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DESIGN AND OPERATION OF A COUNTERFLOW FILL AND NOZZLE TEST CELL: CHALLENGES AND SOLUTIONS

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1. INTRODUCTION

Factory-assembled cooling towers are generally compact enough to be tested and certified in environmental test chambers of reasonable proportions. Field-erected towers however can only be tested on-site after their construction has been completed. In order to rate them beforehand, to comply with the design conditions specified by the end-user, their components must be tested individually in test cells specially designed to that effect. Finding the solutions to problems like the size of the test cells, their configuration and operation, the type of instrumentation used to capture the fundamental thermodynamic data, etc., requires good engineering skills, time and money to be able to acquire meaningful and useful data.

Only a handful of cooling tower manufacturers and equipment suppliers worldwide own and operate fill test cells. Until a few years ago a test cell was available for third party testing on the west coast but it has since been shut down.

In the mid-eighties the Electric Power Research Institute (EPRI), funded by some of the largest US power producers, built a fill test cell near Houston, Texas. EPRI pursued an ambitious test program of many different counterflow fills commercially available at that time. The results were published and made available to EPRI members.

In the past ten years several industry consultants have presented the results of their research on cooling tower fills to the Cooling Technology Institute (CTI) membership. While their work was technically excellent and informative, the raw data and the methodology of data analysis were not divulged to the public, leaving the use of the final data subject to interpretation.

It is therefore an important technological step for a manufacturer to generate reliable data for proprietary fill and spray nozzle performance. This paper will present some of the most relevant aspects of the design, construction, instrumentation and operation of a state-of-the-art fill and nozzle test cell.

2. CHALLENGES

A vast majority of the new cooling towers erected in the field today are specified to be counterflow so the primary focus of R&D is on counterflow applications. A test cell is a scaled-down version of the manufacturer’s proprietary design. It is designed to work in a controlled environment susceptible to produce constant conditions of operation on both the water side and the air side.

At the onset of the design phase the engineer faces several challenges.

- Sufficient water side heat load must be available so that the maximum temperature range – commensurate with the most severe applications - can be obtained easily and kept steady for a reasonable period of time.
- The water flow must be distributed uniformly over the fill. Properly selecting the spray nozzles is critical. Knowing the spray pattern, in other words the relationship between flow rate, pressure and area of coverage, is essential to get meaningful results.
- While in large field-erected towers, the quantity of hot water which bypasses the fill section is relatively small and controllable, this is not true in a small-scale test facility. Quantifying the amount of “wall water bypass” is another critical factor to obtaining reliable results.
- Uniformity of air flow is obtained by selecting the right fan(s) and including aerodynamic features such as guide vanes and settling screens where necessary.
- The instrumentation must be properly chosen and adequately located throughout the test cell. Accuracy and redundancy are important to make sure the measurements are representative of the conditions of operation and the results can be trusted.
- In this configuration, the test section has been designed to minimize thermal transfer in the rain zone below the fill so as to focus on the thermodynamic properties of the fill and spray zone only. Accordingly the water collection system below the fill has been designed to minimize the rain zone while its effect on the airflow profile when the air enters the fill is minimal. (If the rain zone is not minimized, its thermal and aerodynamic contributions must be taken into account in the test interpretation).

3. DESCRIPTION

The counterflow test cell described in this paper is a forced draft configuration with two main parts: a horizontal section where the airflow is produced and quantified followed by a vertical section with the fill and spray nozzles. The cell cross section is rectangular measuring 2.4 m (8 ft) long by 1.8 m (6 ft) wide. The test cell can be broken down into seven segments:

1. Two horizontal tubular inline fans in parallel driven by two 40 horsepower TEFC 3-phase electric motors and a variable-frequency drive produce the cooling airflow.
2. The air flow measurement chamber follows the guidelines of ANSI/AMCA Standard 210. It includes several layers of settling screens upstream and downstream of a bank of elliptically-shaped flow nozzles with piezometer rings to measure the local static and differential pressures. Multiple wet bulb and dry bulb instruments measure the entering air temperatures.
3. Joining the horizontal and the vertical sections is a 90° bend with guiding vanes to distribute the air evenly upward into the fill test section.

