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Pinch Analysis of Triple Pressure Reheat Supercritical Combined Cycle Power Plant

Sui Yan Wong, Keat Ping Yeoh, Chi Wai Hui

Abstract**—**In this study, supercritical steam is introduced to Combined Cycle Power Plant (CCPP) in an attempt to further optimize energy recovery. Subcritical steam is commonly used in the CCPP, operating at maximum pressures around 150-160 bar. Supercritical steam is an alternative to increase heat recovery during vaporization period of water. The idea of improvement using supercritical steam is further examined with the use of exergy, pinch analysis and Aspen Plus simulation.

Keywords**—**Exergy, pinch, combined cycle power plant, CCPP, supercritical steam

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I. INTRODUCTION

THE CCPP power plant, which offers efficient power generation with less emissions than the traditional coal-fired power plant, has been widely adopted in the world. With General Electric's new STAG^{TM} combined cycle technology [1] and Siemens H class gas turbine [2], the thermal efficiency of CCPP power plant is possible to reach over 60%. Concerning optimization approaches towards CCPP are usually based on a Triple Pressure Reheat (TPRH) system using subcritical fluid. The latent heat of vaporization associated with steam limits temperature growth and thus restrict amount of potential available energy in the system. With the use of pinch analysis, it is observed that amount of exergy starts flattening out when water undergoes vaporization. Therefore, the paper is devoted to examining optimization of existing TPRH-CCPP power plant through supercritical steam as working fluid. The analytical method is based on pinch, exergy analysis study and Aspen Plus simulation.

II. LITERATURE REVIEW

Development of combined-cycle technology in the last four decades enabled more flexible and efficient power generation. The GE's model featured its pre-engineered combined cycle product - STAG^{TM} with highest lower heating value (LHV) thermal efficiency above 60% [1]. Fig. 1 is a schematic diagram showing STAG^{TM} TPRH CCPP. The heat exhaust from the gas turbine is used to heat up water. Steam turbines of three pressure levels convert energy from steam.

The temperature profile of GE's STAG combined cycle can be found in Fig. 2. Comparing to TRPH to one pressure CCPP, the TPRH's cold stream is closer to its hot stream relative to that of the one pressure system. Thermal energy is more efficiently transferred from hot exhaust to cold stream in TPRH combined cycle.

Overall, the TPRH system shows better performance in thermal efficiency and net power output than the other configurations. Table I shows comparison of STAG steam cycles, TPRH cycle is found to be the best among other cycles.

TABLE I
PERFORMANCE VARIATION WITH DIFFERENT STEAM CYCLES [1]

	Plant Output (%)	Thermal Efficiency (%)
Triple Pressure, Reheat	+0.7	+0.7
Triple Pressure, Non-Reheat (control)	-	-
2-Pressure, Non-Reheat	-1.0	-1.0
1-Pressure, Non-Reheat	-4.7	-4.7

The reason behind can be explained by T-S diagram. In TPRH, steam saturated temperature increases under increased pressure levels, enclosing more area under T-S curve of steam. Therefore, it generates more work and transfer heat better than the simple cycle.

Although TPRH performs well in capturing more heat from the hot exhaust, bottleneck is observed when boiling occurs. Steam temperature stops growing during vaporization, resulting in a flat portion of the cold composite curve and a large temperature difference with the flue gas as the hot composite curve has a much steeper slope. Supercritical working fluid is thus proposed to mitigate the limitation brought by vaporization.

Supercritical steam refers to steam with temperature and pressure above its critical point. Physically, its temperature and enthalpy change show different behavior compared to subcritical steam under vaporization. As a result of this property, it is believed to bypass the limitation in latent heat of vaporization.

III. METHODOLOGY

A. Aspen Plus Simulation

To obtain enthalpy information from reheating exchangers, simulation of CCPP power plant with TPRH using Aspen Plus is the preliminary step. Since the comparison focuses mainly on the difference between supercritical and subcritical fluid influence on power plant performance, optimization of

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subcritical steam system is needed to give subjective judgement. Therefore, specification of the simulation is derived from model with thermal efficiency over 60%. This study is based on Siemens H-Class CCPP which features maximum steam condition at 150 bar and 585 °C. Fig. 4 indicates Siemens combined cycle process diagram and is used as reference for Aspen simulation. Sensitivity tools embedded in Aspen Plus are used to manipulate uncertain parameters in the system to achieve system optimal performance. Simulation of supercritical steam can be done using similar method. The steam condition for supercritical system is 250 bar and 620 °C.

