COMPARISON OF POWER ENHANCEMENT OPTIONS FOR COMBINED CYCLE POWER PLANTS IN HUMID ENVIRONMENTS

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Introduction

Turbine Inlet Cooling (TIC) is a proven application for gas turbines worldwide. Proven cooling technologies include two broad classes of cooling: evaporative and mechanical cooling. This paper will provide a brief overview of the two technologies and then focus on the difference between the two primary means of mechanical inlet cooling: mechanical electric and absorption, with a focus on climatic and operational issues in SE Asia.

The main difference between the two technologies is that evaporative technologies depend on the ability to cool the air by evaporating more water in the inlet air stream. The limit of this technology is the existing humidity in the air and the ability to maintain the moisture in solution through the filter house. The physical limit to this technology is set temperature approach to the wet bulb. So in the humid Southeast Asian environment, wet bulb in the 26ºC – 29ºC (80ºF - 84ºF) range, the lowest inlet air temperature expected are in the range of 28ºC – 31ºC. The other difference is the amount of moisture in the inlet air and the potential for damage to the compressor from condensation of the moisture. With mechanical cooling, the grains of water per mass of air are dramatically reduced, thus eliminating the risk of condensation.

Mechanical inlet cooling uses either thermal or electric energy to cool the water to and below the range of the wet bulb temperatures, allowing a system to provide inlet air to the icing point of the inlet air. The investment of capital and time mirrors the ability of the system, with the mechanical inlet cooling system being more expensive on a total capital basis and requiring more time to install. The limit of evaporative technologies is shown in Figure 1 below.

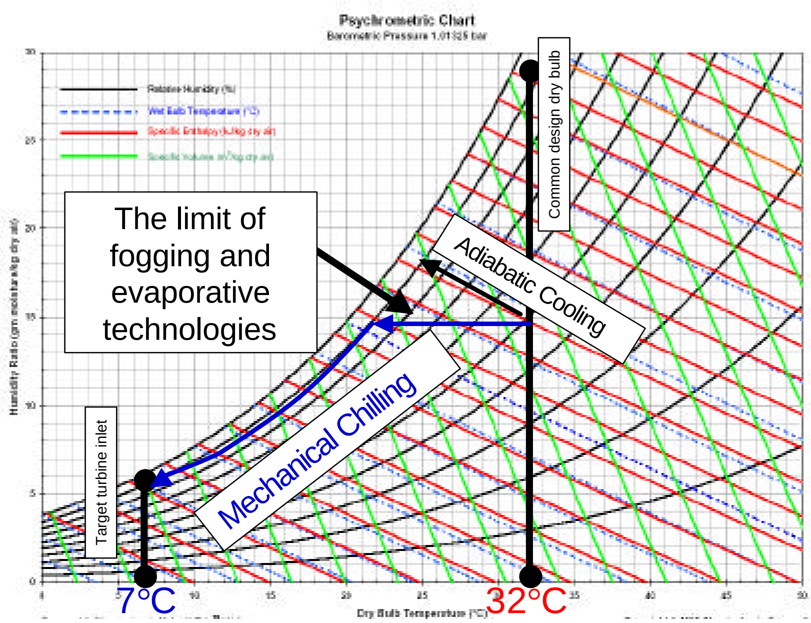

Figure 1, Limit of Evaporative Technologies

The comparison of electric and absorption methods of inlet cooling will utilize common heat balance software to model the performance of the power plant. This will allow potential users to understand the benefits of utilizing steam directly in absorption chillers vs. using the steam to generate electricity and then run mechanical electric chillers to generate the cold water for inlet chilling.

Design Conditions

As an indicative ambient design point, this paper will use Bangkok, Thailand. Annual average hourly ASHRAE data is available for this location. Figure 2 below shows the annual average dry bulb and wet bulb conditions on an hourly basis.

