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Sensitivity Analysis of the Heat Exchanger Design in Net Power Oxy-Combustion Cycle for Carbon Capture

Hirbod Varasteh, Hamidreza Gohari Darabkhani

Abstract—The global warming and its impact on climate change is one of main challenges for current century. Global warming is mainly due to the emission of greenhouse gases (GHG) and carbon dioxide (CO_2) is known to be the major contributor to the GHG emission profile. Whilst the energy sector is the primary source for CO_2 emission, Carbon Capture and Storage (CCS) are believed to be the solution for controlling this emission. Oxyfuel combustion (Oxy-combustion) is one of the major technologies for capturing CO_2 from power plants. For gas turbines, several Oxy-combustion power cycles (Oxyturbine cycles) have been investigated by means of thermodynamic analysis. NetPower cycle is one of the leading oxyturbine power cycles with almost full carbon capture capability from a natural gas fired power plant. In this manuscript, sensitivity analysis of the heat exchanger design in NetPower cycle is completed by means of process modelling. The heat capacity variation and supercritical CO_2 with gaseous admixtures are considered for multi-zone analysis with Aspen Plus software. It is found that the heat exchanger design has a major role to increase the efficiency of NetPower cycle. The pinch-point analysis is done to extract the composite and grand composite curve for the heat exchanger. In this paper, relationship between the cycle efficiency and the minimum approach temperature (ΔTmin) of the heat exchanger has also been evaluated. Increase in ΔTmin causes a decrease in the temperature of the recycle flue gases (RFG) and an overall decrease in the required power for the recycled gas compressor. The main challenge in the design of heat exchangers in power plants is a tradeoff between the capital and operational costs. To achieve lower ΔTmin, larger size of heat exchanger is required. This means a higher capital cost but leading to a better heat recovery and lower operational cost. To achieve this, ΔTmin is selected from the minimum point in the diagrams of capital and operational costs. This study provides an insight into the NetPower Oxy-combustion cycle's performance analysis and operational condition based on its heat exchanger design.

***Keywords*—**Carbon capture and storage, oxy-combustion, netpower cycle, oxyturbine power cycles, heat exchanger design, supercritical carbon dioxide, pinch point analysis.

I. Introduction

THE GHG are main reason of warming the atmosphere temperature and climate change. The Paris agreement is a path to achieve significant reduction in GHG emission. Two-thirds of total GHG emissions are from energy sector with 80% of CO_2 emitted [1]. Therefore, reduction of CO_2 in energy sector is main part to mitigate climate change.

There are three main carbon capture technologies in power plant: pre-combustion, post-combustion and oxy-combustion. The oxy-combustion is a capable technology in CCS with relatively more advantages compare to other techniques. Oxy-combustion of the solid fuels (e.g., coal and biomass) has received a high level of improvement and it is ready to be implemented in newly developed or retrofitted solid fuel power plants. However, the oxy-combustion capture for gas-fired power plants is under development. Although several oxyturbine cycles are proposed and studied by thermodynamic analysis, only two cycles of CES and Allam (NetPower) are currently in demonstration phase, both funded by DOE in the US.

The Allam cycle is one of novel oxy-combustion technologies and it is developed recently with 8 Rivers Capital. The 8 Rivers, Exelon Generation, and CB&I are owners of NetPower. NetPower develops natural gas Allam cycle and it is currently building a 50 MWth natural gas demonstration power plant in La Porte, Texas [2]. This article presents the latest results of our investigation on the effects of heat exchanger design on NetPower oxyturbine cycle with full carbon capture.

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II. Analyzing of NetPower Cycle

A. NetPower Cycle

NetPower cycle is introduced with Rodney Allam. The cycle is an oxy-combustion cycle with working fluid of CO_2. The flow diagram of Allam cycle is presented in Fig. 1. NetPower cycle working flow is mainly CO_2 in a high-pressure and turbine inlet pressure (TIP) is approximately 300 bar and low-pressure-ratio of 10. It is recuperated Brayton cycle [2].

NetPower cycle combustor burns natural gas with pure oxygen supplied from an Air Separation Unit (ASU) and high-pressure CO_2 stream inlets recycled from its power turbine. Recycle Fuel Gas (RFG) is heated with a recovery heat exchanger and flows to the combustor to reduce the Combustion Outlet Temperature (COT) with diluting the combustion products. The RFG flowrate controls temperature of combustion in an acceptable level. The direct-fired supercritical carbon dioxide (SCO_2) turbine is cooled with cooling stream from heat exchanger[3].