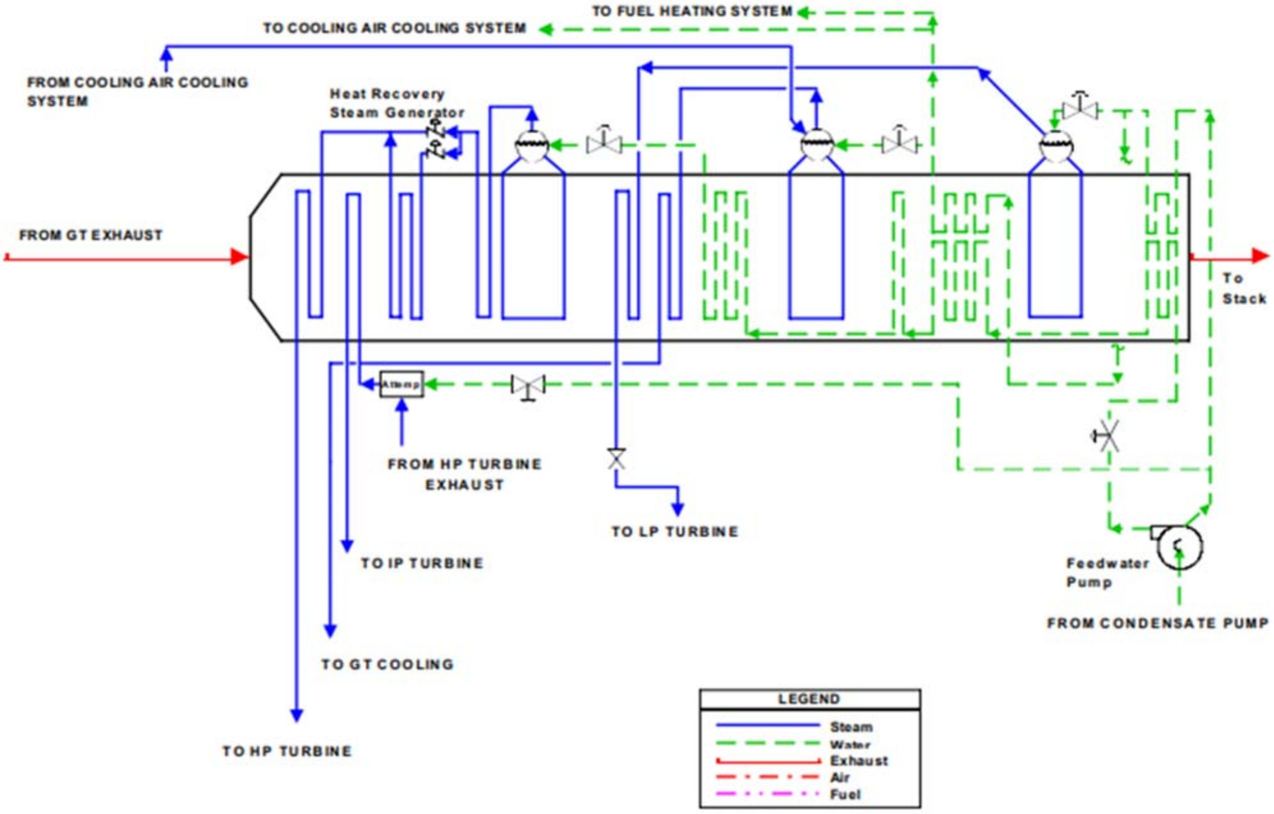

Fig. 1 STAG^{TM} TPRH Combined Cycle system [1]