4. A cold water collection system with several tiers of sloped troughs catches the cold water falling below the fill; the cold water from the troughs is discharged into a box intended to mix the cold water and to direct it to a tank outside the cell; redundant temperature sensors measure the cold water temperature downstream of the box.
5. The fill section is 2.4 m (8 ft) long by 1.83 m (6 ft) wide by 2.4 m (8 ft) high. Fill supports can be adjusted up or down to accommodate various fill depths and keep a constant spray height. Watertight doors in the side walls provide access to install or remove fill packs.
6. The water spray section includes PVC pipes fitted with spray nozzle adaptors, redundant hot water temperature sensors and a spray pressure fitting. This section has changeable pipe supports so the spray height can be adjusted too. This section also contains a system which catches and re-directs the wall water to an outside tank where its flow rate and temperature are measured.
7. A layer of drift eliminators is installed above the spray section. This section also includes multiple leaving wet bulb and dry bulb temperature sensors.
8. The test cell is installed in an environmental test chamber where a system of exhaust and intake fans and dampers are used to control the conditions of the entering air and maintain steady conditions during the test runs.

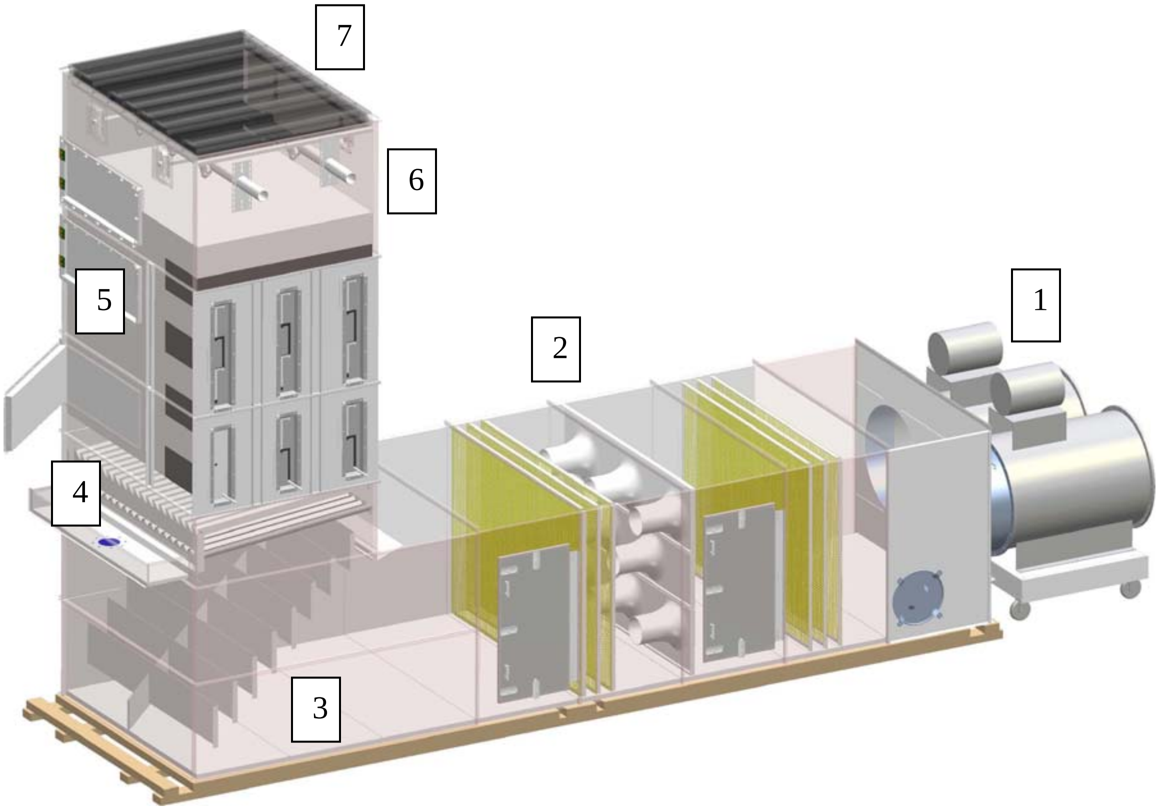


Figure 1: Counter-Flow Test Cell

4. BOUNDARIES

The counter flow test cell operates within boundaries specified to encompass a broad range of conditions:

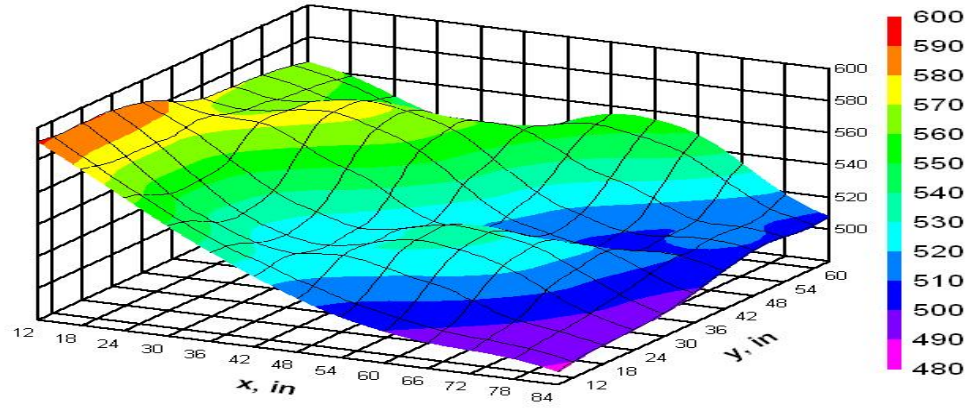
- The ratio of water flow rate to fill plan area ("water loading") can be adjusted from 10 $m^3/h\text{-}m^2$ to 30 $m^3/h\text{-}m^2$ (4 GPM/ft^2 to 12 GPM/ft^2);
- The air velocity within the fill test section can vary from 1.5 m/s to 3.5 m/s (300 FPM to 700 FPM)
- The spray height is adjustable from 0.3 m to 0.9 m (12 in to 36 in)
- The fill height is adjustable from 0.9 m to 2.1 m (3 ft to 7 ft).
- Another test section can be added above to test splash fill up to 5 m (16 ft).
- The heat load normally available is 880 kW (3 million BTU/hr); it can be increased to more than double that value if necessary.

These boundaries bracket the vast majority of requirements of power plant and industrial tower parameters. Unusual conditions such as water loading less than 4 GPM/ft2 or air velocities less than 300 FPM can be tested individually.

