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MODELING STEAM DRYERS

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ABSTRACT

Nuclear steam dryers are used to reduce the moisture carryover (MCO) to levels often well below 0.1%, by weight, water in the steam. The dryers are designed to provide very high quality steam at the full capacity of the steam generator.

The purpose of this paper is to present computational fluid dynamics (CFD) models of the steam flow in a generator and the decisions that are required to evaluate different designs. These computational models are successful and proven in field operations.

INTRODUCTION

The Diablo Canyon Power Plant in San Luis Obispo County, California is located on about 750 acres (3.0 km²) in Avila Beach, California. The plant, shown in Fig. 1, includes two pressurized water reactors (PWR) that replaced steam generators in 2008 and 2009.

Fig. 1, Diablo Canyon Power Plant

The focus of this paper is on the new steam dryers inside the replacement steam generators installed at Diablo Canyon. Computational modeling, described here, was used at the design stage to evaluate the steam dryer performance and ensure the proper separation performance would be met.

Moisture Carry Over (MCO) testing (by Westinghouse, method described in Fournier et al., 2009), which was performed about four months after 100% power operation, demonstrated excellent performance. Specifically, the guarantee was 0.05% MCO and the typical performance guarantee for similar designs is 0.1% MCO. Diablo Canyon MCO test demonstrated that the steam dryers achieved the following:

- SG 21: 0.00459% MCO
- SG 22: 0.00458% MCO
- SG 23: 0.01458% MCO
- SG 24: 0.01360% MCO
- Average for all: 0.0093% MCO

DRYERS IN THE PWR

Figure 2 is a simple schematic representation of a pressurized water reactor (PWR). In this figure, the high pressure and high temperature closed primary loop is shown in red. This loop includes the reactor and the Steam Generator heat transfer tubes. The secondary (steam side) loop is shown in blue. Inside the steam generator, the heat transfer tubes are covered with water and transfer the heat from the primary loop, causing the water to boil into generated steam inside the steam generator.

The generated steam is passed through centrifugal separators that improve the steam quality to at least 90%, (designed and evaluated by Westinghouse for 96.3% average steam quality for Diablo Canyon). The steam dryers, at the top of the steam generator, capture the remaining water and allow dry steam to exit towards the turbine generator. The dry steam exiting the steam generator is at least 99.9% quality, typically (designed for 99.95% dry for Diablo Canyon).

The moisture quality of the steam is very important for thermal efficiency, prevention of erosion due to moisture droplets, and minimization of chemical carryover (Kolev, 2009).

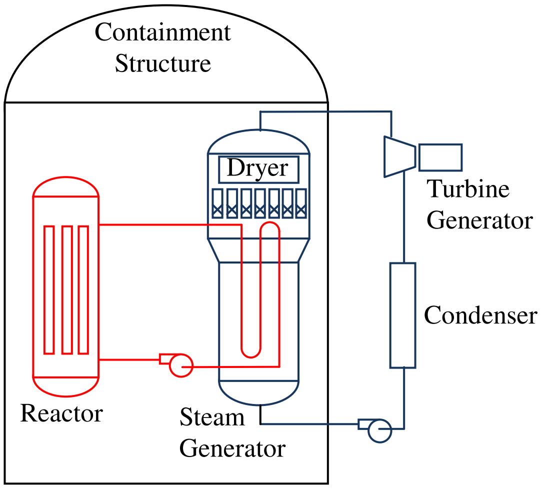

Fig. 2, Steam Dryers in the Nuclear Power Plant

The nominal flow conditions for these dryers are as follows per steam generator:

- Steam flow rate = 3,718,800 lb/hr
- Pressure = 805 psia

PRIMARY SEPARATORS

The steam generated by boiling in the steam generator heat transfer tube bundle is forced upward through a primary stage separator assembly, which for Diablo Canyon consists of sixteen, 20-inch diameter centrifugal swirl vane columns. These separators allow the steam to travel upwards, while forcing the separated water out and downwards to be recirculated through the tube bundle.

