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# A preliminary study on HTGR with air-cooled condenser at Riyadh, Saudi Arabia

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## 1. Introduction

A high temperature gas reactor is best suited to arid area such as rural area of Riyadh, Saudi Arabia where dry air cooling is the only way to exhaust the waste heat during electricity generation. NGNP reactor originally designed by General Atomics is a 350 MWt HTGR with 750°C outlet temperature.[1] NGNP reactor plant adopted a Rankin steam cycle for early deployment and for reducing R&D risk and cost. Original plant design is based on a wet cooling tower with wet bulb temperature of 34°C. This cooling environment may be sufficient for most area in North America. However, we should consider air temperature of 45°C and no available cooling water for any site near Riyadh, Saudi Arabia. A plausible option in such arid area is using an air-cooled condenser(ACC) which is widely used in a combined cycle plant in arid region as shown in Figure 1. ACC is also suitable for freezing area such as northern territory or high elevation remote area.[2]

We have studied impact of the cooling method on the power generation efficiency and the annual average power production referencing NGNP steam turbine.

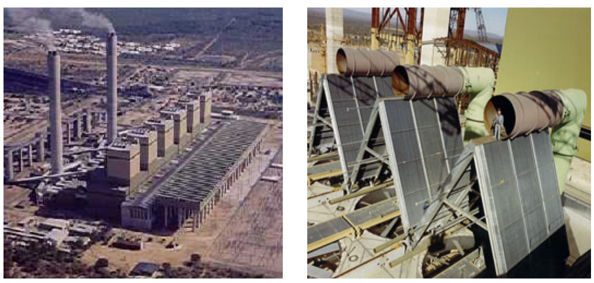

Fig. 1. Majuba power station, South Africa, largest 6x660MWe air cooled condensers [3]

## 2. Cooling condition at Riyadh

ACC performance is primarily dependent on the air temperature. And, wet cooling performance using water evaporation primarily depends on the wet bulb temperature. Fig. 2 shows the weather data at Riyadh, KSA, in 2012.[4] The maximum and minimum air temperatures are 45 and 3°C.

A cumulative probability density function (CDF) is derived in Figure 2. Air temperature distribution is almost linear between 10-45°C, while wet bulb temperature shows near Gaussian distribution. Peak wet bulb temperature is 35°C which is nearly the same as design temperature of cooling tower of NGNP. However, there is not enough water for evaporation at rural Riyadh.

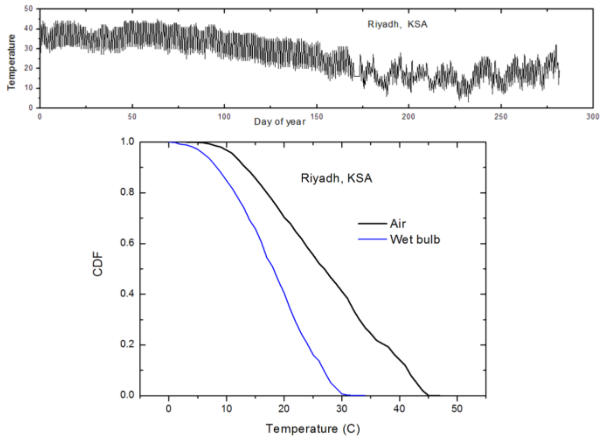


Fig. 2. Weather data at Riyadh. Top: air temperature variation. Bottom: CDF for air and wet bulb temperature.

## 3. Rankin cycle efficiency

*2.1 Fixed extraction rate*

Modern steam turbine utilizes several steam extractions at certain turbine stages to increase overall efficiency. The efficiency can be analyzed with T-S diagram. We have setup a T-S diagram using the heat balance specified in NGNP conceptual design report (CDR) [1] as shown in Fig. 3.

A set of heat balance equation was established using EES v.9 [5] to compute the Rankin cycle efficiency. The extraction pressures at four steam extractions are 12.9, 6.5, 1.6, and 0.75 MPa. The extraction ratios are evenly set to be 6% at four extraction lines as specified in the CDR.

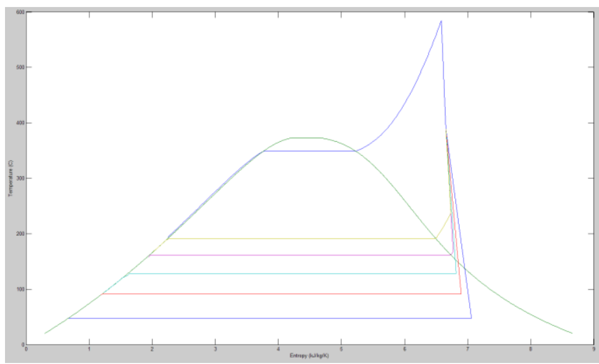

Fig. 3. T-S diagram of NGNP Rankin cycle with 4 extractions.