5. AIR SIDE

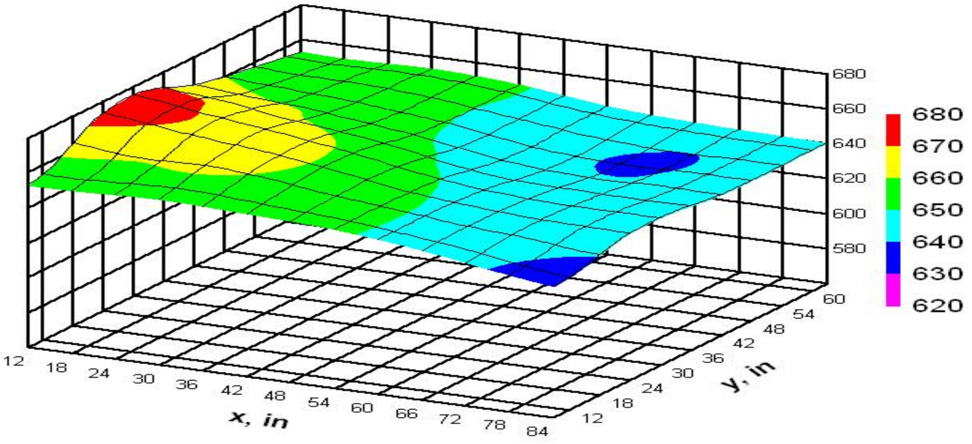
Two tubular inline centrifugal fans are installed horizontally side-by-side to force the cooling air through the fill test cell. Tubular inline centrifugal fans combine the compact, high volume advantages of axial fans with the low sound, high efficiency of tubular centrifugal fans. The air is discharged at an angle from the inlet instead of perpendicularly which gives the fan a higher efficiency. Because of the high fan efficiency the wheel can rotate more slowly resulting in better sound performance. Each 930 mm (36.5") fan wheel is capable of producing up to 1.7 kPa (7 inWG) of static pressure and 7.5 m3/s (16 000 CFM) of airflow when operated at 1700 RPM.

A first step after start-up is to survey the cell exhaust plane to verify whether the air flow in the fill section is uniform. Air velocity profiles were recorded above the fill with a digital vane anemometer under different air flows without water. The first few profiles showed a bias toward one side of the test cell (see figure 2). After analysis the bias was attributed to a lack of symmetry of the water-collection troughs below the fill. By re-arranging the troughs in a more symmetrical manner the deficiency was corrected. As it can be observed in figure 3, the resulting profile was improved significantly. The flow profile was un-biased from front to back, even before re-arranging the troughs, telling that the guide vanes which re-direct the air flow up from the horizontal section to the vertical section are working well.



Airflow profile 1A.grf

Figure 2: Biased Air Flow Profile



Airflow profile 1B.grf

Figure 3: Improved Air Flow Profile after Re-arranging the Troughs

The air flow rate is measured in the horizontal leg of the test cell. Located between multiple layers of settling screens, a flat surface contains eight elliptically-shaped, precision-machined air flow nozzles in a symmetrical pattern. The differential pressure across the nozzles (ΔP) is measured with two piezometer rings, one upstream and one downstream of the bank of nozzles. The static pressure downstream of the nozzles and the entering air wet bulb and air dry bulb temperatures are also measured. The air flow rate is computed from the ΔP across a single nozzle or a bank of multiple nozzles using the ANSI/AMCA standard equations.