The steam and water flow rates exiting each primary separator column are determined based on the output of numerical methods validated to predict the steam generator thermal-hydraulic conditions. A steady-state one-dimensional performance code is used to predict the overall conditions, and then the ATHOS code is used to determine the detailed three-dimensional two-phase flow field, including the steam and water flow rate into each of the primary separators. Using the flow rates determined for each primary separator, empirical performance correlations based on unit-cell testing of the primary separators are applied to determine the efficiency of moisture separation for each of the separators. The outputs are steam and water flow for each column; these flow rates have previously been used as input to a basic one-dimensional bulk performance correlation for the steam dryer. However, the application of CFD modeling allows for improved evaluation of dryer performance as described herein, including consideration of the three-dimensional flow field and assessment of design modifications.

STEAM DRYER DETAILS

Thousands of vanes are carefully arranged in several banks to form a steam dryer. Vane profiles are typically designed to form a zigzag flow path between each two adjacent vanes. A set of eight double pocketed vanes is shown in Fig. 3, arranged to form a vane bank. The vane's material is typically steel and their depth, from the two phase flow inlet to the dry gas outlet, typically varies between 2 to 10 inches (51 to 254 mm). Those used at Diablo Canyon are 8 inches (203 mm) deep.

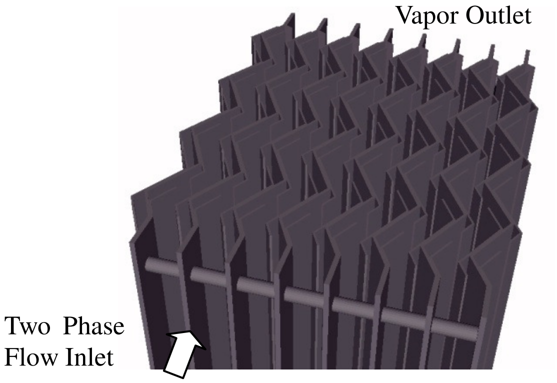

Fig. 3, Eight Double Pocketed Vanes

Steam flows from the two phase flow inlet face to the vapor outlet. Water droplets that enter the vane with the steam deposit on the vane walls and form a water film. Pockets, strategically placed within the vane's body, are used to capture the water film and provide regions for water drainage within the vane body that are sheltered from the steam velocities.

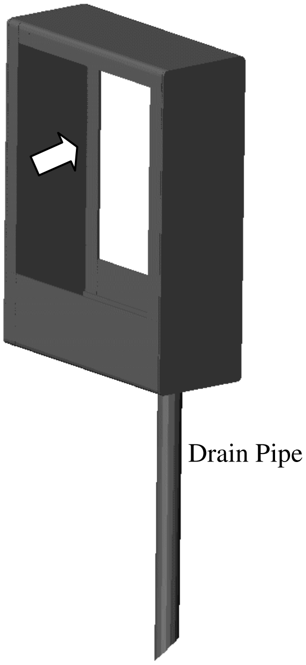

Fig. 4, Vane Bank Frame

Vane banks are typically installed within a frame such as the one shown in Fig. 4. The size of this frame is determined based on the flow rates and properties of the steam and the water that is being removed. The water, captured in the vanes, drains to the bottom of this frame and is transported by gravity out of the frame through a drain pipe. This drain pipe terminates under the steam generator water level away from the steam flow path.

VANE PERFORMANCE

Vane separators result in low MCO when two conditions are satisfied. First, the vane's droplet removal efficiency is higher than the expected droplet size distribution of the inlet moisture. Second, the capacity of the vanes is higher than the steam velocities and water loading into the vane.

Droplet Penetration

Droplet penetration calculations are performed to ensure that the vane profile used is adequate for the application. To evaluate the droplet penetration, an estimate of the droplet size distribution exiting the primary separators (representing the inlet moisture to the dryer) is required. Additionally required is computational or experimental data that represent the vane's ability to remove these droplets. The vane must be able to capture the incoming water droplets in order to yield a low MCO. Specifically, the droplet removal efficiency must be well within the inlet moisture's droplet size distribution.