The exhaust gas with 740 °C enters recuperating heat exchanger that transfers heat from hot outlet turbine exhaust gas to the three cycle streams. This includes the CO_2 rich stream recycled to the combustor (to moderate temperature of combustor), the oxidant stream recycled to the combustor and CO_2 rich stream for cooling turbine blades. Also, the hot compressed air stream from ASU enters recuperating heat exchanger for recovering its heat.

Heat exchanger is one of the main parts of NetPower cycle and it has a main role in NetPower cycle efficiency. The exhaust gas from heat exchanger is cooled down and the CO_2 is separated from water. The water is sent to the wastewater treatment for recovery and treatment. A portion of CO_2 stream form water separation unit is sent for purification and compression unite. Most of CO_2 is compressed and recycled back. Recycle gas compression loop includes 4 stages intercooled compressor and 2 intercooled pumping stages. Inter cooling is with cooling water. CO_2 stream is divided to 3 parts; 45-50% of flow rate is pumped to 305 bars and preheated in the recuperating heat exchanger. 10-12% of the flow rate after heated in the heat exchanger up to maximum 400 °C then it is sent to turbine for cooling blade.

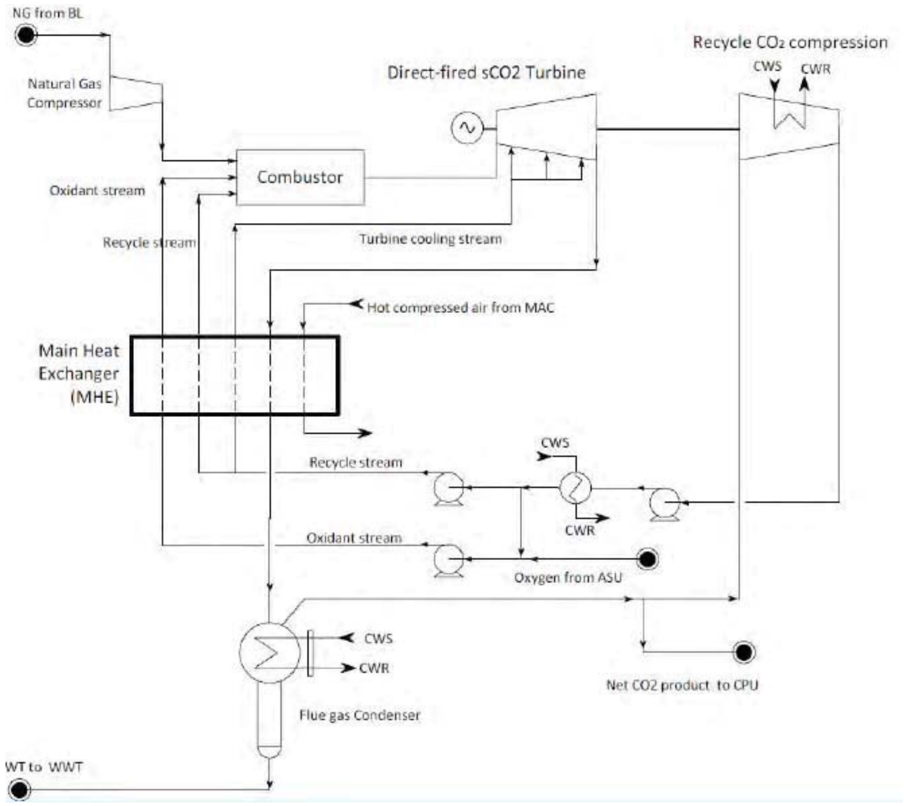

Fig. 1 Schematic model of NetPower cycle

32-45% of CO_2 stream is mixed with high purity oxygen the oxidant stream is heated in heat exchanger up to 720 °C and it is send to combustion to burn fuel [4], the schematic model of NetPower is in Fig. 1. NetPower Plant includes three main parts:

1- NetPower cycle
2- Recycle compression loop
3- CO_2 purification and compression

In this article NetPower cycle and recycle compression loop are modeled using Aspen Plus. The ASU, CO_2 purification compression unit, utility and offside unites are extracted from IEA report 2015 and these are considered constant in this model [4].