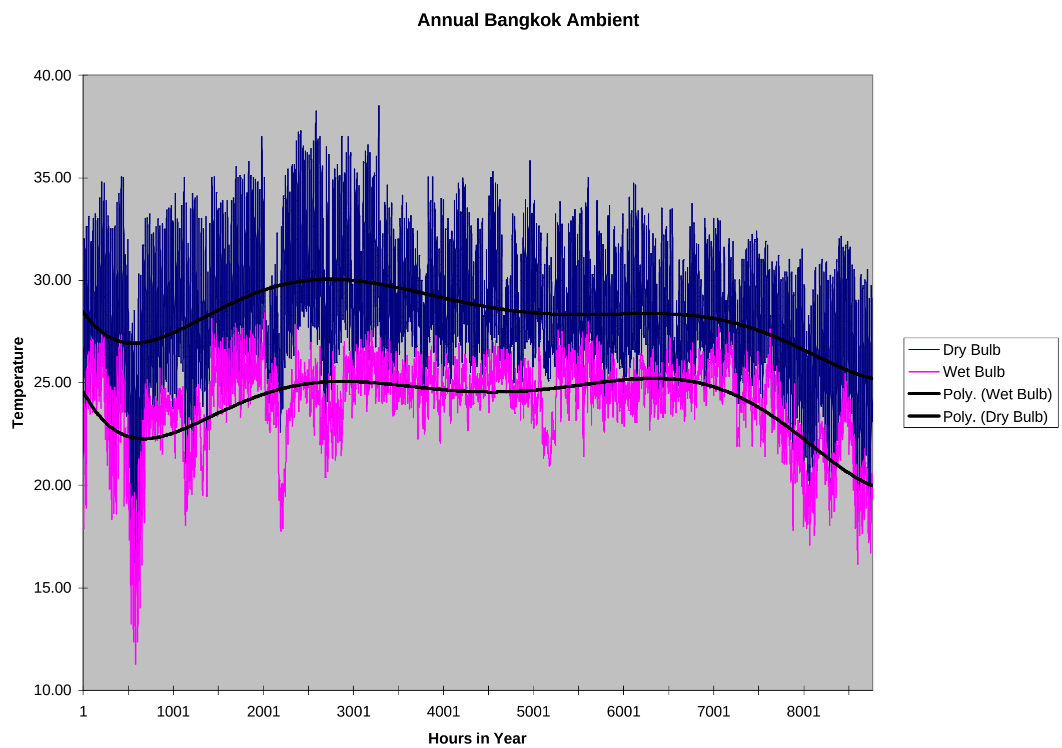

Figure 2, Annual Average Dry and Wet Bulb Conditions

For the average engineer familiar with the operations of gas turbines, the dry bulb temperature is the only temperature that is normally considered, as wet bulb (or relative humidity) does not impact the gas turbine performance. When inlet cooling applications are considered, wet bulb becomes a critical design consideration as this is really a measure of the energy of the inlet air and all inlet cooling technologies require the removal of this energy to effect their cooling. An indicative point is that for similar dry bulb conditions in Las Vegas vs. Bangkok, the gas turbine cooling load will be 40-50% reduced.

Another key design consideration is the daily variation of wet bulb and dry bulb temperatures. This is critical because most engineers utilize relative humidity. Relative humidity varies dramatically on a diurnal basis while for each season the diurnal wet bulb temperature is relatively stable. Figure 3 shows this daily variation. In practice, what happens is that a morning relative humidity of 80-90% is sometimes mistakenly utilizes with the peak daytime dry bulb temperature leading to a dramatically over-stated wet bulb design condition.