The droplet distribution representing the inlet moisture is calculated by proprietary mechanistic models similar to that published by Nakao et al, 1997. The droplet removal efficiency can be obtained using experimental measurements (e.g., Verlaan, 1991 or proprietary reports), computational fluid dynamics with discrete phase modeling (e.g., Kolev 2009; Fewel and Kean, 1992; Verlaan, 1991), or by mechanistic models (e.g., Verlaan, 1991 or proprietary methods that are specific to the particular vane profile used).

The droplet penetration for Diablo Canyon was performed using a proprietary and proven mechanistic model. The calculated smallest droplet size was 150 micron exiting the primary separator having the highest steam velocity and lowest water flow. The calculated largest size was 260 micron exiting the separator having the lowest steam velocity and highest water flow. These diameters are an order of magnitude larger than 10 microns, the size removed with 100% efficiency by the specific vanes used. Therefore, droplet penetration is expected to have negligible effects on the overall MCO.

Capacity

The loading to the vane, specified in terms of steam velocity through the vane and the inlet moisture (IM) content, must be within the vanes capacity over 100% of the vane bank's open area (Fadda et al., 2004). Each vane profile has a capacity curve similar to that sketched in Fig. 5. The x axis of this curve is the steam velocity while the y axis is the water flow rate per vane unit area.

The curve shown in Fig. 5 is provided with no numbers on its x and y axes because it is highly dependent on the operating conditions and the particular vane profile used. Specifically, there are tens of vane profiles with specific curves available through Peerless in addition to many more available by others. The curve shown in Fig. 5 is intended to be generalized to all vane profiles.

For a specific vane profile, this curve can be generated experimentally from air-water (atmospheric) ambient conditions or under controlled high pressure steam conditions. In either case, it is normally generated under controlled conditions where the flow of gas and liquid into the vane can be well regulated and uniformly distributed.

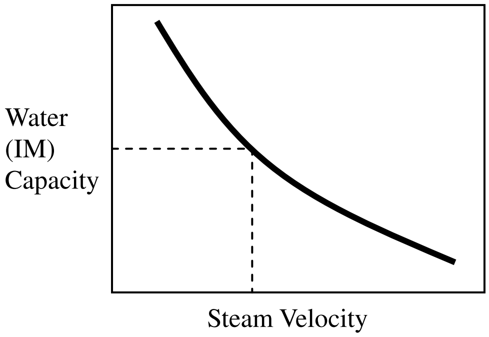

Fig. 5, Vane Capacity Curve
(General Sketch for any Vane)

The curve is interpreted as follows. Vertical and horizontal dashed lines in Fig. 5 represent certain steam velocity and water capacity at that steam velocity. For this represented steam velocity, the vane can handle all water loadings up to the capacity (horizontal dashed line). If the water loading exceeds the capacity, moisture carryover is expected. From a different perspective, given the represented water loading in Fig. 5, the vane can handle steam velocities to the left of the capacity (vertical dashed line). If the steam velocity exceeds the capacity, carryover is also expected.

In a PWR steam dryer, an average steam velocity and an average water loading can be easily calculated given the steam and water flow rates and the dryer's effective area. The dryer's area is set such that the average loading is on the left side and well below the capacity curve. However, without additional analysis, the variations in the steam and water loadings over the dryer's area can easily cause the highest velocity and/or the highest steam loading to exceed the capacity curve. The overall MCO can therefore, be high even though the average loading is well within the capacity curve (Fadda, 1998). It is important to identify the point of highest velocity and water loading and make sure that this point is well within the capacity curve.