B. NetPower Simulation with Aspen Plus

The NetPower cycle is modeled with Aspen Plus software, process flow diagram (PFD) of the model is shown in Fig. 2.

Recovery Heat Exchanger: Heat exchanger on NetPower cycle can be compact multi-channel plate-fin design or printed circuit in Nickel-alloy (e.g. Alloy 617), [4].

Heatric Company supplies four printed circuit heat exchangers (PCHEs) for NetPower to commission the 50 MW demonstration plant in Texas [5]. PCHEs is a multi-stream heat exchanger type. The multi-stream heat exchanger (MSHE) is replaced with Heat Exchanger Network (HEN) on NetPower Cycle, therefore the total annual cost (TAC) is decreased. Multi-stream exchanger (MSHE) enables a simultaneous heat exchange between two streams in a single unit [6]. Multi-stream heat exchanger is a special case of a Heat Exchanger Network without external utilities. Therefore, classical pinch analysis can be performed on Multi-stream heat exchanger [7].

Heatric PCHEs are manufactured by diffusion bonding; these are fabricated with no joints, welds or points of failure, resulting in unit combining exceptional strength and integrity with high efficiency. PCHEs are smaller and lighter than conventional heat exchanger, their specifications are high pressure capabilities, high range temperature, low size , higher structural integrity [8].

The heat exchanger cost effects strongly on the final plant cost. Smaller minimum temperature approach ΔTmin for heat exchanger increases efficiency but also increases the capital cost (CAPEX). Therefore, it is required to optimise between capital cost, operational cost (OPEX) and efficiency. CAPEX vs OPEX studies are required to find optimum operating point of the system. The cost of heat exchange affects significantly by ΔTmin and pressure drop.

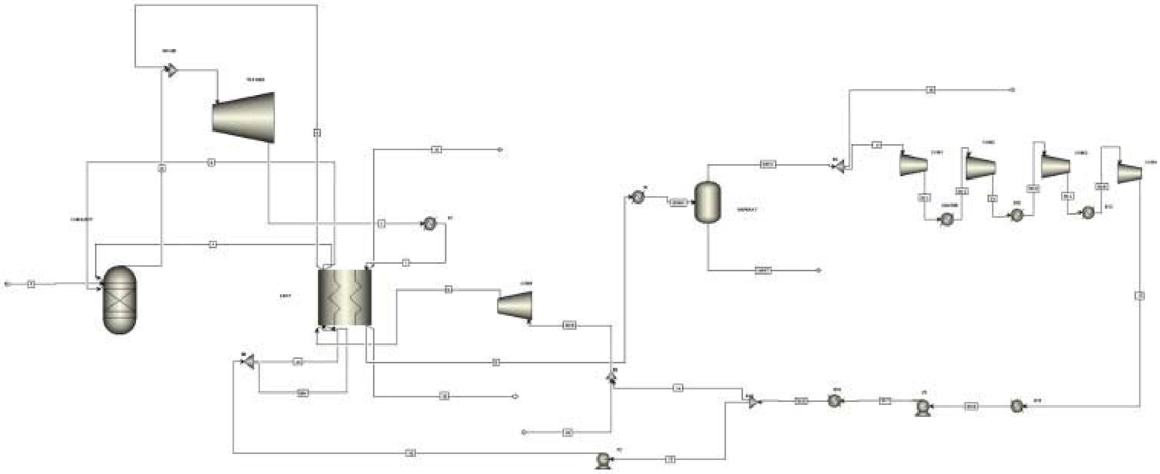

Fig. 2 Aspen Plus model of NetPower cycle

Stream enter recovery heat exchanger: The cold streams include two high-rich recycled CO_2 streams and one oxidant stream. The high-rich recycled CO_2 stream includes one RFG (recycle flow gas), which is heated and enter to combustion, another stream is cooling turbine stream, which is heated and enter turbine for cooling blade. Oxidant stream is heated and enter combustion for burning fuel.

The hot streams include exhaust stream from turbine and hot gas from ASU. The huge difference between heat capacity of CO_2 in hot and cold streams causes significant imbalance. In order to avoid imbalance in heat transfer, first, the cold streams are heated up with heat from operation of CO_2 recycle compressor outside the multi-stream heat exchanger and hot air from ASU compressors inside multi-stream heat exchanger. Then, they are heated with exhaust gas from turbine [2].