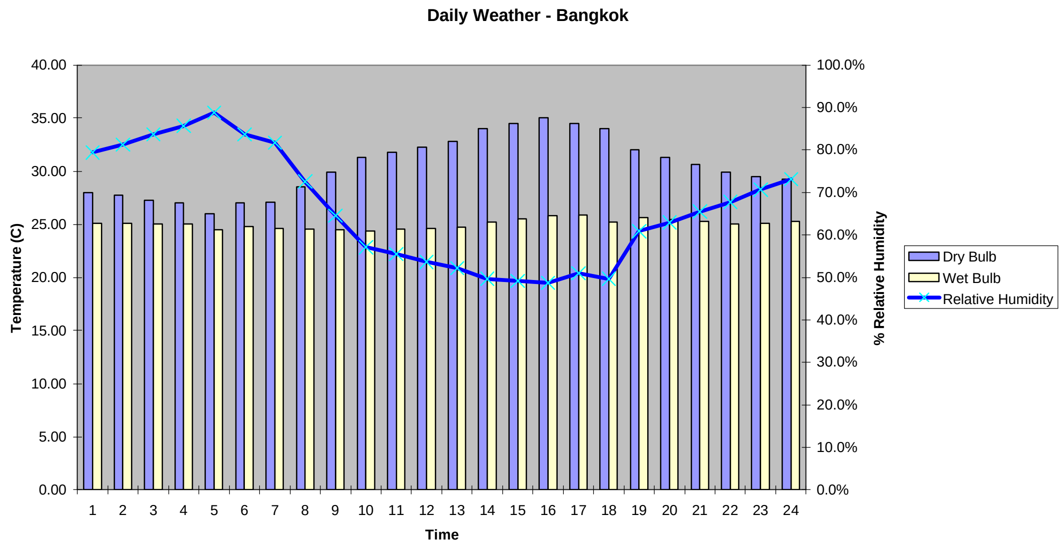

Figure 3, Daily Dry & Wet Bulb with Relative Humidity

Another factor taken into consideration for SE Asia operations is the availability of potable water for use in cooling tower makeup. This is critical, as absorption chillers require the condensing temperatures provided by cooling tower thus proven air-cooled absorption chillers do not exist.

Once the technical design points are understood for the specific location, the actual electricity delivery requirements on a daily basis must be considered. This paper will not discuss these issues in detail, but the daily load curve, compared to the ambient design conditions must be considered. For locations in the SE Asia, there are variations, but many have a double daily peak in mid-morning and then late evening, which drives the need for incremental power when the relative humidity is high and evaporative technologies are limited.

Mechanical Inlet Cooling Design Case

To account for the very humid weather that can occur seasonally, the design case for this study was set at 35.0°C (95.0°F) dry bulb and 27.2C (81.0°F) wet bulb, this equates to a 55% relative humidity. This is considered to be a very harsh wet bulb condition and when not operating at the design case, the inlet cooling systems will reduce the gas turbine inlet temperature on a "one for one" basis with the reduction of the ambient wet bulb.

For this paper, two turbine models, common to the SE Asia region will be utilized: Frame 6B (Model 6581) and Frame 9FA (Model 9351). These models were chosen because of their routine application in SE Asia and the availability of data in common plant design tools. In addition, the mass balance design data can be confirmed with OEM supplied performance tools. Table 1 shows the various options that will be analyzed for this paper. For similar sized E and F class machines the results will be similar. For machines of the same class with higher compression ratios, the results will be improved on a performance basis: (1) More net MW's added and (2) higher efficiencies AND on a capital basis due to the less chiller equipment required. This is due to the need to cool less air per MW generated.

Turbine Model	Base Case	Chilled with Electric Chiller	Chilled with Absorption Chiller
Frame 6B	2 Units in combined cycle	Cooled to 50ºF	Cooled to 53ºF
Frame 9FA	2 Units in combined cycle	Cooled to 54ºF	Cooled to 54ºF

Table 1, Evaluation Cases

The evaluation was completed using identical plant designs with the changes only being the inlet treatment. In the case of the absorption chiller, a portion of the low-pressure steam is supplied to the condensing steam turbine is utilized by the absorption chiller, reducing the electrical output of the steam turbine. The steam turbine size remained the same in all cases due to the concern that when inlet-cooling water was not needed, the steam from the absorber would have to be condensed.

