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INSTRUMENTATION FOR THE ADVANCEMENT OF SHELL AND TUBE HEAT EXCHANGER DESIGN OR FOR IMPLEMENTING AN UPGRADE VIA A RETROFIT PROCESS

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ABSTRACT

This paper presents the instruments developed for shell and tube heat exchangers and their measurements made in operating large scale HX units. These instruments provide in-situ, long-term direct measurement of temperatures and fluid flow rates that are important for evaluation of the desirable and undesirable effects of a HX design. Unique results of this instrumentation are the 3-dimensional measurements of temperature at the inlet, outlet, and along the length of heat exchanger tubes, total tube side flow, and individual tube flow measurements. The temperature measurements are interpolated in a 3-D computational space for design assessment and engineering evaluation. These results have been used to design upgrades for underperforming steam surface condensers. Data from these instruments, the evaluation process, and design effort could lead to development of a new class of better performing heat exchanger designs.

INTRODUCTION

The ASME Steam Surface Condenser Performance Test Code 12.2 provides a standard to the industry for measuring performance. This standard is frequently applied for newly commissioned unit testing as well as benchmarking for unit upgrades. Information in this standard is assumed prerequisite knowledge for this paper.

ASME PTC 12.2 provides the standard for determining a condensers overall performance and does not intended to provide condenser designers or condenser purchasers with information to advance the design/technology of surface condensers. This paper provides instrumentation advancements that complement the ASME PTC standard and provides information that can advance the design standards of shell and tube condensers and result in shell and tube condensers designs that outperform modern designs.

The goal of this instrumentation is to quantify with great accuracy or adequately estimate the heat transfer coefficient of every ~3 ft length of each tube, effectively quantifying the performance of every tube section in every bay (bay meaning sections divided by tube support plates and/or baffles). Having quantified the heat transfer and combining an understanding of the processes to maximize heat transfer, advancements can be made in condenser technology.

There are four primary advancements of the instruments presented in this paper: 1) high density tube discharge cooling water temperature array measurements, 2) single tube flow and discharge temperature instruments, 3) measurement of cooling water temperatures along the length of condenser tubes, and 4) computational methods using these direct measurements and other direct measurements of pressure, temperature and flow to provide a continuous direct measurement-based 3-D thermal model of the monitored condenser. All the instruments described in this paper have been installed in and used to evaluate and/or upgrade multiple large scale (30MW to 1400MW) shell and tube condensers [1], [2], [3], [4].

Figure 1 provides an illustrative view of the entire instrument package used for comprehensive condenser evaluations. The illustration highlights many of the instruments that are currently referenced in the PTC 12.2 standard. Note that the cooling water flow, temperature , and fouling instruments are new, unique, and not referenced in the current standard, ASME PTC 12.2 2010 [5]. The instruments in this category and that are discussed in this paper are high density temperature array tubesheet instruments, the tubesheet flow sensors, and inter-tube temperature array instruments (not shown in the Figure 1).

The subsequent sections describe the outlet tubesheet instruments, outlet flow and temperature instruments, the inter-tube instruments, and an overview of the computational methods. The final section briefly summarizes the results and provides a description of how this information is used to monitor the performance and advance the design of shell and tube condensers and provide upgrades to underperforming condensers.

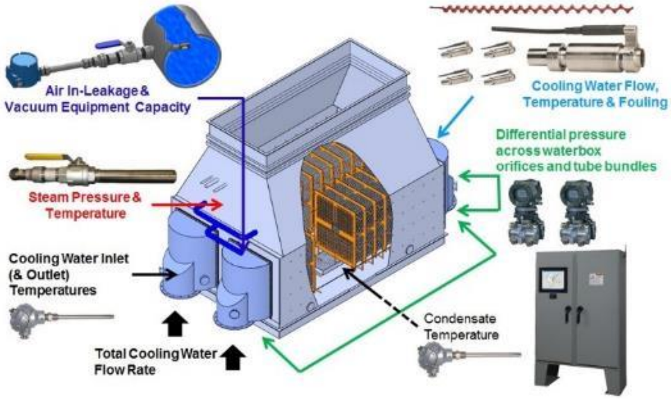

Figure 1: Illustration of the instruments used for the advancement of shell and tube heat exchanger design

HIGH DENSITY OUTLET TUBESHEET INSTRUMENTS

The high density outlet tubesheet temperature instruments are an array of temperature sensors that are pressure molded into a shape that fits within the ligament spacing between tubes on the tubesheet. Figure 2 shows a photograph of an array of 37 temperature sensors molded and ready for installation. The signals are passed through the waterbox using various methods: a low cost backfilled cable gland or a flanged fitting with threaded cable penetrator assemblies.