DRY STEAM CFD MODEL

The CFD model used to evaluate the dryers includes the flow region above the top of the primary separators through the vane banks and up to the dry steam outlet. The purpose of CFD modeling is to ensure that 100% of the vane area operates well within the capacity of the particular vane profile used. During the initial design of a dryer, it is common to find areas of the dryer that operate above the capacity curve of the vanes used. It is also common (when needed) to use perforated plates at the inlet or outlet face of the vane banks to balance the flow and eliminate high steam velocities in the dryer.

Velocity vectors within the CFD model are shown in Fig. 6. The bottom of the model is the top of the primary cyclonic separators. The Diablo Canyon dryer, which consists of six parallel banks of vanes, is identified. Wet steam enters the dryer, which captures the incoming water. The captured water is piped back to the lower steam generator while the high quality "dry" steam exits the vessel. For simplicity, these water pipes are not shown in Fig, 6.

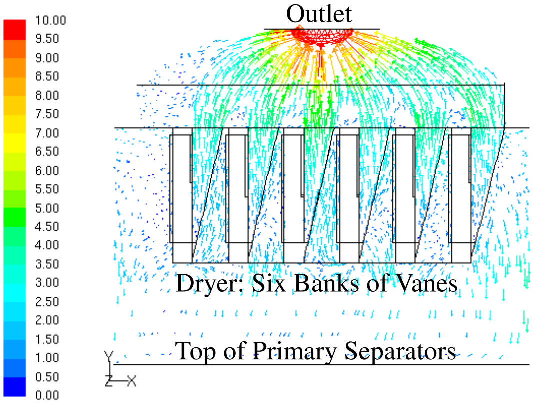

Fig. 6, Velocity Vectors Colored by Velocity Magnitude (m/s)

The boundary conditions of the CFD model are as follows:

- The inlet boundary condition to the CFD model at the bottom is based upon the primary separator calculations described above. Velocity vectors exiting the primary separators are shown in Fig. 7.

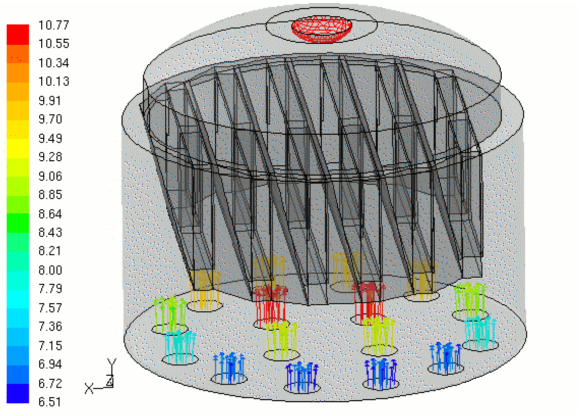

Fig. 7, Velocities at the Outlets of the Primary Separators (m/s)

- The steam outlet nozzle at the top of the vessel contains a flow limiting device which produces high velocities and pressure gradients. A preliminary model is performed to evaluate the outlet and generate an isobaric pressure boundary near the top of the vessel, just below the outlet. This boundary is then defined as the outlet to the complete CFD model of the flow in the dryer, which is subject of this paper.
- The vanes are modeled as homogeneous and non-isotropic porous media (Nield and Bejan 1992). Perforated plates at the inlet face of the vanes are included and also modeled the same way. Inertial second order pressure loss is assumed to occur in the vanes and perforated plates while other non-linear losses (Lage et al. 1997) are disregarded.
- The commercial software, Fluent 6.2, with the K-epsilon model of turbulence was used to perform the CFD simulations.

WATER INJECTION

The expected average steam quality at the outlet of the primary separators at Diablo Canyon is 96.3%. The inlet moisture (IM) to the vanes is, therefore, only 3.7% by weight. This amount is not expected to significantly affect the steam flow patterns in the vessel (Wallis, 1969). The droplet trajectory analysis is, therefore, decoupled from the steam flow using the discrete phase model. The dry steam model is performed first. The water droplet tracking is performed separately based on the converged dry steam flow model.

