Flow Patterns at the Bottom Regions of a Steam Generator Tube Bundle

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INTRODUCTION

With the sponsorship of Northeast Utilities (NU), an experimental study was conducted at the Alden Research Laboratory, Inc. (ARL) using a 1:3 scale model of a C-E Series 67 steam generator to study the flow patterns in the bottom region of the steam generator. The study included determination of flow patterns within the tube bundle by visual observations, and vertical and horizontal velocity measurements using a Laser Doppler Anemometer. Although the study was undertaken mainly to address the problem of sludge deposition in steam generators, the data on flow patterns and velocity distributions obtained from the study are considered useful in the prediction and analysis of flow induced vibrations of tubes.

A few thermal-hydraulic codes are available to predict flow distribution (velocities) within a steam generator bundle (Fanselau, et al, 1980; Inch, 1981; Yang et al, 1985). Electric Power Research Institute sponsored projects (Fanselau, et al, 1980; Inch, 1981) developed the CALIPSO code and the THINST code, both of which use three-dimensional continuity, momentum and energy equations along with equations of state. Argonne National Laboratory has developed a code (Yang et al, 1985). Based on information from Northeast Utilities, the latest code, being developed by Jaycor called ATHOS 3, uses cylindrical coordinates and computes the axial, radial and tangential velocities. In all these models, the tube bundle is modeled as an overall resistance to flow and no consideration has been given to define the wakes generated by the tubes or to define the flow paths along the tube gaps in specific details.

SIMILITUDE AND MODEL DESCRIPTION

The flow of secondary coolant in steam generators is largely driven by buoyancy, from differential heating and bubble formation, the rising bubbles dragging liquid upward. Near the bottom of the steam generator, however, the vapor fraction is very small (Fanselau, et al, 1980; Inch, 1981) and the flow can be assumed to be unaffected by vapor formation and simulated as single phase.

With buoyancy effects neglected the other forces controlling the flow distribution near the bottom of the steam generator are inertial forces and viscous forces. The ratio of these forces is determined by the Reynolds number, Re = Ud/ν, in which U = representative velocity, d = relevant length scale and ν = kinematic viscosity. In full size steam generators, the Reynolds number (based on the velocity normal to the tubes, near the bottom of the tube bundle, and on the tube diameter) is very large (on the order of 100,000). For
large values of the Reynolds number, flow similitude does not require equality of the Reynolds number in model and prototype (full size system) but only that the model Reynolds number be above a minimum value of approximately 10,000. With a geometric scale of 1:3, this was achieved in the model with a flow of about 0.22 cubic meters/sec.

The 1:3 geometric scale model simulated one half of the bottom region of a C-E Series 67 steam generator, up to three egg crates from the bottom sheet. The model was designed and built to include both the hot and cold regions of the prototype steam generator. The model was built of plexiglas to allow Laser Doppler Anemometry (LDA) measurements and visual observations of the flow within the modeled region. Fig. 1 shows a section indicating the model details. A calibrated "Annubar" flow meter was used to measure the flow through the model.

A forward scattering LDA arrangement was used for vertical components of velocities and corresponding turbulence intensities. Horizontal velocities could not be measured with the same LDA system because of the very close spacing between the tubes (less than 3 mm clear space). Hence, the model was laid on its plane backside with the tubes in the horizontal direction and a back scattering LDA arrangement was used with optical fiber probes.

Vertical velocity measurements were conducted along seven radial axes, and at three elevations as marked in Fig. 2. Horizontal velocity measurements were conducted at 19 mm and 64 mm (model) from the tubesheet along each radial axis. Measurements were obtained up to fourteen points on each axis depending on accessibility for laser beam intersection.

RESULTS

The flow patterns as indicated by fine air bubbles at the entrance to the tubesheet and the immediate region up to the first egg crate were observed and sketched as shown in Fig. 3. The flow separated at the corner between the shroud wall and the bottom plate and a clockwise eddy formed in this region. A large and strong anti-clockwise eddy also formed behind the flow separation in the region behind the shroud wall towards the tube bundle.

The flow pattern inside the tube bundle close to the bottom tubesheet as indicated by fine air-bubbles, when the model was laid in a horizontal position, is shown in Fig. 4 for one half of the model tubesheet. The flow very much followed the least resistance path as it entered into the tube bundle, the least resistance path being the blowdown lane between the tubes. Since the flow turned to a direction parallel to the tubes as it moved through the tube bundle, a low flow region existed in the inner middle section of the tube bundle. Some flow from the open blowdown pipe lane (no tube region) entered this region.

Vertical velocities were measured using LDA along 15, 45, 75, 90, 105, 135 and 165 degree radial axes, for an average downcomer shroud velocity of 4.2 m/s. Typical vertical velocity distributions and the corresponding turbulent intensities at 19 cm above the tube sheet along 15, 45, 75 and 90 degree radial axes are given in Figs. 5 and 6. In general, except for the 75, 90 and 105 degree radial axes, significantly lower vertical velocities were measured in the inner middle region of the tube bundles compared to velocities in the outer regions towards the shroud as well as towards the central core open region (no tubes). Along 75, 90 and 105 degree radial axes, more uniform vertical velocity distributions were noticed, being at or closer to the strip of the "no-tube" region.

Turbulence intensities (expressed as a percentage of vertical velocities) in the inner region of the tube bundle generally varied from about 6 to 21%.
Higher turbulence intensities were measured in the eddy region closer to the shroud wall. In general, the turbulence intensities were in the range of 5 to 30% with most values in the range of 10 to 20%.

Horizontal velocities were measured using LDA with the model laid horizontally. Figs. 7 and 8 show the horizontal velocities in the tube gap along the various axes at 1.9 cm in the model (5.7 cm in prototype) from the tubesheet. Velocities varied from about 1.5 m/s at the periphery of the tubesheet close to the shroud opening to about 0.3 m/s in the innermost region of the tubesheet. The average shroud opening velocity (flow divided by area) for the tested flow was about 0.8 m/s. The turbulence intensities varied from about 15 to 30% with no consistent trend. No significant differences in velocities were indicated at the measured two depths. The velocities varied from about 1.2 to 1.8 m/s in the center tube lane gap (no tube region).

Different wake patterns were observed behind the tubes depending on the tube row orientation, predominantly "in-line" with the flow or "staggered." Unfortunately, flow patterns within the wakes could not be studied, the velocity measurements within the wakes being complex and difficult.

CONCLUSIONS

Vertical and horizontal velocity distributions within the tube bundle at the bottom region of the steam generator indicated lower velocities (about 10 to 25% of average) in the inner middle region compared to the outer regions close to the shroud and the central "no tube" region. The turbulence intensities of both horizontal and vertical velocities expressed as a percentage of actual velocities varied from about 5 to 30%, with most of the measurable values in the 10 to 20% range. No consistent trend of turbulence intensities were indicated.

REFERENCES


Figure 5: Vertical Velocities and Turbulence Intensities at 19 cm above tubesheet in the model along 15° and 45° axes.

Figure 6: Vertical Velocities and Turbulence Intensities at 19 cm above tubesheet in the model along 75° and 90° axes.

Figure 7: Horizontal Velocities at 1.9 cm (model) above tubesheet along 15°, 30°, and 45° axes.

Figure 8: Horizontal Velocities at 1.9 cm (model) above tubesheet along 60°, 75°, and 90° axes.