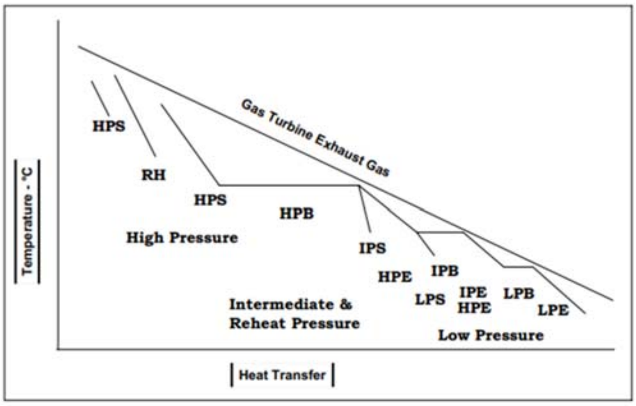

Fig. 2 STAG TPRH [1]

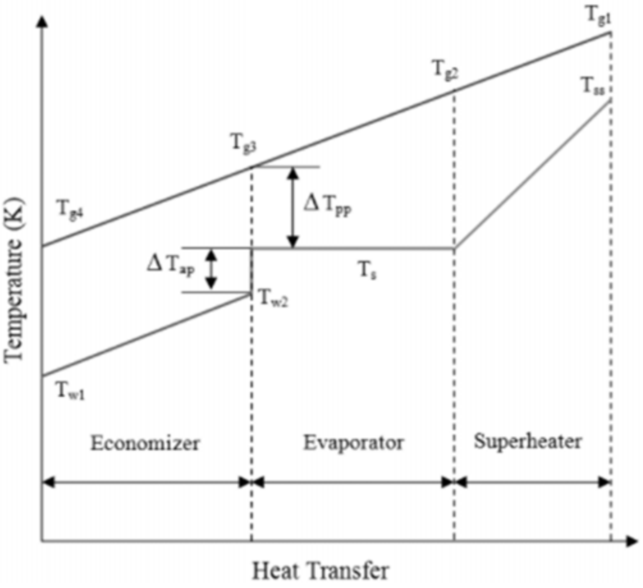

Fig. 3 One pressure combined cycle (right) [3]

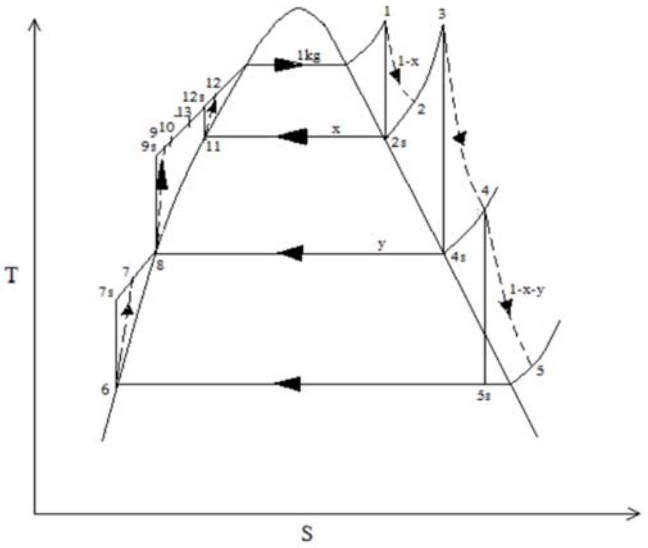

Fig. 4 (a) T-S diagram for TPRH [4]

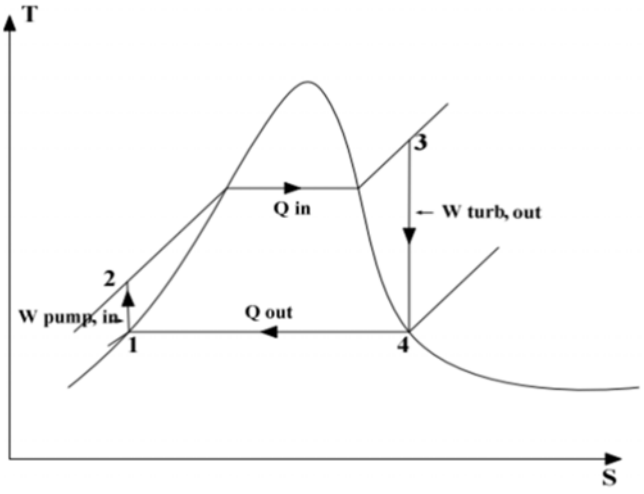

Fig. 5 (b) One pressure combined cycle [5]