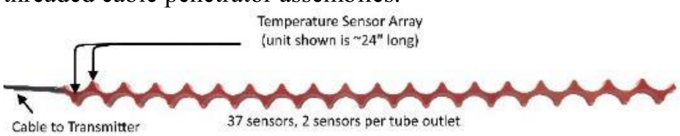

Figure 2: Photograph of the high density temperature array tubesheet instrument

Figure 3 shows a photograph of the array installed on the outlet tubesheet of a 700 MW unit. These sensors have been designed with the intention of a 10-20 year service life and the latest designs have been installed on several units and are still functioning after 4 years of service. Figure 3 is a stitched image, a composite of several installation photographs.

Measured tube water flow (usually estimated from a bulk method i.e. nearby tube flow meters, ΔP, ultrasonic, or other), tube outlet water temperature, tube inlet water temperature (typically measured using a bulk method), and shell side pressure (note this may or may correlate to the water vapor partial pressure) are used to calculate tube heat transfer. The Fourier equation, $Q=m \cdot c_p \cdot \Delta T$, is the basis for determining the transferred heat, Q. Figure 4 shows the resulting performance profile using a form of 2-D interpolation of the measured temperatures along the arrays. A performance profile is the ratio of the measured heat transfer compared to the HEI method or ASME resistance summation method calculated heat transfer. How this data is used to evaluate condensers is discussed in later sections of the paper.

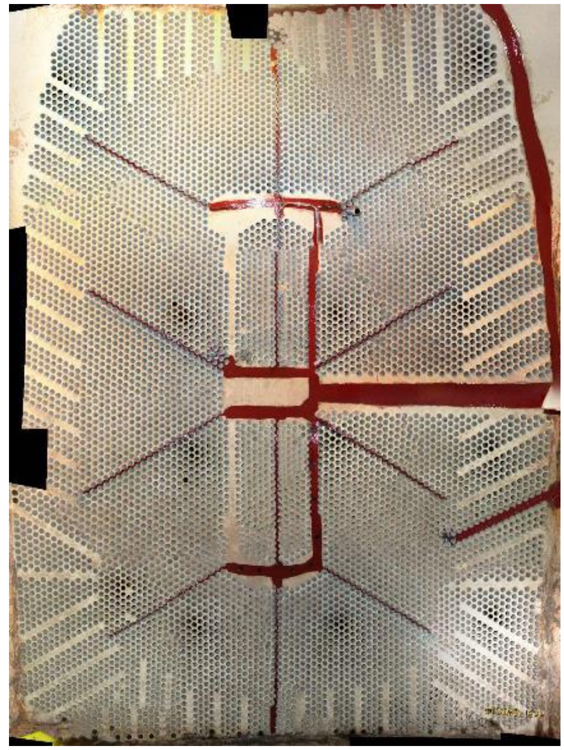

Figure 3: Photograph of the HDTA tubesheet sensors installed on a 700 MW condenser tubesheet

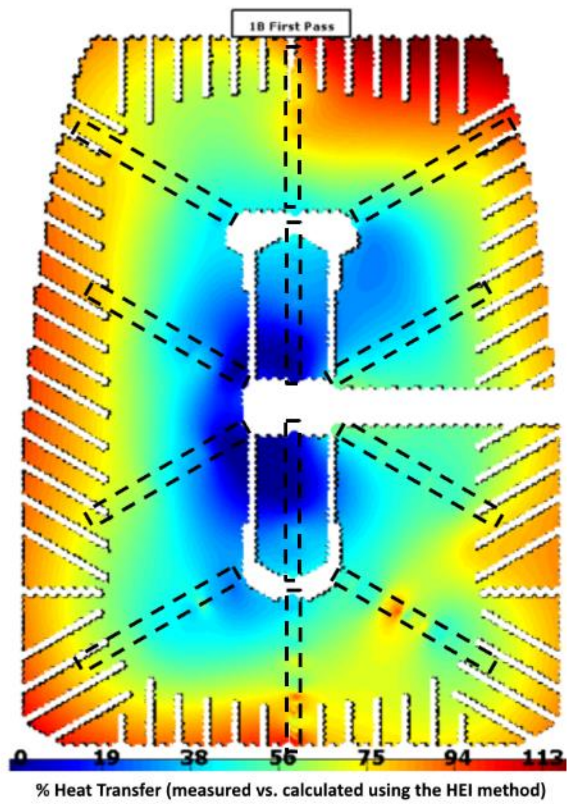

Figure 4: Performance Profile, HD temperature array instrumentation locations are highlighted [6]

OUTLET TUBESHEET FLOW AND TEMPERATURE INSTRUMENTS

The single tube flow meters are designed for permanent submersible applications. The instrument has no moving parts and provides an unobstructed path for water to exit the condenser tube and pass through the flow meter. This unobstructed flow path in the meter allows cleaning balls and scrapers to be used in the monitored tubes. The signals are passed through the waterbox using various methods: low cost backfilled cable gland or flanged fitting with penetrator assemblies. Figure 5 shows a photograph an instrument ready for installation. Figure 6 shows a photograph of an instrument installed on the outlet tubesheet of a 600 MW unit.

