulating water pumps and two auxiliary water pumps withdrawing flow from one end of a cooling tower basin. The cooling tower basin is 15.7 m wide, 68.6 m long, and 1.83 m deep (see Figs. 8 and 9 for the 1:6.5 model of the prototype). The pump sump is not centered at the end of the cooling tower basin as the two share a common sidewall. The sump is approximately 11.68 m wide, 13.65 m long, and 4.88 m deep. The basin floor directly upstream of the pump station slopes down 3.05 m from the floor of the cooling tower basin to the floor of the pump sump over a distance of 18.29 m. The basin and the sump floors are at El. 1089.39 and El. 1086.34 m, respectively. Immediately upstream of the toe of the slope the sump divides into five pump bays. The two circulating pump bays are 2.74 m wide and 13.65 m long, while the two auxiliary pump bays are 1.42 m wide and 11.97 m long. The empty pump bay is 1.83 m wide and 13.65 m long. For the purposes of this study, the bays viewed from right to left (viewed looking downstream) are referred to as an empty bay, Circ 1 (Circulating Pump Bay 1), Circ 2 (Circulating Pump Bay 2), Aux 1 (Auxiliary Pump Bay 1) and Aux 2 (Auxiliary Pump Bay 2), as shown in Fig. 8.

The two circulating water pumps have 1.32 m diameter bells while the two auxiliary water pumps have 0.71 m diameter bells.

Circ 1 and Circ 2 water pumps are rated at 35,300 gallons per minute (gpm) with a runout flow of 43,000 gpm. Their pump bells are centered in the bays 1.07 m from the back-wall of the pump bay and set at El. 1086.74 m (floor-to-bell clearance of 0.4 m). Aux 1 and Aux 2 water pumps are rated at 7,200 gpm. Their pump bells are centered in the bays 0.69 m from the pump bay back-wall and set at El. 1086.55 (floor-to-bell clearance of 0.21 m).

The cooling tower basin low water level is El. 1090.61 m and the high water level is El. 1090.91 m.

III. SIMILITUDE AND SCALE

Scale hydraulic models require that the force relationships in the model and prototype are dynamically similar. To achieve complete similarity, the ratio of the inertia to the gravitational, viscous, and surface tension forces must be the same between model and prototype. Only a 1:1 scale model can achieve all these criteria. Modeling at reduced scale involves identifying the primary force relationship to best simulate prototype conditions, then selecting a model scale to minimize any resulting scale effects [5] and [7]. For free-surface flow conditions of the type being examined in the present investigation, the gravitational force is the dominant force that defines the hydrodynamic flow conditions, and the ratio of the inertial to gravitational forces, represented by the Froude number \(F\) must be equal in the model and prototype.

In modeling flow in a pump sump to evaluate the potential for the formation of vortices, the geometric scale is selected to
minimize viscous and surface tension scale effects. Also, the model should be large enough to allow flow visualization, accurate measurements of flow pre-swirl and velocities, and sufficient dimensional control. The Reynolds number $R$ defines viscous effects and the Weber number $W$ defines surface tension effects. Based on the available literature, the influence of viscous and surface tension forces is negligible if the model bell entrance $R$ and $W$ are above $6 \times 10^4$ and 240, respectively. At a model scale of 1:6.5, the circulating water pumps met the necessary criterion with a bell entrance Reynolds number and Weber number of $1.2 \times 10^5$ and 1122, respectively.

IV. MODEL DESCRIPTION

The model, as shown in Fig. 9 and Photo 1, reproduced the four pump bays, the empty bay, and a portion of the cooling tower basin adjacent to the intake structure. The length of the cooling tower basin represented in the model was approximately 18'-0" and its width was 7'-11" (all dimensions in this section are given in model units). The intake structure was located at the end of the cooling tower basin and built in accordance with the model design drawings as shown in Figs. 8 and 9. The intake structure was built on a raised platform and was constructed using a combination of marine plywood and transparent plastic for viewing of flow patterns.