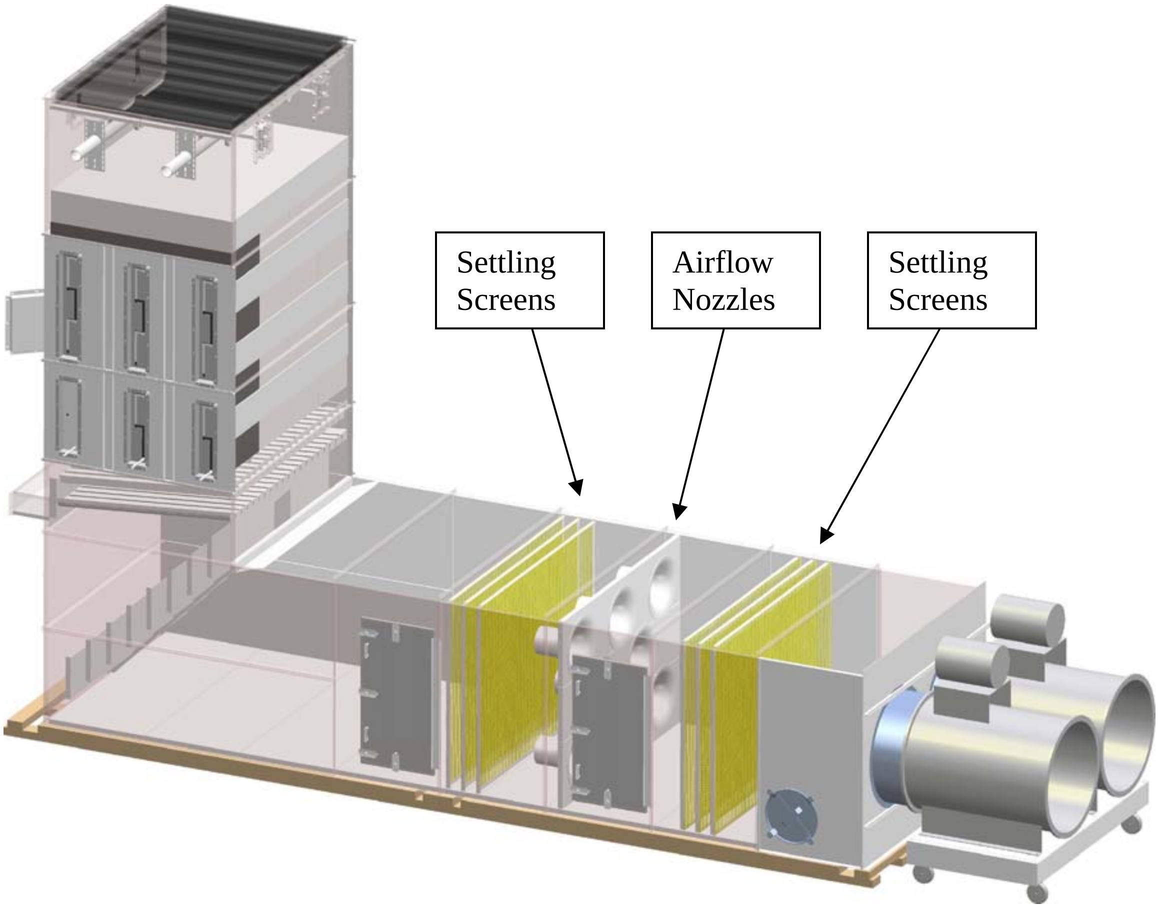


Figure 4: Air Flow Measurement Section

Two nozzle diameters, 152 mm (6 in) and 254 mm (10 in), and up to eight nozzles can be mounted in the measurement plane. The two diameters can be combined. The minimum air velocity across a nozzle should be at least 14.2 m/s (2800 FPM) per ANSI/AMCA. The maximum air velocity is practically dictated by the fan drive maximum amperage.