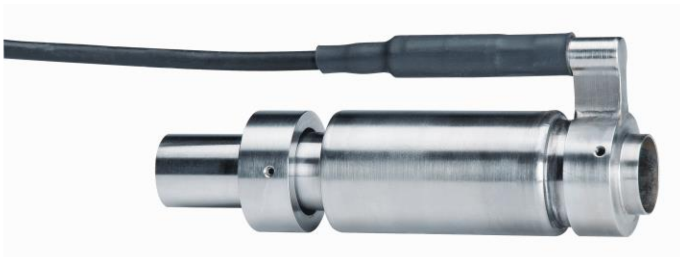

Figure 5

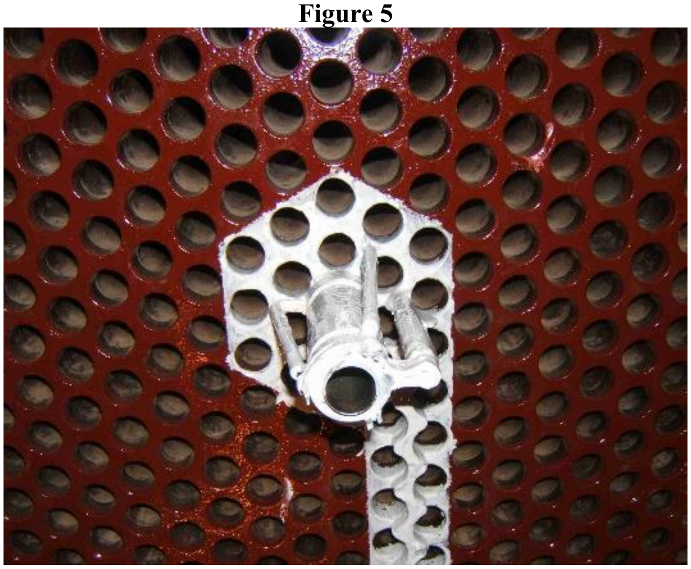

Figure 6

These sensors have been designed with the intention of a 20 year service life and the latest designs have been installed on several units and are still functioning after 5 years of service.

Measured tube water flow, tube outlet water temperature, tube inlet water temperature (typically measured using a bulk method), and shell side pressure (note this may or may correlate to the water vapor partial pressure) are used to calculate tube heat transfer. The Fourier equation, $Q=m \cdot c_p \cdot \Delta T$, is the basis for determine the transferred heat, Q. These instruments are primarily used for fouling quantification but have also been used to corroborate total CW flow. The method for estimating total flow is to use several single tube flow instruments, calculate a mean single tube flow rate, multiply by the number of unobstructed tubes and thus infer total CW flow in a monitored waterbox.

INTER-TUBE TEMPERATURE ARRAY INSTRUMENT

The inter-tube temperature array instruments are designed for permanent submersible applications. They have the shape of a standard submersible cable with a diameter ~0.135". However inside the cable jacket are multiple temperature sensors spaced along the cable length. The manufacturing process allows for very low profile sensing locations and uncompromised cable jacket. Figure 7 shows a photograph an instrument ready for installation. Figure 7 also shows photographs of the instrument inlet and outlet tube adapters of an instrument installed on the outlet tubesheet of a 1400 MW unit. Deflectors are installed on the inlet end of the monitored tube to deter debris from obstructing the monitored tube. These instruments typically remain debris free for several weeks to a few months, which provides sufficient data to determine performance profiles along the length of the tubes. Techniques are used to merge the information from the high density outlet tube temperature arrays to obtain 3-D performance profiles.