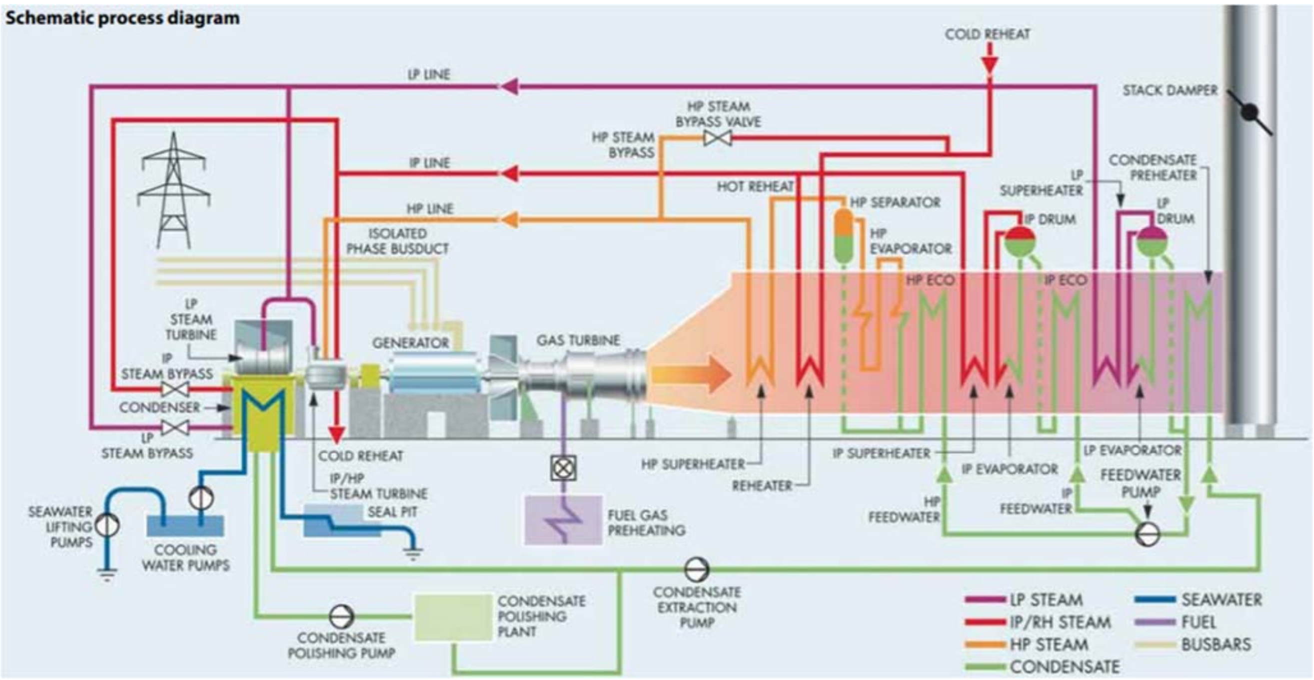

Fig. 6 Siemens combined cycle schematic process diagram [2]

B. Pinch Analysis

After simulation of both subcritical and supercritical power system, data from cold stream (boiler feed water) and hot stream (flue gas exhaust) are gathered and transferred to Sprint software to perform pinch analysis. It is a method to lower energy consumption through optimizing heat recovery systems, stream arrangement, process specification. In this study, Composite Curves (CC) from Sprint are used to investigate feasible energy from flue gas exhaust and amount of heat recovery of the system. The curves are plotted in T-H diagram. Heat recovery data can be obtained from Sprint for pinch analysis. A higher thermal recovery amount indicates that the system has effective heat transfer.

