MCNARY DAM FOREBAY TEMPERATURE IMPROVEMENTS COMPUTATIONAL FLUID DYNAMICS (CFD) NUMERICAL MODEL STUDY

by

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Executive Summary

The goal of this numerical model study was to develop a fully coupled three-dimensional (3D) Computational Fluid Dynamics (CFD) model to investigate the hydrodynamics and thermal stratification within and upstream of the McNary Dam on the Columbia river. Following a general description of the computational models, the advantages of employing a model that can use hybrid unstructured grids are discussed. The hydro-dynamic component of the turbine intake CFD model was validated using data collected on a scaled model at the Engineering Research and Development Center (ERDC) for the single turbine unit model. Comparisons are also provided with a previous model that used structured grids for the same geometry. The temperature component was validated using data collected by the U.S. Army Corps of Engineers (USACE) Walla Walla District during summer 2004. The validation simulations (one with no spill and one with spill) were done for the full forebay model geometry. The model was then used to predict the effect of different operating conditions and/or structural changes to minimize the occurrence of adverse thermal conditions. Four simulations are presented that describe the effects of intake roof modifications and of the introduction of floating vertical barrier curtains in the forebay on the overall temperature distribution in the forebay and powerhouse units. The validated model may be used in future numerical studies to minimize the occurrence of adverse thermal conditions at McNary Dam that can endanger the life of resident and anadromous fish. This work was sponsored by the USACE Walla Walla District, Washington, USA.

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1 INTRODUCTION

This report documents the development, calibration, validation and initial utilization of a three-dimensional (3D) computational fluid dynamics (CFD) model that can use unstructured hybrid meshes to predict the flow and thermal conditions in the McNary Dam forebay on the Columbia River. The objective of the present study is to construct and validate a 3D CFD model capable of simulating the complex hydrodynamic and thermal conditions in the forebay and turbine intakes of McNary Dam and to demonstrate the potential of the CFD model to analyze the impact of structural and operational changes under consideration by USACE on the temperature distribution within the fish passages and gatewells.

Initial solutions to alleviate temperature-related fish passage problems are considered in the present study. They include introduction of a barrier curtain upstream the intake units situated near the southern shore and modification of the roof geometry of the intake units. To address these objectives, two models were developed. The first model was for a single turbine intake (Figures 1 to 6). The model includes all relevant geometrical details within the turbine intake and gatewells that influence the flow within the unit. Hydrodynamic validation of the single turbine unit (STU) model was performed using the 1:25 scale model data provided by ERDC. The second full forebay (FF) model includes the forebay up to 13,000-ft upstream from the dam, all the intake units, spillway bays, and other ancillary geometric features (Figures 9 to 14).

The temperature validation of the full forebay model was done using temperature data collected by USACE, Walla Walla District during summer 2004 in the forebay of McNary Dam. Two operational conditions corresponding to the flow and thermal conditions recorded on August 16, 2004 (with no spill) and June 30, 2004 (with spill) were selected for validation of the temperature model. In addition, simulations that include temperature transport have been run to investigate the changes in the temperature distribution within the forebay and intake units resulting from two modified intake roof geometries and addition of two floating vertical barrier walls into the forebay just upstream the powerhouse units. The design and configuration of the new intake roof geometry and the position and dimensions of the curtains were provided by USACE, Walla Walla District.

The typical grid size for the full forebay simulations was approximately 6 million cells. These large grid sizes were needed to incorporate all the relevant geometrical details of the hydraulic structures and forebay bathymetry over a length of 13,000 ft upstream of the dam face and to accurately resolve the large temperature gradients present near the free surface. This last requirement was found to be essential to accurately predict the temperature distribution within the forebay and intake units. As the memory requirements associated with running 3D RANS simulations on grid sizes in this range are much larger than the amount of memory a single 32 bit processor can provide (2Gb RAM memory), the only option was to run the model in a parallel computer environment. The typical run-time using eight processors for a temperature simulation of the full forebay model was approximately three days.

2 BACKGROUND

Several ecological problems are caused by the presence and operation of hydropower plants in a natural environment. High water temperatures due to atmospheric heating and selective withdrawal of water may be lethal or, at the very least, detrimental to fish in rivers and lakes. One location where there has been temperature related issues is McNary Dam on the Columbia River. During summer months when atmospheric heating is strong and calm wind conditions are present, high water temperatures in the forebay, gatewells, and juvenile fish collection channel have been observed to be harmful to fish survival and health. It is speculated that water along the southern end (Oregon shore) of the forebay tends to warm more quickly and to a higher level than water elsewhere in the forebay. The shallow conditions upstream of the southern side of McNary Dam influence the approach flow and thermal conditions at the southern end of the powerhouse. These factors may contribute to warmer water being drawn into the gatewells at this end of the powerhouse (Generating Units 1 through 4). Juvenile salmonids that enter these gatewells may be subject to large changes in water temperature over small distances/times that may prove harmful or fatal to them. In addition to the immediate impact on fish condition and survival, there may be a long-term cumulative impact of reduced fish health, as the stresses that impact fish as they migrate are cumulative.

Development of effective solution strategies necessitates the knowledge of the flow details through the entire hydropower plant including the forebay area. The flow in these regions is highly three-dimensional with additional complexity added by the presence of thermal stratification. Fully 3D CFD models can be used to obtain this information provided that they can accurately predict the flow and temperature distributions within such complex domains that contain many hydraulic structures and rapidly varying bathymetry. The mechanisms that affect the transport and mixing in the forebay and within the dam are greatly affected by the presence of strong secondary currents within the forebay and vertical mixing which cannot be accurately captured by the more traditional depth-averaged models. Moreover, use of the hydrostatic assumption for the pressure that reduces considerably the computational resources needed to obtain 3D numerical solutions is not justified due to the strong three-dimensionality of the flow in the dam area. As shown in the present study, models that can incorporate all the geometrical details necessary to capture the relevant physics of the flow and temperature transport necessitate meshes that contain millions of grid cells. A second issue related to the grid is the quality of the mesh which in turns affects significantly the accuracy and convergence speed of the simulation. For these complex geometries the most efficient way to generate a high quality mesh (low stretching ratios between cells especially at the block interfaces and relatively low skewness of the elements) is to employ a solver that can use hybrid unstructured meshes. Solving the non-hydrostatic 3D Navier-Stokes equations with a RANS turbulence model on meshes containing millions of cells requires the use of parallel solvers that scale well on a relatively large number of processors when they are run on supercomputers or PC clusters. The problem is not only memory but also speed (time needed to obtain a solution for a given set of conditions), if these CFD models are to be used by USACE in the process of evaluating the different scenarios involving operational and/or structural modifications that can alleviate or minimize the ecological problems at hydropower dams.