The model included accurate representation of the external and internal geometry of the circulating water suction pump bells up to the location of where the pump impeller would be located in the prototype pumps. At the selected scale of 1:6.5, the model circulating water pump bell diameter was 8" and its throat diameter was 3.2". Circulating pump bells were made from transparent plastic and connected to a cast acrylic tube representing the pump column (refer to Fig. 4 and Photo 2). The detailed geometry of the auxiliary water pump bells was not reproduced in the model. Flow was withdrawn through the two auxiliary pumps to ensure accurate simulation of the flow patterns approaching the circulating water pump bays.

The model used a self-contained circulation system to produce the model flows, which were controlled with butterfly valves installed in each of the pipes that supplied flow to the head box located at the end of the model cooling tower basin. The model circulating water and auxiliary water pumps were connected through a discharge manifold to the suction end of a centrifugal laboratory pump. Individual pump flow rates were adjusted with butterfly valves in each of the model pump suction lines. Water levels in the cooling tower basin were varied by changing the amount of water in the model.

The flow requirements in the model ranged from 1.2 cubic foot per second (cfs) for a single circulating water pump operating with two auxiliary water pumps to 1.8 cfs for operation of all four pumps.

V. MODEL MEASUREMENTS AND INSTRUMENTATION

The following measurements were required for the model:

A. Flow Rates

The total model flow rate was measured using orifice-plate flow meter, with air-water manometer used to measure the pressure differentials. An orifice plate was installed in accordance with ASME Test Code Standards. Individual pump flows were measured using elbow meters that measured the pressure differential between the inside and outside of a 90 degrees bend installed in the discharge line for each pump. These elbow meters were calibrated in-place using the orifice-plate flow meters.

B. Free-Surface Vortices

Free-surface vortices were measured by visual observation using dye and were based on the Hydraulic Institute's free surface vortex strength scale of Type 1 to Type 5 (Fig. 1).

C. Sub-Surface Vortices

Sub-surface vortices were measured by visual observation and based on the Hydraulic Institutes sub-surface vortex strength scale of Type 1 to Type 5, as shown in Fig. 1. Similar to the free-surface vortex tests, dye was used to identify these vortices.

D. Flow Pre-swell

Swirl meters installed in circulating model pump bells, as shown in Photo 2, provided a measure of average intensity of swirl angle, $\theta$, according to the following equation:

$$\theta = \tan^{-1}\left(\frac{\pi dn}{u}\right)$$  \hspace{1cm} [1]

where: $d$ = diameter of the pipe at the swirl meter $n$ = revolutions/second of the swirl meter $u$ = average axial velocity at the swirl meter

E. Water Levels

Water levels were measured using staff gauges in the cooling tower basin and the individual pump bays.

F. Approach Flow Patterns

Visual aids such as colored dye and neutral-density particles were used to document the flow patterns in the cooling tower basin and individual pump bays.

G. Velocity Distribution at the Throat of the Pump Suction Bell

Pump inlet velocities were measured with a miniature propeller velocity probe installed at the throat of Circ 1 pump. Velocities were measured at eight locations at a constant radius from the pump axis around the circumference of the pump throat. Statistical values such as maximum, minimum and maximum temporal fluctuation were computed from the velocity probe data.
**H. Photographs and Video**

Still photographs and video footage were taken throughout the test program to provide a visual documentation of the model study progress and key results. Relevant photographs have been included in this report.

![Fig. 2](image1.jpg) (photo 1) View looking downstream at the four pump bays, the empty bay, and the sloping forebay area

![Fig. 3](image2.jpg) (Photo 2) Close-up view of the model pump bell for Circ 1 pump with swirl meter and high-speed velocity probe installed.

**VI. TEST PROGRAM**

The test program consisted of the following three phases:

**A. Initial Design Testing**

Tests conducted to evaluate the performance of the initial design and determine the most severe flow condition(s). Three initial design tests were conducted at the lowest expected water level (El. 1090.61 m).

**B. Modification Testing**

Tests conducted to develop modifications for the initial design to improve the performance of the intake operating under the most severe flow condition(s) that were identified in the Initial Design Testing.

**C. Final Testing**

Tests to confirm that the final adopted design will meet the specific operational criteria over the full range of operation conditions. Seven detailed documentation tests were conducted with the proposed final modifications installed in the model.