The water droplets are released as spheres at the outlets of the primary separators and allowed to flow in the CFD model based on 150 micron and 260 micron droplet diameters. The discrete phase model is used and droplet trajectory coordinates calculated by the CFD code are written to a text file. A C program is written to track the droplets from the point of their release to their termination point.

The vanes are divided into sections where the coordinates of each section are defined. Droplets that enter a vane section are terminated numerically in that section of the vanes. The number of droplets is converted to water loading into that particular section of the vanes.

There are additional droplets that never reach the vanes. Instead, they terminate at the floor or the wall of the vessel (set as "trap") below the vane banks. These droplets are expected to form a film and fall out due to gravity.

For each droplet diameter (150 micron and 260 micron) the droplet trajectory analysis was repeated five times. The highest loading that reached each vane section was used as a conservative estimate of the expected loading to the vanes.

RESULTS

The Diablo Canyon dryer is modeled with and without perforated plates at the inlet face of the vane banks. The steam velocities in the vane banks resulting from the CFD model are shown in Fig. 8 after perforated plates were added to the inlet side of each vane bank.

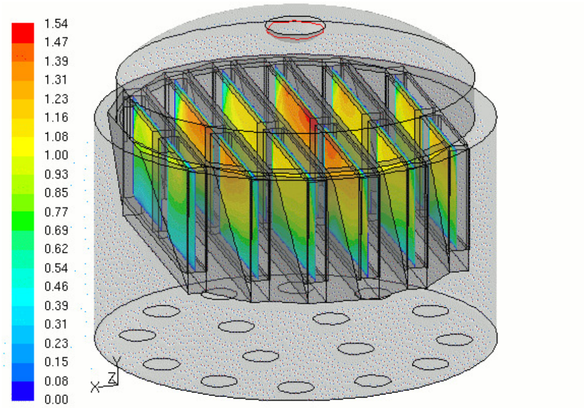

Fig. 8, Steam Velocity in the Vane Banks (m/s)

Results of the droplet trajectory analysis provide the water loading to each section of the dryer. Combining the steam velocities with the water loading results in set of points representing the loading to the dryer are superimposed on top of the capacity curve as shown in Fig. 9. The average loading to the dryer is shown as a blue point and also identified. Around the average loading is an area bounded by a green and a red curve. This area includes the range of velocities and water loadings that are expected over the overall vane bank's cross-sectional area with perforated plates (green) and without perforated plates (red).

The moisture carryover (MCO) is minimized by ensuring that the complete set of loading points to the dryer is well within the capacity of the vanes used (Fadda et al., 2004). Specifically, the complete elliptical shape is below the vane's capacity curve as shown in Fig. 9 after the perforated plates are included in the model.

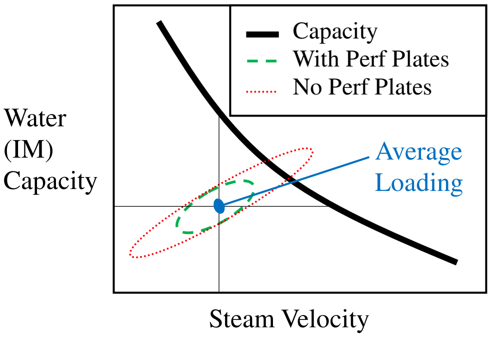

Fig. 9, Capacity and Loading to the Vane

CONCLUSION

The CFD modeling approach, used at the design stage to evaluate PWR nuclear steam dryers, is presented. The purpose of CFD modeling is to make sure that 100% of the vane area operates well with the capacity of the vanes.

Perforated plates on the inlet face of the vane banks are included at Diablo Canyon to flatten the velocity distribution and ensure that the loading to the vanes is well within the capacity curve of the vanes used.

The Diablo Canyon nuclear steam dryers reduce the moisture carryover (MCO) to levels often well below 0.1%, by weight, water in the steam. Specifically, these dryers have achieved an overall average of 0.0093% MCO.

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