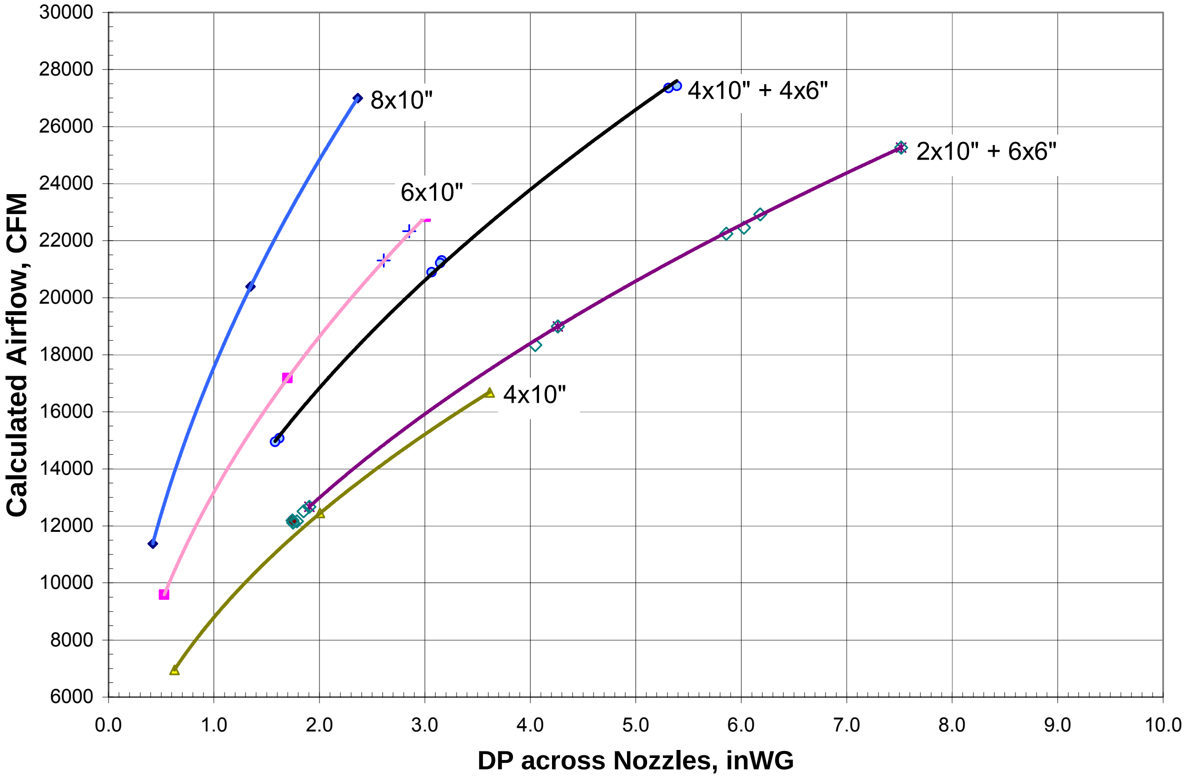


Figure 5: Airflow Nozzle Characteristic Curves

The relationship between ΔP and airflow is different for every nozzle configuration. Multiple configurations of nozzle diameters and locations were tested, recording ΔP, static pressure and air temperatures while at the same time surveying the upstream and downstream planes with a digital vane anemometer. For each nozzle configuration the computed airflow was plotted as a function of ΔP: see figure 5.

Each curve is characteristic of a number and diameter of nozzles. From these curves, it becomes clear that the accuracy of the airflow calculation is greater when the slope of the characteristic curve is less steep.

6. WATER SIDE

A horizontal centrifugal pump forces the water to flow through a plate heat exchanger which produces the heat load from the boilers. The water flow rate is measured by two separate instruments: a calibrated 6 inch venturi flow meter coupled with a water-over-fluid U-manometer and a calibrated magnetic flow meter with digital output. A straight length of pipe with Pitot taps is also installed in the circulating water loop to double-check the two main flow meters against a Pitot tube if required.

The hot water is distributed over the fill by two pipes fitted with spray nozzles. Redundant temperature sensors measure the hot water temperature before it enters the test cell; a pressure sensor is installed to monitor the spray nozzle operating pressure.

The cold water leaving the fill is collected in troughs which discharge it via a box into a tank with a make-up float valve and a strainer in the suction. Redundant cold water temperature sensors are located below the mixing box.

With respect to spray nozzles, the relationship between flow rate, operating pressure and area of coverage is critical. As mentioned earlier one of the challenges of the test cell is to achieve a constant water-to-air ratio (L/G) over the fill. Some nozzles are designed to operate by interaction and overlap of sprays, other nozzles have a substantially conical spray pattern, yet others have a square or rectangular spray pattern. In a small-scale test chamber the "overlapping" nozzles are not well adapted because the water exiting them has a significant horizontal component, as a consequence the amount of water reaching the cell walls - and bypassing the fill - is excessive. The test engineer is then faced with a quandary: which spray nozzle is the most adequate? While the interaction/overlapping sprays are the most efficient in large field-erected towers, the conical or square sprays are more controllable in the small-scale test cell. In a field-erected tower, the wall water bypass can be controlled to less than 1% of the incoming water flow rate but in a small test cell it can amount to as much as 40%. After testing different spray nozzles and comparing the overall thermal results, we opted to use spray nozzles with a square pattern.