**VII. TEST RESULTS**

**A. Initial Design Testing**

Three evaluation tests were conducted with the initial design installed in the model and at the specified low water level in the cooling tower basin (El. 1090.61 m). Tests included a single circulating water pump operating and two circulating water pumps operating at design flow (35,300 gpm). All of the initial design tests were run with two auxiliary water pumps operating at 7,200 gpm, as outlined in Table 1.

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Water Level</th>
<th>Circ 1</th>
<th>Circ 2</th>
<th>Aux 1</th>
<th>Aux 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1</td>
<td>1090.61 m</td>
<td>35,300</td>
<td>x</td>
<td>7,200</td>
<td>7,200</td>
</tr>
<tr>
<td>1-2</td>
<td>&quot;</td>
<td>x</td>
<td>35,300</td>
<td>7,200</td>
<td>7,200</td>
</tr>
<tr>
<td>1-3</td>
<td>&quot;</td>
<td>35,300</td>
<td>35,300</td>
<td>7,200</td>
<td>7,200</td>
</tr>
</tbody>
</table>

Water entering the pump station separated from the upstream end of the walls of the circulating water pump bays. The separation was more pronounced in Circ 2 when only one circulating pump was operating. This flow separation generated a high lateral variation in the flow velocity across the bay width, which led to moderate levels of flow pre-swirl up to 7 degrees (56 rpm) clockwise (as viewed from above) recorded in Circ 2. A more uniform flow distribution was observed during Tests 1-1 and 1-3 where the flow pre-swirl was less than 2 degrees (14 rpm).

No free surface vortex activity was observed in any of the three initial design tests. However, intermittent Type 3 and constant Type 2 sub-surface vortices were observed originating from the back-wall, floor, and sidewalls of the circulating water pump bays for all operating conditions.

Velocity data recorded within the throat of Circ 1 produced a maximum deviation of 9% from the mean (Test 1-1), which was within the specified criterion of ±10%. Temporal fluctuations produced a maximum deviation of ±6% from the time-averaged signal (Test 1-3), which was also within the specified criterion of ±10%.

The head loss measured from the cooling tower basin to the pump bays was approximately 3.0 cm (1.2 inches).

In summary, the levels of pre-swirl and vorticity were found to exceed the HI-specified performance criteria. Maximum pre-swirl was demonstrated to be most pronounced when Circ 2 pump was operating at design flow (35,300 gpm) in combination with both auxiliary water pumps operating at
7,200 gpm (Test 1-2) while subsurface vortex activity was demonstrated to be pronounced in all three initial design tests.

B. Modification Testing

Following the initial design testing, a series of design modification tests was conducted. The objective of these tests was to develop and implement changes to the initial design that would reduce or eliminate the adverse flow conditions observed for the initial geometry. Modification testing was conducted at the specified low water level in the cooling tower basin (El. 1090.61 m).

A total of eight different geometrical arrangements were investigated in the model as part of modification testing. Some of the modifications were examined independently, while others were examined in combination with other modifications. Modifications examined in the model included the following:

- installation of sidewall fillets, back-wall fillets and a center floor splitter within the circulating water pump bays;
- installation of a curtain wall at various depths and locations within the circulating water pump bays;
- addition of inlet piers at entrances to the circulating water pump bays;

Installation of Fillets and Splitters

Fillets and splitters are often utilized to reduce/eliminate sub-surface vortex activity along the boundaries of the sump in the vicinity of the pump bell. Fillets and splitters were used in all modification tests and proved to be successful in eliminating the sub-surface sidewall and floor vortices. The presence of fillets and splitters also contributed to a reduction in the flow pre-swirl angle to 2 degrees (20 rpm) in Circ 1 and Circ 2 pump bays. Based on these results, the installation of fillets and splitters within the circulating water pump bays was recommended.