Relevant CFD investigations that attempted to simulate flow in river reaches of realistic geometry using 3D Navier-Stokes non-hydrostatic models and contained comprehensive validation studies include the ones by Sinha et al. (1998) who simulated the tailrace of Wanapum Dam and by Meselhe et al. (2000) who simulated the flow in the forebay of Wanapum Dam. Both studies used a multi-block 3D finite-difference solver (see Sinha et al., 1998 for a detailed description of the model) and the k-ε model with wall functions. Small scale bed roughness was accounted using a two-point wall-function approach. Recently, Huang et al. (2004) and Weber et al. (2004) used a general CFD solver (RIVER3D-U2RANS) to study the flow through a reach of the Chattahoochee River, near Atlanta, GA., containing hydraulic structures (bridge piers and several water intakes) and the flow downstream of the Wanapum spillway, respectively. One of the main contributions of the study of Weber et al. (2004) was the incorporation of a model for total dissolved gas prediction that accounts for gas production, exchange and transport physics. Though U2RANS is capable of using hybrid unstructured meshes, multi-block structured grids were used in these studies. Overall, good agreement between field/model measurements and the model simulations was observed in these studies. However, none of these studies was concerned with the prediction of temperature stratification effects. Also, the grid sizes in these studies were around one million cells. The primary objective of the present work is to construct and validate a 3D CFD model which is capable of simulating the hydrodynamics and temperature distribution within the forebay and turbine intakes at McNary Dam during stratified conditions. Some of the large simulations are conducted using unstructured meshes with around 6 million elements which to our knowledge are the largest used for this kind of applications. Though use of unstructured grid models are in principle more time-consuming than structured ones, their superior flexibility in representing very complex geometries and the possibility to generate higher quality meshes represent important advantages. If the CFD solver can be run efficiently on parallel computers (e.g., the present simulations were run on a Xeon PC cluster), which is the case of the solver (FLUENT) used in the present study, than very large simulations become feasible and these models can be used as a design/prediction tool by USACE.

In FY 2002 and 2003, a CFD model using U2RANS as the CFD engine of the McNary Dam forebay was developed using structured grids. The hydrodynamic validation of the single turbine unit model (grid used in these simulations is shown in Figure 2) was completed using the 1:25 scale model data provided by the District. An initial validation of the temperature module using a grid with close to 1.5 million cells was done using the 2002 USGS temperature data collected at the McNary Dam. Analysis of the simulation data showed that use of finer and higher quality meshes was needed to develop a model that can accurately predict temperature distributions in the forebay and within the intake units. In February 2004, it was decided to regenerate the computational mesh using a hybrid unstructured grid generator and to use FLUENT as the main CFD engine. The advantages were that it allowed the possibility to more easily accommodate additional structural changes into the full forebay model and to mesh efficiently the very shallow areas near the banks.

3 CFD MODELING APPROACH AND GRID GENERATION

FLUENT a state-of-the-art commercial CFD software is used in the present work. The parallel pressure based non-hydrostatic RANS steady solver in FLUENT is employed. The implicit RANS solver employs a cell centered finite volume scheme and can use hybrid unstructured meshes. The continuity equation is satisfied using the SIMPLE pressure-velocity algorithm. An additional scalar transport equation is used to account for temperature effects via the Boussinesq approximation. The Boussinesq approximation is appropriate for the present applications where the maximum temperature difference recorded in the forebay at a given time is around 6^0 C. The convective terms in the momentum and temperature transport equation are discretized using a second order upwind scheme, such that the solution is second order accurate in space. The incompressible RANS equations for buoyant flows are (time derivatives are omitted for the steady state solutions discussed in the present work, however FLUENT can do time-accurate simulations, in which case the unsteady terms have to be included):

$$\nabla \cdot \left(\rho_0 \vec{V} \right) = 0 \tag{1}$$

$$\nabla \cdot \left(\vec{V}\vec{V} \right) = -\frac{1}{\rho_0} \nabla p - \vec{g}' + \nabla \overline{\overline{\tau}} \tag{2}$$

$$\overline{\overline{\tau}} = \nu_{eff} \left[\left(\nabla \vec{V} \right) + \left(\nabla \vec{V} \right)^T \right] - \frac{2}{3} k \overline{\overline{I}} \tag{3}$$

$$\vec{g}' = \frac{\rho - \rho_0}{\rho_0} \vec{g} \tag{4}$$

$$\nu_{eff} = \nu + \nu_t \tag{5}$$

where ρ_0 represents the density of water at the reference temperature T_0, $\overline{\overline{\tau}}$ is the stress tensor, $\overline{\overline{I}}$ is the identity tensor, ν_{eff} is the effective eddy viscosity and k is the turbulent kinetic energy. The relative gravity $\vec{g}'$ in Equation (4) accounts for the effect of density variation in the momentum equations. The standard k-ε model with wall functions is used. The eddy viscosity ν_t is computed from:

$$\nu_t = C_\mu \frac{k^2}{\varepsilon} \tag{6}$$

The turbulence variables k and ε denoted as ϕ are obtained from the solution of their transport equation which can be written in the general form as:

$$\nabla \cdot \left(\vec{V}\phi \right) = \nabla \cdot \left[\left(\nu + \frac{\nu_t}{\sigma_\phi} \right) \nabla \phi \right] + S_\phi \tag{7}$$

$$S_k = G_k - \varepsilon \quad ; \quad S_\varepsilon = C_{\varepsilon 1} \frac{\varepsilon}{k} G_k - C_{\varepsilon\varepsilon} \frac{\varepsilon^2}{k} \tag{8}$$

$$G_k \equiv \nu_t \nabla \vec{V} : \left[\left(\nabla \vec{V} \right) + \left(\nabla \vec{V} \right)^T \right] \tag{9}$$

The source terms S_ϕ are given in Equation (8). The model constants are $C_\mu = 1.09$, $C_{\varepsilon 1} = 1.44$, $C_{\varepsilon 2} = 1.92$, $C_{\varepsilon 2} = 1.92$, $\sigma_k = 1.0$, $\sigma_\varepsilon = 1.30$. The temperature transport equation is (no source/sink terms):

$$\nabla \cdot \left(\vec{V}T\right) = \nabla\left(\alpha_{eff} \nabla T\right) \tag{10}$$

$$\alpha_{eff} = \alpha + \alpha_t \tag{11}$$

In Equation (11) α and $\alpha_t = \nu_t / \sigma_t$ represent the molecular and eddy diffusivity (the fluid is water and a value of $\sigma_t = 0.85$ is used).

The steady state simulations were run until the velocity magnitude and temperature was found to vary with less than 1% in representative sections in addition to observing a decay of 3 to 4 order of magnitude for the residuals. Typically for the full forebay simulations with Boussinesq that required around 10,000-15,000 iterations.