For this evaluation, it was important to utilize complete chilling systems such that the actual field installed costs and performance could be repeatable for other projects. This analysis utilized standard TAS packaged cooling system and Trane centrifugal and absorption chillers. This combination of technologies has been used successfully all over the world in many climates and applied successfully in the Asian market. Table 2 provided a performance summary for each of the chiller systems.

	Tas Model	Rated Capacity (per unit)	Energy Usage		Coefficient of Performance
Electric Centrifugal	F-43C	5000 tons	0.78 KW/ton	N/A	5.5
Absorption (single)	B-12C	1200 tons	0.30 KW/ton	18 lb/hr/ton	0.67
Absorption (double)	B-12C	1200 tons	0.30 KW/ton	11 lb/hr/ton	1.1.

Table 2, Mechanical Chiller Performance Summary

Results

Evaluation using an integrated heat balance analysis of the base and chilled cases showed that, as expected, all of the chilled cases had improved plant output. The key consideration for this study was the impact on total plant efficiency and which chilling technology provided the most effective solution on a cost and performance basis.

For the combined cycle E-class (Frame 6B) gas turbine case:

- Overall the chilling cases added between 10 and 14 gross MW to the plant’s output.
- The net MW added ranged between 9 and 11 with the mechanical electric providing the greatest increase of 11 MW or almost 10 % of total output.
- The efficiencies were slightly reduced by between 2 and 4 %, with the most efficient solution being the mechanical electric solution.

For the combined cycle F-class (Frame 9FA)gas turbine case:

- Overall the chilling cases added between 74 and 89 gross MW to the plant’s output.

- The net MW added ranged between 70 and 74 with the mechanical electric providing the greatest increase of 74 MW or over 11 % of total output.

- The efficiencies were slightly reduced by between 1.5 and 2.0 %, with the most efficient solution being the mechanical electric solution.

The small overall variation in performance, between the technology choices, could be ignored if evaluated on a total plant basis. To consider the real impact, the comparison was completed on a chiller efficiency basis. To complete this comparison the loss of steam turbine output due to the reduced steam flow to the steam turbine must be included as a "chiller parasitic load".. When this evaluation is complete, it can be noted that the equivalent electrical load for chiller operations is as follows:

- Case 3: Mechanical Electric: 0.78 KW/ton

- Case 4: Double effect absorption: 0.98 KW/ton

- Case 3: Single effect absorption: 1.05 KW/ton

Interestingly this is not as great as the comparison of the coefficient of performance for each would indicate, see Table 2 above. The efficiency of the combined cycle plant to utilize the lower pressure steam seems to have reduced the expected advantage of the mechanical electric chilling scheme. This analysis shows that the mechanical electric solutions 38 % more efficient than the single effect product and 25% more efficient than the double effect absorption product for the E-Class technology. For the F-class units, the figures are 22% and 43% respectively.

	Frame 6B Base Case	Frame 6B Electric Chiller	Frame 6B Single Effect Absorption Chiller	Frame 6B Double Effect Absorption Chiller
Gas Turbine Output	72.2	84.9	84.0	84.0
Steam Turbine Output	42.1	43.9	39.8	40.8
Gross Total Plant Output (% increase from base)	114.3	128.8 (12.7%)	123.8 (8.3%)	124.8 (9.2%)
Net Total Plant Output (% increase from base)	111.5	122.5 (9.9%)	120.3 (7.9%)	120.6 (8.2%)
Refrigeration Tons	N/A	4889	4560	4560
Projected Chiller Capital Costs Installed (Note 1)	N/A	3,800,000	4,540,000	4,490,000
Incremental Capital Costs ($/KW)	N/A	344	514	490
Cooling System Operating Costs ($/MWH) (Note 2)	N/A	$0.35/MWH	$0.38/MWH	$0.38/MWH