Installation of Curtain Wall

Pump sump designs frequently examine the use of a curtain wall as a method of reducing/eliminating the level of surface vortex activity, velocity non-uniformity, and flow pre-swirl. At this stage of the test program no significant surface vortex activity in the vicinity of the circulating water pumps had been observed. Hence, testing was conducted to examine the use of a curtain wall as a method of reducing/eliminating velocity non-uniformity and flow pre-swirl. For the present study, testing was conducted with a curtain wall installed in both circulating water pump bays at alternative locations and elevations. It was found that the placement of the curtain wall was influential on reducing velocity non-uniformity and the intensity of flow pre-swirl. For example, by setting the bottom of the curtain wall at El. 1089.95 and locating the wall 3.71 m from the back-wall of the sump, flow pre-swirl was reduced to less than 1 degree (8 rpm) in Circ 1 pump bay, and zero degrees (4 rpm) in Circ 2 pump bay. In addition, velocity data recorded within the throat of Circ 1 produced a maximum deviation of 5% from the mean and the temporal fluctuations had a standard deviation of 3% from the time-averaged signal. Although the curtain wall was effective in reducing flow pre-swirl and velocity non-uniformity, its installation was still optional given the fact that the sump met all performance criteria with just the installation of the fillets and splitters as described above.

Installation of Inlet Piers

Inlet piers are often installed at the entrance to the pump bay as an alternative method of reducing flow pre-swirl and velocity non-uniformity. The placement of a three-pier arrangement, equally spaced with respect to the pump bay width and installed with their upstream faces flush with the toe of the sloping fore-bay at the sump entrance (in combination with fillets and a floor splitter), was found to be relatively ineffective and their use is not recommended for this project.

Installation of Concrete Support Beam

Upon completion of modification testing, it was found that a concrete support beam (0.4 by 0.5 m) spans the pump bay entrances (see Figs. 8 and 9 and Photo 3). The top and bottom elevations of the beam are 1090.66 and 1090.26 m, respectively. The beam was partially submerged at low water level and fully submerged at high water level. Further modification testing was therefore conducted with the support beam installed in the model.

It was found that the presence of the beam produced intermittent Type 3 surface vortices in the vicinity of both circulating pump bays (see Photo 3). As a result, the installation of a curtain wall within both bays, as described above, was deemed necessary to eliminate the surface vortex activity.

Proposed Modifications

On the basis of the above modification testing, the proposed design modifications included:

- installation of sidewall fillets, back-wall fillets and a center floor splitters; and
- installation of a curtain wall set at El. 1089.95 and 3.71 m from the back-wall of the sump;

With both circulating water pumps operating at design discharge of 35,300 gpm and both auxiliary pumps operating at 7,200 gpm for the low water level, the head loss in all four pump bays was negligible (approximately 3.0 cm). The flow pre-swirl angle was 1 degree (11 rpm) clockwise in Circ 1, and zero degrees (2 rpm) clockwise in Circ 2. No vortex activity was observed at the surface, sidewall or on the floor. The only vortex activity was constant Type 1 vortices occurring near the back-wall as a result of flow separation from the pump column. The spatial variation of velocities within the throat of the bell (Circ 1) was within 5% and the temporal velocity fluctuations were 3% or less (both are within the specified criteria of ±10%).
Fig. 4. (Photo 3) View of intermittent Type 3 vortex formation after installing the support beam at the water surface of Circ 1 pump bay with pump operating at a design discharge of 35,300 gpm.

Table II
Final Test Program

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Water Level</th>
<th>Operating Pump Discharges (gpm)</th>
<th>COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Circ 1</td>
<td>Circ 2</td>
<td>Aux 1</td>
</tr>
<tr>
<td>1</td>
<td>1090.61 m</td>
<td>43,000</td>
<td>x</td>
</tr>
<tr>
<td>2</td>
<td>&quot;</td>
<td>43,000</td>
<td>7,200</td>
</tr>
<tr>
<td>3</td>
<td>&quot;</td>
<td>35,300</td>
<td>35,300</td>
</tr>
<tr>
<td>4</td>
<td>1090.91 m</td>
<td>43,000</td>
<td>x</td>
</tr>
<tr>
<td>5</td>
<td>&quot;</td>
<td>43,000</td>
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<tr>
<td>7</td>
<td>Variable</td>
<td>35,300</td>
<td>35,300</td>
</tr>
</tbody>
</table>

C. Final Testing

The objective of the detailed documentation testing was to ensure that the modifications to the intake would perform satisfactorily for a range of operating conditions. The seven tests listed below in Table 2 were conducted with the above modifications installed in the model.