Two different models were created to simulate the hydrodynamics and temperature distribution at the McNary Dam forebay and its powerhouse units. The first one is referred as the Single Turbine Unit (STU) Model and the second one as the Full Forebay (FF) Model. The fish screens (ESBS & VBS screens) in these models were modeled as porous media to account for the hydraulic head loss through them. Unstructured mesh topologies that contain only hexahedral cells were employed to generate the grids used to perform the simulations corresponding to the both the STU and FF models. Use of hexahedral cells along with an unstructured grid paving technique was found to produce the highest quality meshes in terms of low stretching ratios and skewness of the cells given a certain constraint in the total number of grid points to mesh a certain domain. It also allowed us to refine the mesh around smaller but important structural elements (e.g., turning vanes) of the powerhouse units or in the bank areas of the forebay and then to transition smoothly but over a relatively short distance to larger size elements away from these critical regions. More importantly, the overall quality of the unstructured meshes was much higher than one of the original multi-block structured meshes that were used to build the STU and FF models. Several grid quality check-up tools available in the grid generator software were used to improve the mesh quality. The design drawings, bathymetry and bank lines and other geometric features of the dam were provided by the District.

3.1 Single Turbine Unit Model

The physical domain of the STU model included a generic block at the upstream of the turbine unit, three intake bays, the gatewells, the ESBS and VBS screens, the spiral scroll case and a vertical cylindrical outflow. The turning vane within the gatewells was also part of the model. Approximately 464,000 hexahedral cells were used to generate the multi-block unstructured mesh for the STU geometry using a paving technique (see Figure 1). The previous multi-block structured mesh contained 825,000 hexahedral cells (see Figure 2). The quality of the unstructured mesh is higher than the one of the previous structured mesh while the cell sizes in the critical regions are very similar in the two meshes. Close to 361,000 mesh cells were saved for the STU model using the unstructured hybrid grid topology. A 2-D longitudinal section through the centerline of bay B is shown in Figure 3 for the unstructured mesh model. A similar vertical section of the structured mesh is shown in Figure 4. Figures 5 and 6 show a horizontal section cutting through the scroll case for the unstructured and structured mesh models, respectively. These figures illustrate the differences in grid topology between the two mesh types. It can be seen from Figures 1 through 6 that a significant number of mesh points were saved in the unstructured model, especially in the gatewell area and in the spiral scroll case region.

All 14 powerhouse units were simulated in the FF model (Figure 12). The grid used to mesh each of these units (Figure 10) was much coarser and did not contain the scroll case and the vertical cylindrical outflow. Results of a STU simulation using this coarse mesh are also presented.

3.2 Full Forebay (FF) Model

The forebay model (Figure 9) includes the 14 powerhouse units of the McNary Dam (Figure 10), 22 spillway bays (Figures 11 and 13), the navigation lock and the complex forebay bathymetry upstream of the dam (Figure 8). Initially the forebay model extended 5,000-feet upstream of the dam. To reduce the influence of the upstream boundary conditions on the flow and temperature distributions close to the dam, the model was extended to 10,000-feet upstream of the dam. Subsequently, the model was further extended to 13,000-feet upstream of the dam to coincide with Transect T6 of the 2004 summer temperature data collection program (see Figures 7 and 8). It is noted here that the present model includes the new shore line of the Columbia River at McNary Dam as provided by USACE. Each powerhouse turbine unit includes three intake bays (denoted A, B and C) and is modeled to the downstream end of the intermediate piers (see Figure 12). The intake roof, main and intermediate piers, VBS and ESBS screens, turning vane and other geometric features have been reproduced correctly in all the powerhouse units.

The forebay bathymetry (Figure 8) has been reproduced using the hydrographic survey data supplied by USACE. Local model coordinates were used. The state plane coordinates (E-N) and the elevations were converted to the local model coordinates in such a way that the elevation Z=233.63 ft above MSL in the prototype represents Z=0.0 in the model coordinates. Cross-sections were extracted at various spacings from the supplied data to reproduce the bathymetry in the forebay area. Starting 120 ft upstream of the dam axis, three cross-sections were used at intervals of 40 ft (up to 200 ft). Two cross-sections were extracted at a spacing of 50 ft from 200 to 300 ft upstream of the dam. For the reach segment 300 to 500 ft upstream of the dam, two more cross-sections were extracted at an interval of 100 ft. The distance between the cross-sections was 100 ft from 500 to 2,000 ft upstream of the dam. The spacing was 200 ft for distances from the dam in the interval of 2,000 to 10,000 ft. Finally, a 300 ft cross-section interval was used up to the position of the temperature measurement transect T6. It is noted here that the present model has an inflow section that corresponds to the position of Transect T6. The temperature transects within the limits of the model are shown in Figure 7. The final bathymetry of the forebay between the extracted sections has been automatically created by the grid generator using an interpolation technique. A general view of the forebay bathymetry is shown in Figure 8. Approximately 6.1 million hexahedral cells were used to generate the unstructured mesh for the dam and forebay geometry. A 3D view of the forebay mesh is shown in Figure 9. Figure 10 shows a detail view of the 3D unstructured mesh in the region corresponding to the powerhouse units. Figure 11 shows an enlarged 3D view of the mesh in the spillway bays area. 2-D views of the mesh in the regions close to the dam face at the powerhouse units and at the spillway bays are shown in Figures 12 and 13, respectively. In these figures the advantages of the unstructured paving techniques used to transition between the fine mesh region inside the bays of the powerhouse units and the region upstream the dam are evident. In a structured environment the number of points over the width of the model would have been constant with the result that either a coarser mesh would have been used in the critical regions inside the powerhouse units and near the spillway bays or the total number of cells in the model would have nearly doubled to accommodate the mesh refinement needed in the powerhouse units region.

In most of the forebay domain, the number of mesh cell in the vertical direction was equal to 34. Clustering of grid points near the free surface and near the bed was needed to accurately capture the large thermal and velocity gradients present in these regions. Figure 14 shows a cross section through the unstructured mesh at x=-2500 ft near the southern shore along with a detail view of the critical boundary region between the mesh used to grid the very shallow bank area and the mesh used in the main forebay region. On the right of these mesh plots one can observe the distribution of the grid points near the water surface used in the main forebay area. It is noted here that the adequacy of the present vertical resolution in the forebay has been tested by running several temperature simulations with different levels of grid refinement until the temperature gradient near the free surface was satisfactorily captured (within 0.5^0 C at most of the stations). The regions situated near the forebay shore lines have been meshed using a reduced number of mesh cells over the depth. For instance, only three mesh cells were used near the vertical edge close to the shoreline, while 34 cells were used at the opposite vertical edge to connect with the main forebay mesh. This is one of the most important advantages of using an unstructured mesh. This level of flexibility results in a relatively high quality mesh over a domain where the depths vary greatly between the river bank areas and the center of the forebay.

Thus, in the less important regions of the computational domain, where there are only minor changes in velocity and temperature, a coarser mesh was used without compromising the overall accuracy of the solution. In regions where high gradients were present, a finer mesh was used. The typical cell size in the main forebay area is 15-24 ft in the horizontal directions and 3 ft in the vertical direction. Near the bottom and free surface the cell size in the vertical direction is decreased to about 0.5-0.75 ft, corresponding to o a non-dimensional distance to the wall of about 500-700 wall units which is reasonable for the high Reynolds numbers ($Re \sim 5*10^6$) present in the simulations discussed in this report. The quality of this new unstructured mesh was higher than that of the previous structured meshes due to the reduced skew ness and lower stretching ratios. In addition, a significant number of mesh points were saved (approximately 25%). Though unstructured solvers are more expensive than structured ones, the higher quality mesh generated using the unstructured mesh generator needed less iterations to converge. Overall the time needed to obtain a solution using similar grid sizes is similar for both the unstructured and structured solvers, but what is essential is that higher mesh quality translates into more accurate solutions and obtaining the same level of mesh refinement in critical regions and same overall grid quality for complex domains requires much larger (2-10 times) grid sizes if a structured grid generator and solver are used.