In addition a simple system of narrow gutters and wall slots has been designed and built in to catch and re-direct the water flowing on the walls. By means of this system the wall water flow rate and temperature can be precisely quantified before the water returns to the cold water basin.

7. TEST INTERPRETATION

Each test is run for a minimum of one hour after reaching steady-state. The HP data logger generates one-minute averages from the 20+ sensors. At the end of a test the test data file is transmitted via the company network to the test engineer's computer for data analysis and interpretation. Graphs are generated to visualize the stability of test data and to select the most stable period. The test data are averaged over the representative period and the data scatter is quantified by computing the standard deviation.

Figure 6 depicts a typical one and one-half hour test with a 60-minute window of stable conditions. Figure 7 depicts the instantaneous deviations from various temperature sensors during a given test.

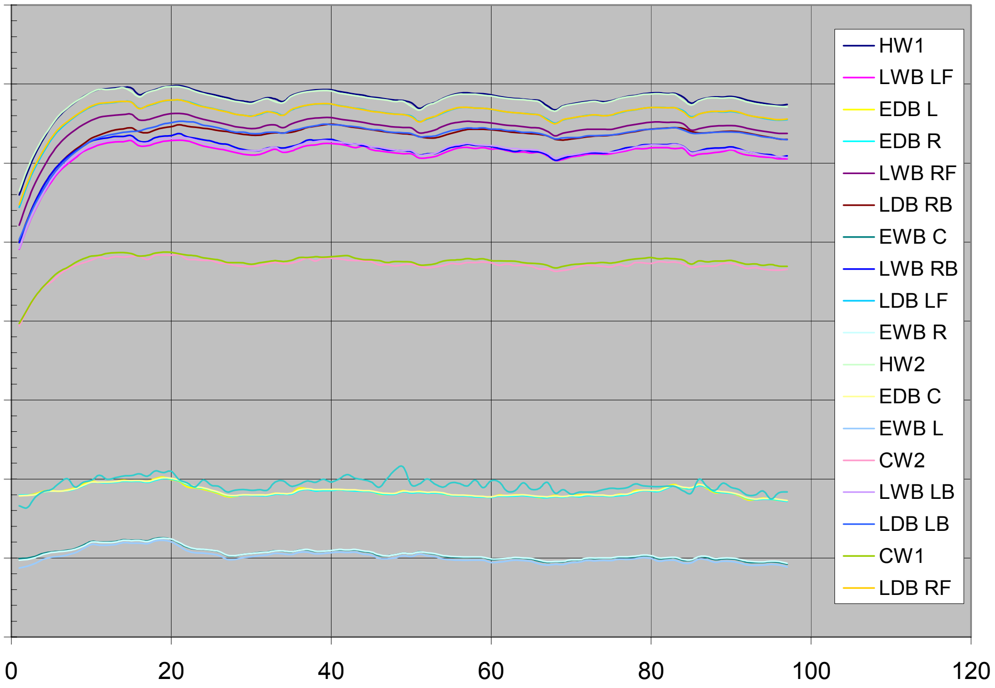


Figure 6: Test Data

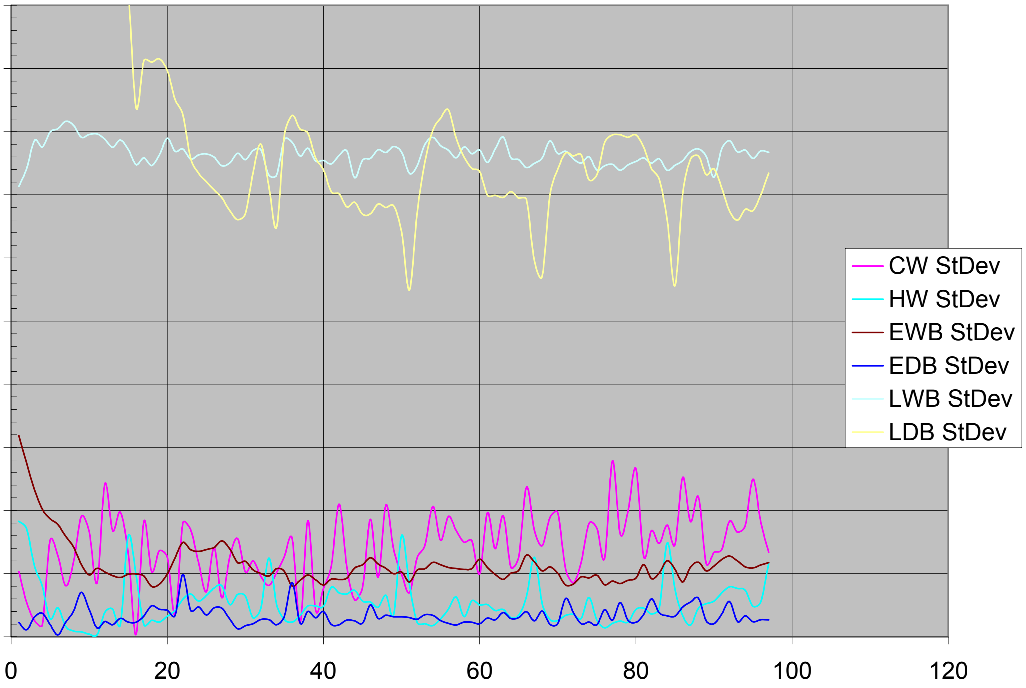


Figure 7: Test Data Standard Deviations

From a selected window of stable data, the test averages are computed along with standard deviations. The heat balance is checked. A standard deviation in excess of 0.2 ºC (0.4 ºF) of an average temperature is cause for further scrutiny of the data and eventually rejection of the test in question if no other window of stable data is available.

Heat balance refers to the expected equilibrium which in principle exists between the heat released by the water as it flows downward while some of it evaporates, and the heat and moisture gained by the air as it passes upward through the fill and rain. It is practically impossible to count every single BTU exchanged in the system. Coming to within a few percents of a perfect heat balance is a tough goal to reach. Instrumental scatter or errors, invisible leaks and losses contribute to increase the gap between air-side heat and water-side heat. Our target is a gap of less than 10%.