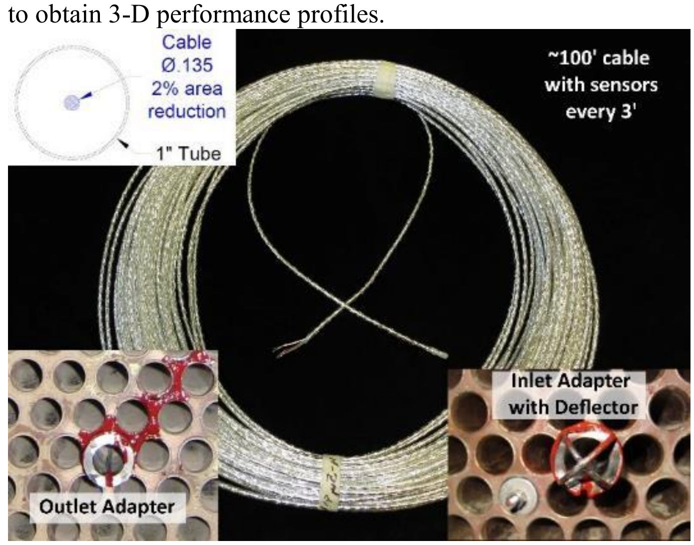

Figure 7: Inter-Tube Temperature Array Cable with installation and adapter details

Additional examples of how this data is used to evaluate condensers is discussed in later sections of the paper.

MAKING USE OF THE DATA

As stated in the introduction, the goal of this instrumentation is to quantify with great accuracy or adequately estimate the heat transfer coefficient of every ~3 ft length of each tube, effectively quantifying the performance of every tube section in every bay (bay meaning sections divided by tube support plates and/or baffles).

The instrument packages installed with these systems includes a data archiving unit that records measurements from hundreds to thousands of measured parameters. The unit also calculates useful parameters such as CW total flow per flow path, target pressure, Cleanliness/Performance Factor and fouling factors. The processing power necessary for creating complete 3-D thermal profiles is significant and requires the data to be downloaded from the archiving unit and processed separately.

Figure 8 shows a 3-D thermal profile and Figure 9 shows the 3-D performance profile of a 2-stage Westinghouse condenser. The performance profile provides the information necessary to make an evaluation of the condenser design and potential improvements. Regions of low heat transfer, <60%, are prime targets for improvement. The authors of this paper have already demonstrated these performance gains by relocating and/or resizing air cooler sections in existing large scale power generation main condensers. If improvements are made then with the same condensing surface area, steam duty, cooling water flow, vacuum system capacity, etc. a condenser can operate at a lower pressure, lower dissolved gases in the condensate, and higher immunity to air in-leakage [3], [4], [7], [8], [9]. Making advancements in future designs to realize these advantageous features is the vision for the use of this instrumentation.

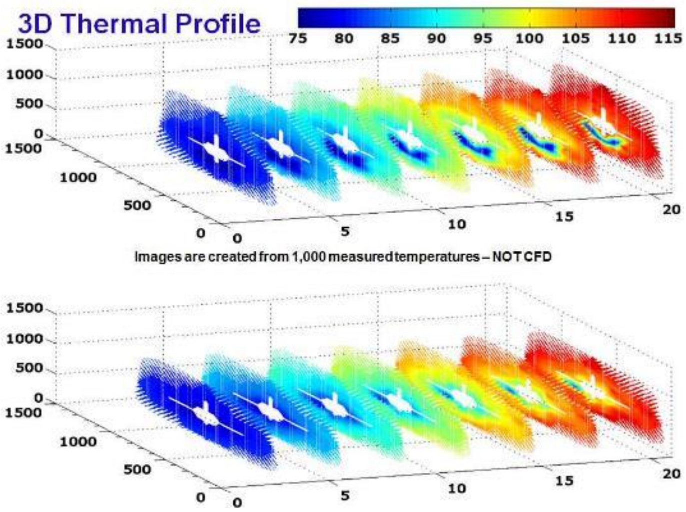

Figure 8: 3-D temperature [°F] profile 1GW unit (>1,400 sensors)

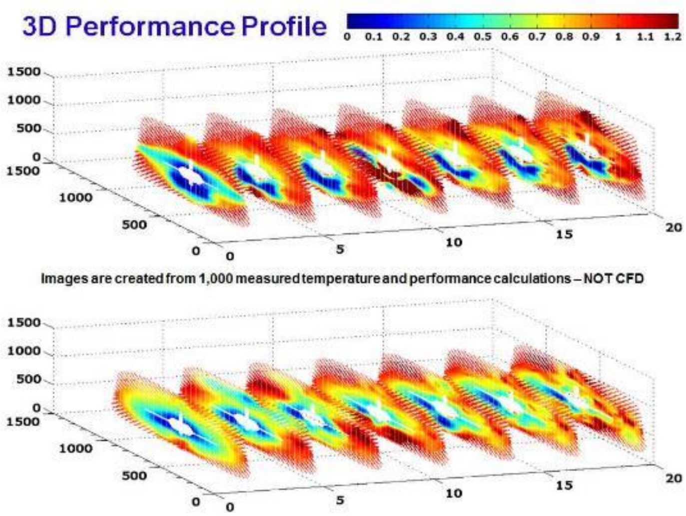

Figure 9: 3-D performance profile 1GW unit (>1,400 sensors)

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