4 HYDRODYNAMIC VALIDATION (SINGLE TURBINE UNIT MODEL)

The hydrodynamic validation of the CFD model has been done for the unstructured grid STU model (grid contained 464,000 cells) by comparing with the 1:25 scale model data available from ERDC. This simulation is denoted as the fine mesh simulation. It is noted here that in the first phase of the study the hydrodynamic validation was also done for the structured grid STU model (grid contained 825,000 cells). Comparison between the unstructured fine grid simulation and the simulation with the previous structured grid in the STU model is provided (see Figures 16 to 18). Additionally, results from a simulation on a coarser mesh corresponding to the grid used inside each of the powerhouse units of the full forebay model are also included and compared with fine mesh results (see Figures 19 to 21) and with the scaled model data (Figures 24 to 31).

4.1 Simulation Set Up

The following boundary conditions were used for the hydrodynamic validation runs:

1) A flow rate of 16,450 cfs was specified at the upstream inflow section, identical to the one used in the 1:25 scale model runs.
2) A pressure outlet boundary condition was used at the downstream end of the model except for the coarse unstructured mesh simulation for which a mass outflow boundary condition was used.
3) A symmetry boundary condition was specified at the water surface.
4) The VBS and ESBS screens were modeled as porous media to simulate the pressure loss through the screens. The porosities of the bar screen and perforated plate were considered in the estimation of the equivalent screen porosity.
5) All walls were specified as no slip walls (all three velocity components were set equal to zero).

Hydrodynamic validation runs have been performed in which the fish screens (ESBS and VBS) were simulated as porous media to account for the hydraulic head loss through them similar to the procedure used in the previous CFD study using structured grids. Table 1 in Appendix-B gives the combined head loss coefficients and equivalent porosities in the different panels used to simulate the flow through the VBS screen in the fine unstructured mesh and structured mesh simulations. It is noted here that the VBS panels are numbered from bottom to the top. The effect of the head loss in the bar screen and perforated plates were accounted for by combining the head loss coefficients in each component. Equivalent porosities for the ESBS screen and for each panel of the VBS screen were estimated using the correlations established by Miller et al. (1990) (see Figure 15). It should be noted that these correlations have also been verified by Weber et al. (2000) for flat bar screens and perforated plates. Following the suggestion from the

District, the final validation of the single turbine unit model was completed using an uniform porosity for the ESBS screen. The VBS and ESBS porosities used in the final simulation are shown in Tables 1 and 2 in Appendix-B. A parametric study has been conducted using various ESBS porosities which revealed that a lower value of the ESBS porosity produces better results. In the present STU simulations an equivalent uniform ESBS porosity of 13% instead of the value deduced using the correlations proposed by Miller et al. (26%) has been used for validation of the hydrodynamic module. In the coarse unstructured mesh simulation a uniform porosity of 16% (mean value) was specified for all VBS panels.

4.2 Analysis of Validation Results

Velocity profiles from the fine unstructured mesh simulation at relevant vertical sections inside the three bays A, B and C of the powerhouse units were compared with the scale model data and the fine structured mesh results. The agreement in terms of velocity magnitude and velocity orientation at all the sections is satisfactory (within 10% at most measurement points), especially if one takes into consideration the scatter from the experimental data. A sample of these results is provided in Figures 16 to 18 for bays A, B and C at three sections (see Figure 23). In these figures the black vectors represent the present simulation using the fine unstructured mesh, the purple vectors represent the scale model data, and the white vectors correspond to the previous structured fine mesh solution. The predicted flow field within the main intake block and the gatewells appears to be physically correct.

The other quantities that are predicted as part of the present fine mesh simulations are the flow splits through the three bays and the three gatewells given as a percentage of the total discharge through the three bays (see Figure 22). The small asymmetries present in the geometry of the three bays and the spiral scroll case force a non-symmetric velocity profile at the exit from the bays. Consequently, these flow splits are not equal between the three bays. The predicted flow splits through bays A, B and C are 35.6%, 34.9% and 29.5% of the total bay discharge while the measured ones are 36%, 34.7% and 29.3%, respectively. The predicted flow splits through the gatewells in the bays are close to

11.2% of the total discharge, while the measured values are 10.8%. The structured fine mesh results show similar level of agreement with the scale model data for the flow splits through the bays. The flow splits through the gatewells are somewhat under predicted at 9.5%. Also included are results from the coarse model simulation in which the mass outflow through the three bays was prescribed according to the scale model data. The flow splits through the gatewells are somewhat over predicted at 12.2%. Comparison between the coarse mesh (black vectors), fine mesh (white vectors) and scale model data (red vectors) at the same three sections is shown in Figures 19 to 21 for bays A, B and C. Good qualitative agreement is observed even for the coarse unstructured mesh results. A more quantitative way to assess the performance of the fine and coarse mesh simulations is to plot the correlations between the model results and the scale model data at representative sections. This is done in Figures 24 to 31 for the velocity correlations at sections 1 to 3 (see Figure 23). Bay A results are shown in Figures 24 to 26, Bay B results are shown in Figures 27 and 28 (model data was not collected in section-2) and Bay C results are shown in Figures 29 to 31. As expected, the fine mesh results tend to be closer to the 45^0 line corresponding to perfect correlation between simulation and scale model data (e.g., see Figures 24, 29, 30 and 31). Although the coarser mesh results show poorer correlation with the experimental data it is not expected that this resulted in decreased performance of the FF model with respect to temperature. However, given these results, some additional grid points will be added in the intake region to improve hydrodynamic validation of the full forebay model in the intake region.

Overall, the STU validation results demonstrate the capability of the hydrodynamic model to simulate the essential hydrodynamics in complex geometries using unstructured grids.

5 TEMPERATURE VALIDATIONS (FULL FOREBAY MODEL)

The District conducted a comprehensive data collection program during the summer of 2004. This was done to provide temperature data needed to validate the fully coupled 3D CFD stratified flow model. Within the boundaries of the forebay CFD model, temperature measurements occurred at 46 stations along six different transects in the forebay. The locations of the measurement stations within the model boundaries are shown in Figure 32. Temperature measurements were carried out at a time interval of 15 minute from June 30, 2004 to August 30, 2004. In addition, temperature measurements were also recorded on the trash racks, within the gatewells and at the fish orifices.