Once a test is considered valid, the test data interpretation consists in calculating the fill heat transfer coefficient (such as the KaV/L or the NTU) and the fill static pressure drop. Multiple data points are later reduced into equations to be incorporated into the manufacturer's proprietary fill data and computer model.

Of course it is essential to keep full consistency of methodology between the stage of test data interpretation and that of performance prediction.

8. BASELINE

One of the final steps is to verify that there is no major flaw with the test cell, the instrumentation or the test interpretation methodology. One must proceed to carry out baseline tests: by this, we mean the testing of a known component in such a manner that the results of such tests will be compared to the known results and – if all goes well – found to be consistent with them within the boundaries. We have used cross-corrugated fill with 19 mm flute opening as our baseline.

9. CONCLUSION

At the start of the project there were many challenges: define the boundaries of operation of the test cell, achieve uniform L/G, quantify wall water by-pass, pick accurate and redundant instrumentation, establish a "baseline", etc.

Research, patience and perseverance are indispensable ingredients to address the challenges one by one. But after several weeks spent debugging and fine-tuning the installation, the baseline tests came out on target.

The knowledge acquired from the fill test cell is not enough. The final proof comes from full scale field tests. But this is another story.

"The joy of engineering is to find a straight line on a double logarithmic diagram", Thomas Koenig, University of Karlsruhe (Germany).

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