We set the entropy loss at turbine end stage as 5% to reproduce the specified efficiency of 42.26% at 47.7$^o$C of condenser temperature (or vacuum pressure of 0.11bar). This corresponds to 34$^o$C of wet bulb temperature at cooling tower and confirms all requirements to have only subcooled water at any feed water pumping stage. Condenser split temperature (leaving temperature difference) of the NGNP wet cooling tower design is set to 13.7K, while typical condenser split temperature of the ACC is 11~17K. We adopted the same split temperature both for wet cooling tower and ACC. Fig. 4 displays the variation in cycle efficiency and turbine back pressure with the ambient air temperature for fixed extraction rate. As displayed in the figure, the efficiency degrades at the rate of -0.129%/K. It should be noted that the turbine back pressure increases rapidly with ambient air temperature. Considering the temperature difference between the air and wet bulb temperature in median is 8.75K, the efficiency of the ACC is estimated to be 1.12% lower than that of the wet cooling tower.

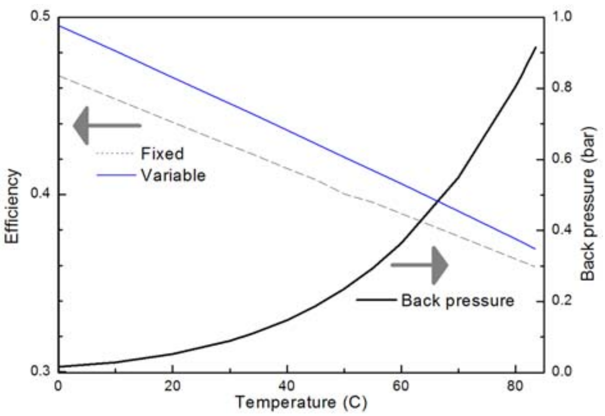


Fig. 4. Efficiency and turbine back pressure variation according to ambient air temperature. Left scale: the efficiency. Dashed line – fixed extraction rate. Solid line – variable extraction rate. Right scale: the turbine back pressure.

The annual average cycle efficiency is computed by weighting the temperature probability distribution function (PDF) which is obtained from the cumulative probability distribution function (CDF),

$$\bar{\eta} = \int_{T_{\min}}^{T_{\max}} p(T)\eta(T)\,dT$$

, where $p(T)$ is the PDF, T is the air temperature, and $\eta(T)$ is the cycle efficiency. Using the CDF at Riyadh, KSA, we obtain the annual average cycle efficiency of 43.1%.

### *2.2 Variable extraction rate*

It is possible to vary steam extraction rate using controlled throttle valves. In this case, necessary condition of feed water condensing can be met by designing reasonable split temperature at each stage of condenser. We adopted 30K for the first 3 and 10K for the last extraction condenser. This design match with NGNP CDR. With the condensing constraints, we obtained optimum extraction rates as 10.8%, 13.7%, 18.7%, and 13.8% at 34$^o$C of air temperature. About 3% increase in power production can be achieved for 34 $^o$C air temperature. It was observed that only the last extraction rate needs to be varied between 17.1% to 12.7% with the changes in the ambient air temperatures from 0$^o$C to 40$^o$C.

The annual average cycle efficiency using the CDF of Riyadh, KSA, is 45.5% which is 2.4% higher than that of the fixed extraction rate turbine. Power generation is 5.6% higher than fixed case.

## 3. Conclusion

Even though condenser split is assumed to be the same between ACC and wet cooling tower, large difference in air temperature and wet bulb temperature makes large efficiency loss in the ACC. The ACC efficiency is lower than that of the wet cooling tower by 1.12%. To make up this loss, we proposed the variable steam extraction rates operation.

An air cooled condenser is a practical

## ACKNOWLEDGEMENT

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## REFERENCES

[1] Conceptual Design Report – Steam cycle modular helium reactor (SC-MHR) demonstration plant, NGNP-R00016, General Atomic, 2011.
[2] D.G. Kroeger, Air cooled heat exchangers and cooling towers, Penwell Corp. Tulsa, USA, 2004.
[3] Direct Air-cooled Condensers, GEA Aircooled Systems, http://www.gea-energytechnology.com/opencms/opencms/ gas/en/products/Direct-AirCooled_Condensers.html, accessed on 2012.
[4] Access http://www.wunderground.com/
[5] EES – Engineering Equation Solver version 9, http://www.fchart.com/, 2012.