The time history of the water temperature for the duration of the measurements was analyzed to determine suitable test cases for validation during which the flow and temperature conditions in the forebay were close to steady state. In addition, an important factor in the selection of relevant validation test cases was the presence of a relatively large temperature difference at the inflow section of the model. The analysis showed that some of the largest temperature gradients (4^0-5^0 C) occurred during the third week of August 2004 (August 16-August17). It was also found that fairly steady plant operational conditions were present during the afternoon of August 16 (no spill conditions), as shown in Figure 33. In the case when spill was present, it was observed that steady plant operating conditions occurred on June 30 when the maximum temperature variation at the inlet section was around 2.5^0 C. In Figures 34 and 46 the 4h and 2 hr time averaged temperature profiles at all stations of transect T6 are also shown for the non-spill (August 16) and spill (June 30) conditions respectively. The mean (4h and 2h time averages corresponding to temperature measurements at station T6P2) vertical temperature profiles specified as temperature boundary condition at the inlet section are also shown in Figures 34 and 46, respectively. The validation was accomplished by comparing measured temperature profiles at stations within the forebay and temperatures at the gatewells with predicted (simulated) temperature profiles at the same stations and gatewell temperatures for two validation test cases: one without spill (August 16, Case_1) and one with spill (June 30, Case_2).

5.1 Simulations Set Up

The mesh used for the validation runs includes all 14 units of the powerhouse and 22 spillway bays. Similar to the hydrodynamic validation, the VBS and ESBS screens were modeled as porous media using the same equivalent porosities (for VBS, the mean value deduced for the fine mesh STU simulation was specified at all panels in the FF model simulations) as used for the STU model hydrodynamic validation.

The time averaged powerhouse flows for August 16 and June 30 were extracted from the 5-minute plant operational conditions supplied by The District. The percentages of the total flow in each unit given in the records were used to calculate the discharge in each of the powerhouse units.

For the first test case (August 16, 2004) the river discharge (155,000 cfs) was taken equal to the total powerhouse flow over a period of 10 hours (10:00 a.m. to 6:00 p.m.) when operating conditions were nearly steady. However, as the temperature variation over this time was relatively high, such that over the 10 hours period the temperature fields are not steady, we decided to simulate a four hour interval (2:00 p.m. to 6.00 p.m.) over which the temperature field data was observed to be relatively steady. The forebay elevation during this period was 338.97 ft. The 339.0 ft forebay elevation was used in the simulation. As there was no spill on that day, the total powerhouse flow (straight dotted line in Figure 33) equals the total river discharge for the operating conditions recorded on the same day. Tables 3 summarize the outflow rates specified at the downstream end of each unit for Case_1. Given a river discharge of 155,000 cfs, the mean velocity at the inflow section is around 0.75ft/s. If the mean depth in the forebay is used as length scale (d~60 ft), the associated physical Reynolds number in the forebay is close to 5 million. This strongly suggests that temperature transport and mixing in the forebay are mainly governed by advective rather than buoyancy effects.

Although some ADCP velocity measurements were available at various transects within the model boundaries, this velocity data presented very high fluctuations over both width and depth. Though several methods to filter the data to remove the fluctuations were tried, due to the mobile transect method used to collect the data satisfactory profiles to be used for validation were not attainable. Additionally some point velocity data were available at transects T6 and T1 on August 16 and at Transect T3 on August 17. However, the measurement time was outside the time interval simulated in the present study. One of the main reasons to extend the model up to 13,000 feet upstream the dam was to allow the temperature and velocity profiles to adapt to the river bathymetry over the initial part of the computational domain such that the predictions near the dam will be relatively insensitive to the exact velocity profile specified at the inflow section.

For the second test case (June 30, 2004) the river discharge was taken equal to the sum between the total powerhouse flow (167,500 cfs) and the total spill discharge (49,800 cfs) (see Figure 46b). The average forebay elevation during this time period of two hours (4:00 PM to 6:00 PM) was 339.7 ft. In the simulation a forebay elevation of 339.0 ft was used. The powerhouse discharges at the 14 units and the spillway discharges at the 22 spillway bays during the simulation period (4:00 pm to 6:00 pm on June 30) are given in Tables 4 and 5, respectively. Similar to the first test case, a constant discharge equal to the total river discharge was specified at the inlet section.

The 4h (August 16) and 2h (June 30) averaged temperature profiles at the different stations situated in transect T6 seem to suggest that the temperature distribution varied mostly over the depth. The time averaged temperature profile at station T6P2 was used to specify the inflow temperature boundary conditions for both Case_1 and Case_2 (temperature measurements were available over the entire depth at this station). It is observed (Figure 34, T6P2 profile) that on August 16 the temperature varies sharply (~4^0 C) over the first 10 ft from the free surface while over the remaining depth the gradient is much smaller (~0.8^0 C over the next 60-70 ft). On June 30 (Figure 46, T6P2 profile), the stratification is milder and deeper (2.5^0 C over the first 30 ft below the free surface). Below this depth the temperature is practically constant (18.5^0 C).

Outflow boundary conditions were specified at the outlet of each powerhouse unit and spillway bay according to the values in Tables 3, 4 and 5 (the velocities are extrapolated from the interior values and then corrected such that mass outflow in each section is equal to the specified value in the corresponding table). The temperature and pressure at the outflow were also extrapolated from the interior of the domain. Consequently, there is no need to impose a value of the temperature at these boundaries.

The free surface elevation was known and a shear-free symmetry boundary condition was used for the velocity components (the normal component is set to zero, while for the other two components a zero shear stress value is imposed). In the two main simulations on August 16 and June 30 the wind effects were neglected. However, to investigate the possible effects of a high wind situation an additional simulation corresponding to conditions on August 16 with a wind blowing from North to South were considered. The wind speed was 10mph and the direction was chosen such that mixing near the Southern shore will be increased due to the wind action. The velocity boundary condition at the free surface was changed such that the additional shear stress induced by the wind in the N-S direction will be taken into account. The results of that simulation are included in Figure 45.

The temperature distribution on the free surface was specified at points corresponding to the 46 stations where temperature profiles were measured over the depth (the stations corresponding to the six transects are shown in Figure 32), by extrapolating the time averaged (4h and 2h, respectively) values corresponding to the first two measurement points below the free surface. One should mention that this is the most consistent and correct way to specify the temperature boundary condition on the free surface for validation of the internal components of the model and determination of the grid sensitivity.

In the preliminary simulations a mean constant temperature was used on the free surface rather then the extrapolated values of the temperature from the measurements at the available stations. The results were found to be comparable. In future simulations the heat flux will be estimated from weather data over the same period as the temperature inflow conditions (long wave and shortwave radiation and other effects will be accounted for). The incorporation of a heat flux, short-wave radiation, and long-wave radiation boundary condition is expected to be part of the next phase of this modeling effort. A new time accurate model which will account for the short-wave radiation absorption near the free surface, wind effects and atmospheric conditions is being currently tested. If successful, this will allow resolving the complex temporal thermal characteristics of the flow upstream the bay over 1-2 day periods including the temperature variations in the gatewell water temperatures.