Table 3, Results – Frame 6B

Note 1: Includes chiller, inlet air coils & installation
Note 2: Includes routine & major maintenance, cooling tower makeup & chemicals

	Frame 9FA Base Case	Frame 9FA Electric Chiller	Frame 9FA Single Effect Absorption Chiller	Frame 9FA Double Effect Absorption Chiller
Gas Turbine Output	435.5	514.7	514.7	514.7
Steam Turbine Output	237.5	247.6	225.6	233.1
Gross Total Plant Output (% increase from base)	673.1	672.3 (13.3%)	740.3 (10.0%)	747.8 (11.1%)
Net Total Plant Output (% increase from base)	656.5	730.3 (11.3%)	721.1 (9.5%)	727.0 (10.7%)
Refrigeration Tons	N/A	19,600	19,600	19,600
Projected Chiller Capital Costs Installed (Note 1)	N/A	16,640,000	19,850,000	19,460,000
Incremental Capital Costs ($/KW)	N/A	225	318	276
Cooling System Operating Costs ($/MWH) (Note 2)	N/A	$0.35/MWH	$0.38/MWH	$0.38/MWH

Table 4, Results – Frame 9FA

Note 1: Includes chiller, inlet air coils & installation
Note 2: Includes routine & major maintenance, cooling tower makeup & chemicals

Operational Issues

With regard to overall plant operational flexibility the inlet cooling schemes provide the highest total plant output as well as the most consistent delivery of power. The only difference between the electric and absorption chillers are the ability of the electric to drive the inlet temperature below 52°F when the inlet air wet bulb temperature is reduced from the design condition. Absorption chillers are only capable of generating 6.6°C (44°F) water in the SE Asia conditions. With this supply water temperature, the obtainable inlet air temperature is approximately 11.1°C (52°F). For the design case, this will not be an issue, but as the wet bulb temperature is reduced, the absorption system will not be able to continue to reduce the inlet air temperature below approximately 11°C, while the mechanical electric system can drive to the limit of the system capacity.

When considering mechanical chillers, the ultimate heat rejection source must be considered, in this case, cooling towers are utilized. Due to the lower system efficiency, for equal chiller tons, the absorption chillers will reject 20-30 percent more heat than the mechanical electric chiller. This will result in a higher cooling tower makeup water rate and chemical usage. This will be offset by the higher steam turbine power generation in the case of the electric chiller.

When considering an optimal inlet cooling system, the ability to control plant output over the range of the incremental power added by the chiller can be important. Operating with a variable inlet temperature will allow the combined cycle plant to operate at more efficient base load condition and still vary output up to ten percent. Due to better response times, the mechanical electric system will performance this function more effectively.

Summary

The use of inlet cooling will add significant power to a combined cycle facility in a humid environment. This output will be driven primarily by the increased gas turbine output due to the lower inlet temperature – true in all chilling cases. When using mechanical electric chillers, the steam turbine output will also be in creased. Designs utilizing absorption chillers will reduce the low-pressure steam supply to the steam turbine thus reducing the overall steam turbine capacity. The overall difference between absorption and mechanical electric chillers is small when considered on a total plant basis. When the overall chiller efficiency is considered, the mechanical chiller proves to be at least 25% more efficient than the best absorption technology, which for these design cases are double effect absorbers.

The capital and operating costs of the electric chiller increase the advantage of the electric system as the electric chiller system is approximately 20 percent less expensive on an installed basis than the absorption system.

Operationally, the absorption system will reject more heat, requiring between 20 and 30 percent more cooling tower capacity and cooling tower makeup water and chemicals. In addition, the response time of the electric chillers is much faster than the absorption system.

In conclusion, the perception that directing steam directly to an absorption chiller when a condensing steam turbine is available proves to be a serious design error. In all three areas of review: performance, capital costs and operational costs & issues, the mechanical chiller is the better choice.