C. Exergy Analysis

Exergy analysis defines amount of useful work to be extracted from the system. It is a thermodynamic concept formulated based on Carnot Efficiency which the efficiency is proportional to absolute temperature of hot reservoir. Exergy is also called Free energy, available energy, or latent work. Exergy indicates room for improvement available in the system. A high exergy value refers to little room for improvement. Before performing the exergy analysis, temperatures of hot and cold reservoir are computed into Carnot Efficiency. The Carnot Efficiency is then plotted against enthalpy information of streams withdrawn from simulation. The area under the curve plotted is the exergy amount.

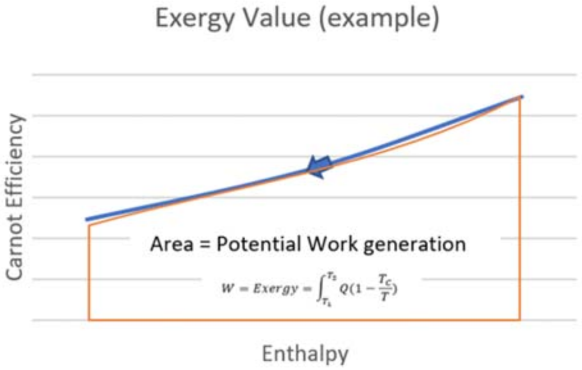

Fig. 7 Example of Exergy graph

IV. MATH

Thermal efficiency of CCPP is an important standard to evaluate effectiveness of energy conversion from chemical energy to electrical energy. Its equation is given by,

$$\eta_{TE} = \frac{Net\ Power\ Output}{Total\ Thermal\ Value\ of\ fuel} \quad (1)$$

From the above-mentioned analysis, exergy involves calculation of Carnot Efficiency, the equation of Carnot Efficiency is derived by,

$$\Delta W = \int PdV = (T_H - T_C)(S_B - S_A) \quad (2)$$

$$\Delta Q_H = T_H(S_B - S_A)$$
$$\Delta Q_C = T_H(S_B - S_A)$$
$$\eta_{CE} = \frac{\Delta W}{\Delta Q_H} = 1 - \frac{T_C}{T_H}$$

Exergy can be calculated from the area under the curve of Carnot Efficiency – Enthalpy diagram. The calculation is given by,

$$W = Exergy = \int_{T_1}^{T_2} Q(1 - \frac{T_C}{T}) \quad (3)$$

These equations are used to analyze CCPP performance.

V. RESULTS

A. Aspen Simulation

The TPRH process utilizing subcritical steam is based on Siemens' H class model. It consists of three pressure level steam turbines, two drums and one separator. Apart from the absence of HP separator, the remaining arrangements in supercritical system is same as that of the subcritical system. Fig. 7 shows detailed process arrangements of the TPRH systems.

For setting of the two systems, according to Siemens' white paper, the subcritical CCPP operates with advanced HP steam at 585 Deg C and 150 bars. The remaining setting are decided by Aspen Plus embedded sensitivity tools to obtain systems' highest thermal efficiency. Table II reveals the important setting in simulation.

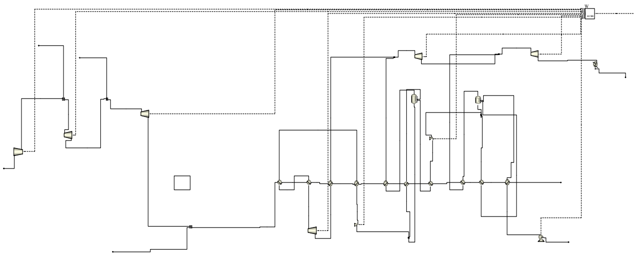

Fig. 7 Process Flow Diagram of TPRH CCPP

TABLE II
IMPORTANT SETTING IN SIMULATION

	Subcritical	Supercritical
Compression ratio (Gas Turbine)	20	20
Combustion Temperature (Gas Turbine)	1500 °C	1500°C
Max. Steam Pressure	160 bar	250 bar
HP Temperature	585 °C	620 °C
IP Temperature	448 °C	448 °C
LP Temperature	249 °C	249 °C
Ambient Temperature	25 °C	25 °C

Simulation result shows that the highest thermal efficiency of subcritical system obtained is 64.9% while the supercritical system attains 65.5% efficiency.