5.2 Analysis of the Simulation Results for Validation Case_1 (August 16, 2004)

The predicted contours of the in plane velocity magnitude and 2D streamlines in a plane situated at z=100.4 ft, close to the free surface, are shown in Figure 35. As a result of the river discharge all passing into the powerhouse intakes, a zone of relatively high velocity is predicted in the forebay just upstream the intake units. As for the simulated conditions there is no spill flow, a low velocity zone is observed around the navigation lock. Also, a similar slack water zone containing several eddies is predicted at the southern downstream region of the forebay. As expected near both banks the velocities are quite low and depending on the shoreline shape several small recirculation region are observed. No clear vortical patterns are observed inside the two major downstream recirculation zones. This is simply because the bathymetry in these regions, situated close to both the dam structures and the shorelines, is very variable. This induces a high degree of three-dimensionality into the flow eddies observed in these areas. For instance, a large bed hump is present near the southern shore inside the recirculation region. Away from the shores the flow is quasi-parallel until about 4000 ft from the dam where it starts converging toward the powerhouse units.

Figure 36 shows the simulated temperature field in the same plane (z=100.4 ft). At this depth, near the inlet there are some temperature variations probably induced by the fact that the velocity profile in the inlet section was assumed uniform. For stream wise locations closer than 7,500 ft from the dam it appear that gradually there is a warming of the water on the side of the forebay corresponding to the southern shore while the opposite appears to take place on the other side. In the middle part, the temperature is in the range of 23^0-23.5^0 C until less than 1,000 ft from the dam. The largest temperatures (24^0-24.5^0 C) are observed in a region close to the southern shore in between 5,000 and 2,000 ft. Also, a thin streak of larger temperatures (in the same range of 24^0-24.5^0 C) is observed to entrain warmer water toward the intake units on the southern side (observe also the converging streamlines in Figure 35 corresponding to that streak). The distribution of the temperature in the region close to the dam and the southern shore is not uniform however the temperatures are consistently higher by 0.5^0-1.0^0 C than the ones recorded in the corresponding region closer to the northern shore. The cooler temperatures observed in this regions are a consequence of the interaction between the incoming vertically stratified flow, the bathymetry and the presence of the navigation lock. The overall effect is the convection toward the free surface or relatively cooler water from deeper levels. The presence of warmer water near the dam on the southern shore side is consistent with the general trends observed in the temperature distribution in the vicinity of McNary Dam during summer and more importantly with the present (August 16, 2004) field data measurements.

A more quantitative way of assessing the accuracy of the present predictions is to compare the simulated and measured temperature profiles at the 38 stations where field data was collected (Figure 32). This information is shown in Figures 37 and 38 for transect T1, in Figures 39 and 40 for transect T2, in Figures 41 and 42 for transect T3, in Figure 43 for transect T4 and in Figure 44 for transect T5. It should be mentioned that measurements were not available over the entire depth at some of the stations (e.g., T5P2 to T5P6). In these figures the predicted profiles are shown with the continuous line, the symbols (circles) correspond to the field data, and the horizontal lines through the symbols correspond to one standard deviation calculated from the 4h field temperature data measurements. The line is missing at the locations where the standard deviation was negligible (typically at deeper levels). Given the fact that the field data at transect T6 is used to set up the temperature profile in the inlet section, the good agreement between simulation and field data at transects T4 and T5 is somewhat expected. The agreement is especially good (within 0.5^0C) in the deeper region (more than 20 ft below free surface) where there is very little stratification.

In transect T4 situated roughly at about 3000 ft from the dam the agreement is very good for stations T4P1, T4P2, T4P5 and T4P6. Even at the other two stations T4P3 and T4P4 the agreement is quite satisfactory. Overall the agreement is better than at T5 which is closer to the inlet. This may look somewhat surprising as it is generally expected that the agreement to be the best for the stations closest to the inflow, but in this simulation the velocity profile at the inflow section is not known and it was assumed constant. As the velocity profiles adjust to the forebay geometry the temperature distribution appears to get closer to the field data.

At transect T3 the predictions at the stations (T3P4 to T3P8) situated outside the recirculation regions close to the dam on the southern shore are within 0.5^0 C, except very close to the free surface (within first 7-10 ft) where the temperature gradient is overestimated in the simulations. These are also the measurement points where the largest variations are recorded in time and where a small error in determining the exact measurement depth can result into a large plotting error due to the large temperature gradients below the free surface. The stations where the agreement is poorer are T3P1, T3P2 and T3P3 where the temperatures between 5 and 25 ft below the free surface are clearly underestimated.

Similar trends are observed at the stations situated immediately downstream closest to the dam T2P1, T2P2 and T2P3, though with the exception of the first measurement point below the free surface the error is within 1.5 to 2 standard deviations. Also the simulations are successfully predicting (within 0.2^0 C for T3P1 to T3P3 and within 0.5^0 C for T2P1 to T2P3) the temperature values near the bed at all these stations. As one moves away from the southern shoreline the predicted temperature profiles become again closer to the measured values, first at the larger depths (station T2P4) and then over the whole depth (T2P5 to T2P8).

Finally, just upstream the intake the agreement is again quite satisfactory at stations (T1P4 to T1P8) which are not very close to the recirculation region near the southern shore. Away from the free surface the predictions are within 0.3^0 C from the field data while near the free surface they are within one standard deviation from the field data with the exception of the first measurement point below the free surface. For stations T1P1 and T1P2 the simulation under predicts the measured temperatures by about 1.0^0-2.0^0 C between 5 and 25 ft below the free surface (one standard deviation is of the order of 0.6^0-1.0^0 C in this region) and then over predicts them by about 0.4^0-0.6^0 C at the deeper levels.

The recorded field temperatures within the gatewells were also compared with the simulated ones. Figure 45 (line with square symbols) shows that the model predicts the gatewell temperatures with reasonable accuracy, within one standard deviation (corresponding to the 4h average) at all units. The under prediction of the temperatures near the free surface at stations T1P1 to T1P3 is found to negatively affect the gatewell temperature predictions especially at powerhouse units 2 and 3 situated near the southern shoreline. The agreement is very satisfactory at units 7 to 14 where the error is within 0.2^0 C, much less than one standard deviation. Also at these units the model successfully predicts the relative changes in the gatewell temperatures among the units. It is expected that further improvement in the predictions can be obtained by further refining the mesh in the forebay, just upstream the powerhouse units where most of the warm water is drawn toward them.

The test simulation, in which the effect of a 10 mph wind in the N-S direction was considered, showed (see line with diamond symbols plotted in Figure 45) an overall improvement (especially for units 3 to 5) in the prediction of the gatewell temperatures. This shows that under certain conditions (e.g., speed, direction) wind effects may have non negligible effects on the temperature distribution within the bay and the turbine units. Its effects should be further analyzed in future simulations.

5.3 Analysis of the Simulation Results for Validation Case_2 (June 30, 2004)

The predicted contours of the in plane velocity magnitude and 2D streamlines in a plane situated at z=100.4 ft close to the free surface are shown in Figure 47. Though in this case about one fifth of the total river discharge is diverted toward the spillway bays, the overall velocity pattern near the free surface is similar to that observed in Case_1. The zone characterized by relatively high velocity magnitudes is situated just upstream the intake units. Some of the down flow toward the spillway bays is also captured but the velocity magnitudes are relatively low. The streamlines patterns in the shallow water regions close to the two shorelines and the dam are also similar. Figure 48 shows the simulated temperature field in the same plane (z=100.4 ft).