In all cases, the recommended modifications to the circulating water pump bays were successful in providing acceptable flow conditions entering the pump. Although slight flow separation was still apparent at the entrance to the intake structure, the curtain wall was effective in eliminating flow disturbances in the vicinity of the pump bells. The pre-swirl angle did not exceed 1 degree (11 rpm) for any of the test conditions examined.

Vortex activity on the water surface and sidewalls of the circulating water pump bays was eliminated. With the installation of a center floor splitter beneath the circulating pump bells there was no evidence of floor vortex activity. Subsurface vortex activity near the back-wall was limited to constant Type 1.

Velocities at the throat of the circulating water pump (Circ 1) were recorded for four of the seven tests. In all cases, the maximum deviation in the average flow velocity was ±5% or less and the maximum temporal fluctuation recorded was ±3% or less.

A test to determine the minimum acceptable water level within the cooling basin was conducted by slowly lowering the water level in the model with both circulating water pumps operating at their design discharge of 35,300 gpm and both auxiliary water pumps operating at 7,200 gpm. When the water level reached El. 1089.75 m, the inlet to the pump intake structure became a hydraulic control point and flow entering the pump station became supercritical. As a result, the water level in the cooling tower basin would not fall below 1089.75 m, whereas the water level within the intake structure could continue to decrease to the point where excessive quantities of air was entrained. Based on this test it is recommended that the water level within the cooling tower basin be maintained at El. 1089.90 or higher for all operating conditions.

Fig. 5. (Photo 4) View of the model looking downstream showing the curtain wall and the revised fillets and floor splitters.

Fig. 6. (Photo 5) With the installation of a center floor splitter, sub-surface vortex activity in this area was reduced from Type 3(I) to Type 0. Both pumps are operating at their design flow of 35,300 gpm.
VIII. CONCLUSIONS

Testing conducted for the initial design of the intake structure demonstrated that moderate flow separation at the entrance to the intake generated non-uniform flow approaching the pumps, thereby resulting in moderate levels of flow pre-swirl entering the pumps. The maximum flow pre-swirl angle recorded was 7 degrees (56 rpm) clockwise in Circ 2 pump bay. The initial design was also shown to be susceptible to the formation of sub-surface vortices. Intermittent Type 3 and constant Type 2 submerged vortices originating from the back-wall, floor, and sidewalls of the pump bay were observed in the circulating water pump bays for all operating conditions. Intermittent Type 3 surface vortices were also observed after the installation of a horizontal beam representing a concrete support beam in the prototype. Velocity measurements at the throat of the circulating water pump (Circ 1) indicated that the maximum deviation in the average flow velocity and the temporal velocity fluctuations were within the Hydraulic Institute’s specified limits.

Several modifications to the initial design were developed in the model. The objectives of the modifications were to improve the lateral distribution of flow within circulating water pump bays and to reduce the vortex activity in the vicinity of the pump such that the hydraulic conditions in the sump would meet the specified performance criteria. The modifications developed in the model included the following (refer to Photos 4 and 5):

- installation of sidewall fillets and back-wall fillets within circulating water pump bays;
- installation of a center floor splitter beneath both pump bells; and
- installation of a curtain wall within both circulating water pump bays set at El. 1089.95 m and located 3.71 m from the back-wall of the sump.

With these modifications installed, flow pre-swirl, surface and sub-surface vorticity, and pump bell velocity distribution were all within acceptable limits for the range of expected operating conditions examined in the model. The minimum recommended water level in the cooling tower basin is El. 1089.90 m.

REFERENCES

Notes:
1) ALL DIMENSIONS ARE GIVEN IN MODEL INCHES
2) ALL ELEVATIONS ARE GIVEN IN PROTOTYPE METERS
3) MODEL SCALE 1" MODEL = 6.5" PROTOTYPE

Fig. 8. Model Layout (sump details)
Notes:
1) ALL DIMENSIONS ARE GIVEN IN MODEL INCHES
2) MODEL SCALE 1" MODEL = 6.5" PROTOTYPE
3) BASIN CONSTRUCTION TOLERANCE ± 0.25
   PUMP BELL CONSTRUCTION TOLERANCE ± 0.05
   PUMP BELL LOCATION TOLERANCE ± 0.13

Fig. 9. Model pump bell geometry