B. Pinch Analysis

Enthalpy data of hot exhaust and cold stream are obtained after Aspen simulation. The data are extracted into Sprint software to generate CC. Fig. 8 shows the CC.

Using same amount of fuel, both CCPP have same amount of enthalpy change and same temperature regarding hot exhaust. From Figs. 8 and 9, while the two systems show exact hot stream data, their cold streams are different. Temperature of subcritical steam stops growing at 340 °C, 150 bar when it is undergoing latent heat of vaporization. Lots of enthalpy is trapped during vaporization, leading to a flat cold CC. However, temperature of supercritical steam continues increasing, thus the gap between the hot and cold CC is smaller. Heat is recovered more effectively in supercritical CCPP. The process heat recovery calculated in Sprint is 1.35E + 09 kW for subcritical CCPP while it is 1.40E + 09 kW for supercritical CCPP. Therefore, supercritical CCPP recover more heat from hot exhaust.

C. Exergy Analysis

The enthalpy and temperature information obtained from simulation are further interpreted for exergy analysis. Results can be found in Figs. 10 and 11.

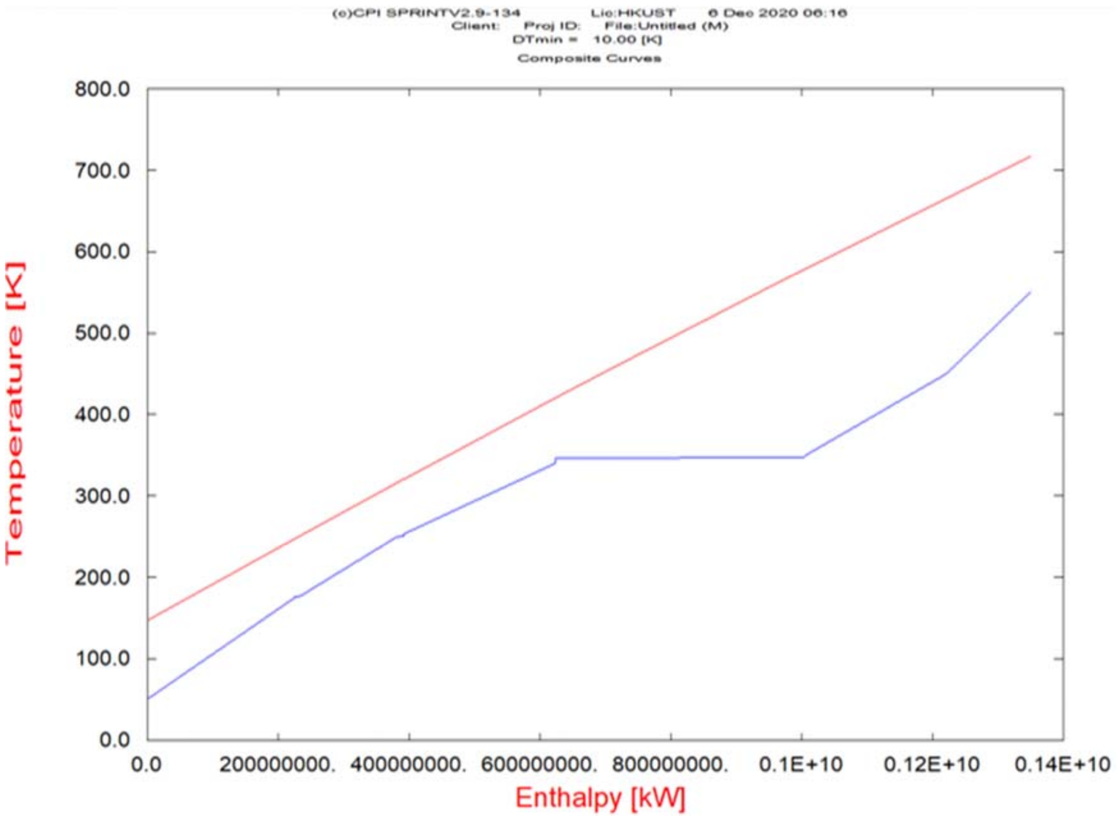

Fig. 8 CC of subcritical CCPP

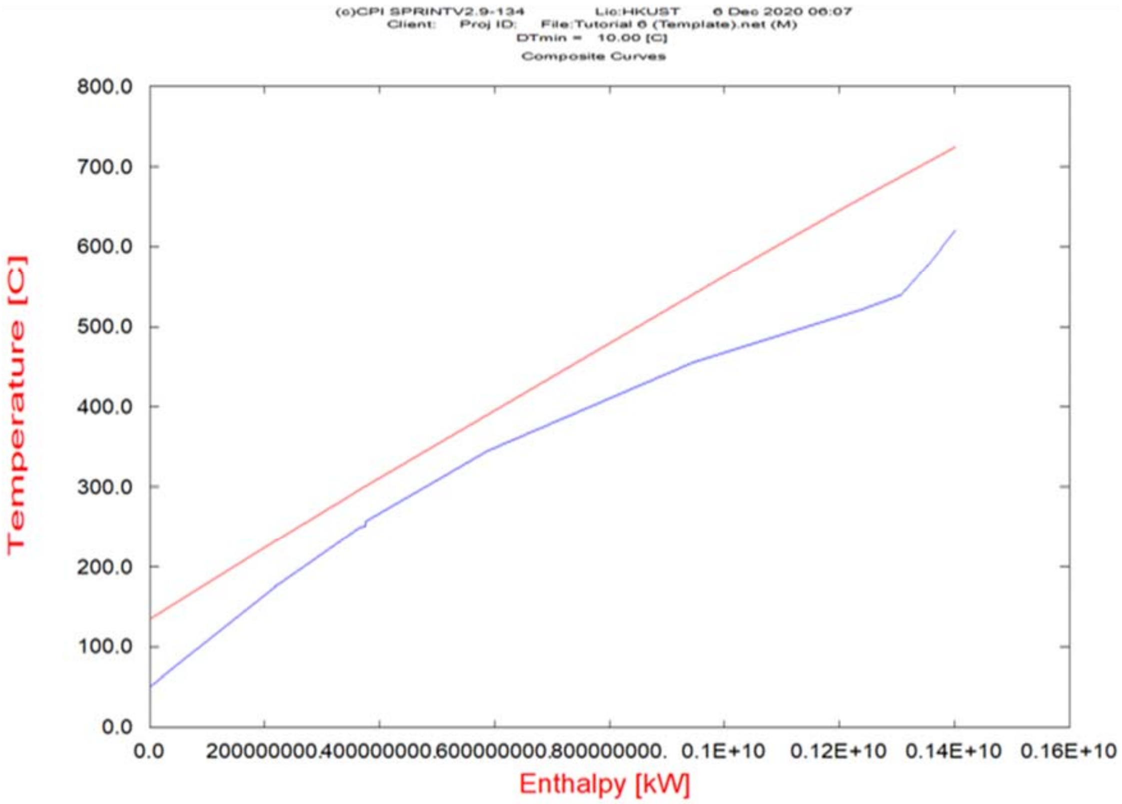

Fig. 9 CC of Supercritical CCPP

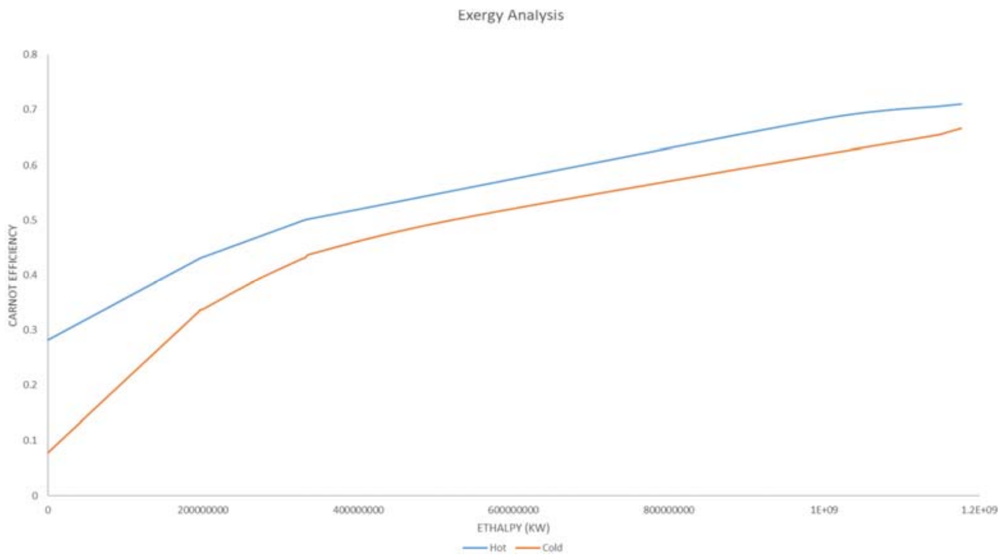

Fig. 10 Exergy Analysis for Supercritical CCPP

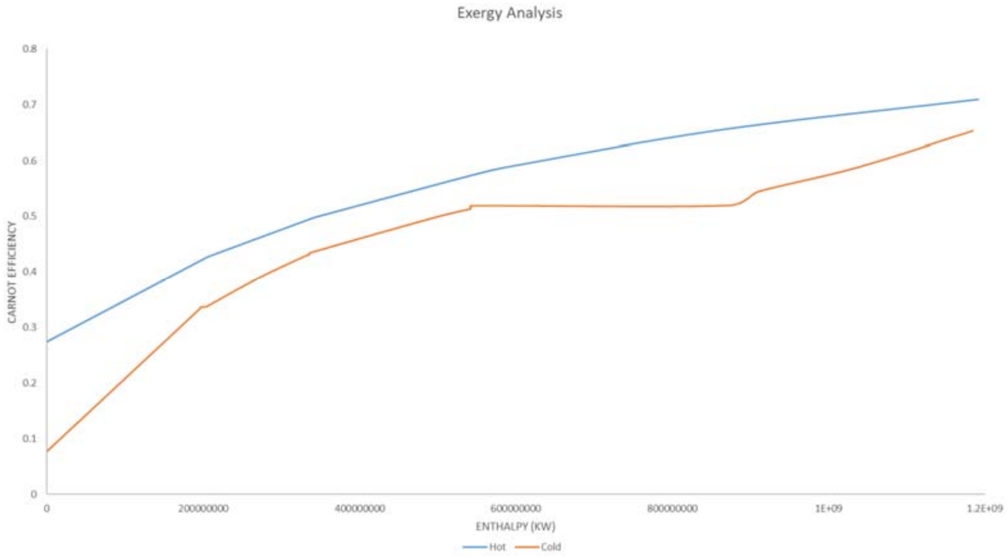

Fig. 11 Exergy Analysis for Subcritical CCPP

The exergy value of hot stream is 6.70E + 08 kW. For cold stream, the exergy value of supercritical system is calculated to be 5.38E + 08 kW while subcritical CCPP is 5.36E + 08 kW. The total amount of useful work extracted from supercritical system is 80.236% and 79.922% for subcritical system. As a result, supercritical cold stream extracted more work from hot exhaust than that of subcritical stream.

D. Other Findings

Other than comparison between subcritical and supercritical systems, some important findings are observed during simulation. For example, increasing combustion ratio of gas turbine reduces exhaust temperature, possibly limiting the power output in steam turbines side. Also, more steam is expanded in HP turbine instead of IP and LP turbines to generate more work and obtain higher efficiency.

VI. CONCLUSION & FUTURE WORK

In conclusion, the present TPRH technologies have pushed CCPP to over 60%. CCPP power plants are a popular choice to be developed nowadays in the light of its higher efficiency and lower environmental pollution. To further optimize CCPP thermal potential, supercritical fluid is introduced in this study to increase heat recovery of the CCPP power plants. In this study, exergy and pinch analysis are used to compare systems using supercritical and subcritical steam. Results prove that supercritical steam is more effective to capture heat and extract more energy from hot exhaust. Although the use of supercritical steam increases overall CCPP's thermal efficiency, equipment to support its operation should be available to support the application of supercritical steam. Research on supercritical steam turbines and other equipment should be conducted to take advantage of the opportunities offered by using supercritical systems.

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