In contrast to the velocity magnitude distribution, the temperature distribution in this plane is quite different than the one observed in Case_1. The clearest feature is the region of relatively high temperatures that forms close to the inlet and the northern shore and extends up to the powerhouse units situated close to the southern shore. Again relatively lower temperatures (by about 0.5^0 C) are predicted on the northern side region close to the dam. On the southern side though a circularly shaped lower temperature region is observed at about 2,000ft from the dam, relatively high temperature values are predicted between 1,500ft and the dam face from the southern shore practically to the last powerhouse unit closest to the northern shore. This is mostly due to the different temperature stratification present upstream of the dam (in the inlet section) and to the different operating conditions. The overall temperature difference range is only 2.0^0 C in Case_2 compared to about 4.5^0 C in Case_1. The flow conditions over the 2h interval appear to be substantially closer to steady state compared to those recorded in Case_1. This is confirmed by the relative size of the standard deviation of the temperature measurements at points situated close to the free surface in Figures 49 to 56 and especially in the standard deviation of the measured gatewell temperatures which at most units is close to 0.5^0 C in Case_2 compared to about 1.0^0 C in Case_1. This may also explain, at least partially, the better overall agreement with the field data observed in Case_2. The comparison between the predicted temperature profiles and the field data (including the standard deviation corresponding to the 2h average) is shown in Figures 49 and 50 for transect T1, in Figures 51 and 52 for transect T2, in Figures 53 and 54 for transect T3, in Figure 55 for transect T4 and in Figure 56 for transect T5. Similar to Case_1, measurements were not available over the entire depth at some of the stations (e.g., T5P2 to T5P6).

Similar to Case_1 the predicted temperature profiles are closer to the experimental data at transect T4 compared to the stations at transect T5 which is closer to the inlet section. This is again attributed to the fact that the velocity distribution in the inlet section was non-physical (it was assumed uniform due to lack of measurements) and the flow needs a certain distance to adapt to the bathymetry. At transect T4 the agreement is especially good (within 0.25^0 C at most of the measurement points) for stations T4P2 to T4P5. Some larger errors are recorded at the two stations situated closest to the two banks. At T4P1 the predictions are good near the free surface but the simulation over predicts by about 0.6^0 C the temperatures at middle depths while at station T4P6 the model over predicts by about 0.6^0 C the temperatures close to the free surface.

In transect T3, the agreement is very good at the stations situated in the middle of the forebay and closer to the northern shore T3P5 to T3P8 especially over the bottom half where the error is typically within 0.25^0 C. As one moves toward the stations situated in the shallower regions close to the southern shore (T3P1 to T3P4) the agreement becomes poorer in great measure to the largest temperature decay predicted by the simulation over the first couple of feet below the free surface.

Interestingly, the agreement becomes better in transect T2 for the stations situated close to the southern shore especially at stations T2P3 and T2P4 situated just in front of units 1 and 2. The agreement remains very good at stations T2P6 to T2P8 including in the regions close to the free surface. As expected the agreement is very good over the whole depth for the stations in transect T1 situated in front of the half units closer to the northern shore. Some disagreements (up to 0.35^0 C) are observed at middle depth at station T1P5 where the predicted temperature decay is milder and takes place over a longer distance compared to the field data measurements. However, the agreement is again very good at stations T1P4 and T1P3. At stations T1P1 and T1P2 situated just in front of the southern powerhouse units the predicted temperature variation away from the free surface is smaller than the measured one. The temperature is under predicted over the upper half depth and over predicted over the bottom half depth.

The recorded field temperatures within the gatewells were compared with the simulated ones in Figure 57. The model predicts the gatewell temperatures quite accurately (within 0.30^0 C at all but one unit), close to one standard deviation (corresponding to the 2h average) at most of the units. Very encouraging is the fact that the predicted gatewell temperature variation among units 6 and 14 is successfully captured by the model (though the actual values are about 0.2^0C larger than the corresponding mean values). The under prediction of the temperatures near the free surface at stations T1P1 and T1P2 is again responsible for the gatewell temperature under predictions at powerhouse unit 1 (however, the agreement is excellent at powerhouse units 2 and 3).

6. USE OF THE CFD MODEL AS A PREDICTION TOOL

The model is used to investigate the effects of several structural modifications under consideration by USACE. These include two variations in the intake roof geometry (see Figures 58, 59b and 59c) to reduce the advection of warmer water from the upper layers into the gatewells and introduction of a floating vertical barrier wall near the southern shore units inside the forebay that would act as a selective withdrawal barrier and prevent the movement of warm surface water into the turbine intakes (two designs are studied). The results of these four simulations are compared with the base case (Case_1) in which the original curved intake roof geometry was used for all intake units (Figure 59a) and no curtain was present in the forebay. The dam operating conditions, inflow and free-surface temperature boundary conditions were identical to those used in Case_1. A detailed view of the surface mesh in the vicinity of the curtain for curtain_1 and curtain_2 cases is shown in Figure 75.

6.1 Simulations with Modified Intake Roof Geometries

It is believed that the warmer water from the upper layers near the water surface in the forebay region is drawn into the gatewells. This has adverse influences on the fish health and their migration capabilities as they are diverted by the ESBS toward the collection channel. A remedy under consideration by The District is the use of two different types of intake roof geometries. Two modified intake roof geometries are considered, one in which the slope of the roof is 1:2 (roof_1, see also Figures 58 and 59b) and one in which the slope is 1:4 (roof_2, see also Figures 58 and 59c). Two simulations were performed corresponding to the two roof modifications. The same types of unstructured meshes were generated for the new roof intakes.

Comparison of results showed that the effects of the intake roof geometric modifications are practically negligible in the forebay. However, very close to the intake and within them some differences are observed especially between the free surface and the upstream face of the roof (e.g., see Figure 59 in which 2D streamlines and velocity magnitude contours are represented in a vertical section cutting through Bay B of powerhouse unit 9. By examining the temperature contours in the center bay vertical sections of the 14 powerhouse units in Figures 60 to 73 it can be seen that the changes in water temperature in the gatewells as a result of modifying the roof geometry are not very large. For instance, the effect of both roof modifications on the temperature distribution in Bay B of unit 9 is shown in Figure 68. At a first glance it appears that both new roof designs have the effect of drawing warmer water into the intake from the area very close to the free surface just upstream the roof (observe the temperature contour line corresponding to 23.5^0 C in the three plots which is situated at a lower level in roof_1 and roof_2 cases compared to Case_1). However at the gatewell level and around the VBS screen it is observed that for Case_1 and roof_1 simulations the 23.5^0 C isocontour line is present in these regions while for roof_2 the contour line does not enter the gatewell area where the temperature is slightly lower (by 0.25^0 C compared to Case_1). Thus for powerhouse unit 9 the design corresponding to roof_2 case appears to induce a slight temperature decay at the gatewell level. The changes in gatewell temperatures in the center bay (B) of each unit are summarized in Table 6 (positive numbers correspond to colder temperatures relative to the base case Case_1). From these results it is clear that roof_2 design appears to produce the largest overall decrease in the gatewell temperatures in intake units 4 to 14, though the changes are mostly of the order of 0.1^0-0.2^0 C. A slight temperature increase is predicted for units 1, 2 and 3 situated close to the southern shore. This shows that even roof_2 design is unable to alleviate the temperature problems observed at the intake units (1 to 4) situated closest to the southern shore. The highest decrease in the gatewell temperature is recorded at unit 11 (close to 0.3^0 C).

6.2 Simulations with a Curtain Wall Present in the Forebay near the Southern Shore

To decrease the temperature in the gatewells, The District is considering introducing a vertical floating barrier (curtain) wall in the forebay. The first configuration (curtain_1, see also Figures 74 and 75a) corresponds to a 2200-foot long barrier starting at the pier between turbine units 3 and 4, the angle between the wall and the powerhouse is 115 degrees. In the second configuration (curtain_2, see also Figures 74 and 75b), the wall is a 2100-foot long barrier that starts at the pier between the station service unit and turbine unit 1. This barrier makes an angle of 108 degrees with the dam. The depths of the two barrier walls are indicated in Tables 7 and 8 in Appendix-B. The curtains were reproduced in the model according to the conceptual designs supplied by the District. The curtain was modeled as a solid non-porous wall. A zero heat flux boundary condition was used for the curtain. Below the curtain, the model was left open.

The simulated contours of the velocity magnitude and 2-D streamlines in a plane close to the free surface (z=100.4 ft) for all three forebay configurations (Case_1, curtain_1 and curtain_2) are shown in Figure 76, where one can see that for curtain_1 design the flow pattern in the region close to the dam situated near the southern shore was significantly changed. Instead of the complicated recirculation region present in Case_1 and curtain_2 simulations, the flow originally situated near the southern shore in the upstream region appears to be convected in between the shore and the curtain (observe the higher velocity magnitudes and the converging streamlines in this region) and from there beneath the curtain toward the powerhouse units. Figure 76 also shows that the curtains do not introduce new recirculation regions near the free surface. This is partly because a significant amount of flow passes underneath the floating curtain. Figure 77 shows the temperature distributions inside the forebay in the same plane (z=100.4 ft) close to the free surface. The temperature distributions are very similar in the base and curtain_2 cases, the presence of the curtain wall in the latter hardly affects the temperature distribution near the region close to the southern shore and the dam. In contrast to that, curtain_1 case predicts lower temperatures in this area by about 0.2-0.5^0 C (observe the relative size reduction of the green patch of larger temperatures situated between 4,000 and 1,500 ft in the forebay side closer to the southern shore in curtain_1 simulation with respect to the other two cases). These changes are also reflected into the relative changes with respect to Case_1 in the gatewell temperatures summarized in Table 9 for the center bay (B) of all the units. In the other parts of the forebay the temperature distributions are fairly close for all three cases. The simulated contours of the predicted temperatures in the intakes and gatewells in a vertical section cutting through Bay B for each of the units are shown in Figures 78 through 91. From these figures it is obvious that overall curtain_1 design appears to be more efficient than curtain_2 design.

The maximum decrease in the gatewell temperatures (Table 9) is found in unit 10B (0.43 degrees for curtain_1 and 0.24 degrees for curtain_2). The reason for that is evident in Figure 88 where it is clearly observed that the effect of the curtain presence (especially for curtain_1 design) is to draw less of the warmer water from the region just upstream the intake roof into the gatewell region. In some of the units the model predicts higher gatewell temperatures for curtain_2 case (units 1, 2, 3 and 4). The relatively large temperature increases in units 1 (0.255^0 C) and 2 (0.312^0 C) predicted in curtain_2 case are especially troublesome as our main goal is to decrease the gatewell temperatures especially in units 1 to 4. The reason for this increase might be the presence of strong eddies near the curtain which lead to a higher degree of mixing near unit 1 and forces the warmer water from the free surface to be drawn into the gatewells. By comparison, curtain_1 simulation predicts lower gatewell temperatures for units 1 to 4 compared to Case_1, however the reduction for units 1 and 2 is less than 0.1^0 C. Among the four cases considered, curtain_1 appears to be the best option.

7 CONCLUSIONS

A three dimensional CFD model using FLUENT was developed to study flow hydrodynamics and temperature stratification effects in the forebay and within the powerhouse units of McNary Dam on the Columbia River with the goal of improving the understanding of how fish passage at hydropower dams is adversely affected during strong thermally stratified conditions. Two models were developed, one for a single turbine unit and one for the full forebay. The present CFD model can be applied to address a wide range of problems related to water quality and fish protection in large hydropower dam forebays with complex geometry.

The model for the single turbine unit was validated using the hydrodynamic data collected in a 1:25 scale model by ERDC. The velocity profiles within representative intake bays sections and the flow splits among the three bays were predicted satisfactory by the model. For the full forebay model, validation concentrated on the temperature distribution within the forebay using data from a recent comprehensive field data collection program conducted by USACE during summer 2004 where strong thermal stratification was present upstream the dam. The full forebay model simulations discussed in the present study used large meshes containing 5.0-6.0 million cells. This large number of computational cells was needed to increase accuracy of the temperature predictions within the forebay and the intake units, while incorporating the 14 powerhouse units, 22 spillway bays and all the relevant structural details inside the powerhouse units into one model. The use of a hybrid unstructured mesh system provided the additional flexibility needed to generate a mesh of acceptable size for the complex geometry of the forebay and powerhouse units while not compromising the mesh quality requirements needed to obtain accurate solutions. Given the overall constrains in total mesh sizes, this level of mesh quality is practically impossible to achieve using an approach based on multi-block structured grids.

The temperature predictions for the two validation test cases (without and with spill) considered in the present study were found to be reasonable in the forebay. Though the simulation results in both cases were able to predict the occurrence of warmer water in the shallow regions near the southern shoreline and in the corresponding gatewells of the powerhouse units near the southern shore (good qualitative agreement with field data measurements), the decay of the predicted temperature levels very near the free surface was found to be faster than those observed in the field data. This was found to negatively affect the accuracy of the gatewell temperature predictions in the powerhouse units closest to the southern shore in the validation test case without spill. However, the gatewell temperature predictions were close to being within one standard deviation of the mean (time averaged) field data at all 14 powerhouse units (the time period used to produce averages in these simulations was 4h and 2h, respectively). Overall, the validation results proved the capability of the model to be used for decision support by The District.

Next, two types of structural changes demonstrated the potential capability of the model for evaluating design alternatives. The first consisted of modification of the intake roof geometry in the intake units (two designs) and the second was the introduction of a floating barrier curtain in the forebay (two different positions of the curtain relative to the dam were considered).

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