Recovery Heat Exchanger modeling in aspen plus: The recovery heat exchanger is modeled with multi stream heat exchanger MHeatX block in Aspen plus, this calculates heat duty between multi hot and cold streams. Furthermore, this block calculates the overall UA (overall heat transfer coefficient) for the exchanger, ΔTmin ΔTmin, Number of Transfer Units (NTU), analyses a detailed zone analysis and composite curve (AspenTech).

The multi-stream heat exchanger is type of the heat exchanger network, the minimum vertical distance between the hot and cold composite curve is ΔTmin (minimum temperature difference or minimum approach temperature) [7].

The design parameters of multi-stream heat exchanger for NetPower cycle are dependent to the following items:

- Flow rate composition
- Heat capacities
- Temperatures of stream

To calculate design parameters of multi-steam heat exchanger for power plant it requires all material of energy balance, design of combustion and turbine to be done. The energy integration can be considered the last step of the design for power plant.

After calculation of design parameters such as UA (overall heat transfer coefficient) and ΔTmin. In order to design efficient multi-seam heat exchanger with minimum size and cost the following parameters should be considered:

- o Temperature difference
- o Conducting material
- o Fluid turbulence (more turbulent more heat exchange)
- o Fluid velocity
- o Surface area
- o Direction of Flow

The main issue in heat exchanger design for power plant cycle is pinch point. During partial load or unsteady state circumstances, sometime pinch point or temperature crossover might happen in the multi-stream heat exchanger. In these conditions, the heat exchanger will not perform effectively.

1.CO_2 Direct-Fired Turbine

Turbine is one of the important parts of a power plant cycle. The turbine cooling causes difficulties in calculations to find efficiency of CO_2 Direct-fired turbine. In our simulation, the efficiency of turbine for NetPower cycle are considered constant.

First SCO_2 turbine is supplied with Toshiba for the plant build in Texas, USA [9]. NetPower cycle turbine is intercooling turbine and it requires following developments:

1- NetPower turbine has higher inlet pressure than conventional turbine so the shell requires adoption.
2- Blades and shell require cooling because high turbine inlet temperature (TIT) of NetPower cycle.
3- Working flow in NetPower cycle is CO_2 so it is necessary

that the conventional facilities are redesigned for CO_2 working flow.

The blades in NetPower turbine are cooling with open circuit blade cooling method and they are protected with cooling film and cooled by convection.

Higher Inlet turbine temperature (TIT) causes higher efficiency in NetPower cycle. Metal working temperature of turbine blades is a barrier to increase turbine temperature. The efficiency of power turbine will increase by increasing its metal working temperature. Furthermore, heat transfer coefficient of the cooling flow which is almost pure CO_2 is very high compared to conventional cooling flow.

The exergy of a system is the maximum energy that is available to be used. Increasing gas turbine inlet temperature decreases in combustion chamber exergy destruction [10]. This is due to the fact that this increase leads in decreasing the entropy destruction. On the other side TIT in power turbines is required to be a higher value to avoid exergy destruction [11]. Increasing TIT increases significantly both efficiency and specific work output [11].

In NetPower cycle TIT (turbine Inlet Temperature) or COT is controlled with RGF (recycle gas flow), while multi-flow heat exchanger recovers heat from turbine exhaust gases [12].

2.Turbine with Cooling Blades Modeling in Aspen Plus

Modeling turbine with cooling blade system is challenging in Aspen Plus but other components such as compressor, pump, combustion and separator are available in the software blocks. This means simulation of the turbine block with cooling blades is not a straight forward modelling in this software. There are deferent methods to simulate turbine with cooling blade system. One of the methods to simulate turbine with cooling blades is assuming that working fluid is an ideal mixture of ideals gas species. This method has been used in some commercial simulation codes (e.g. GT Pro) and private simulation codes (e.g. GE simulation code by Politecnico di Milano) [13]. Another method which is modeled with EL-Maris is cooled expansion model [14]. This model is improved with Roberto Scaccabarozzi for simulation of turbine with cooling blade in Aspen Plus; the turbine is splitted to infinite expansion steps and used a correlation to improve accuracy of model [12]. This method is required to calculate correction factors to correct results and limited to specific range of temperature.

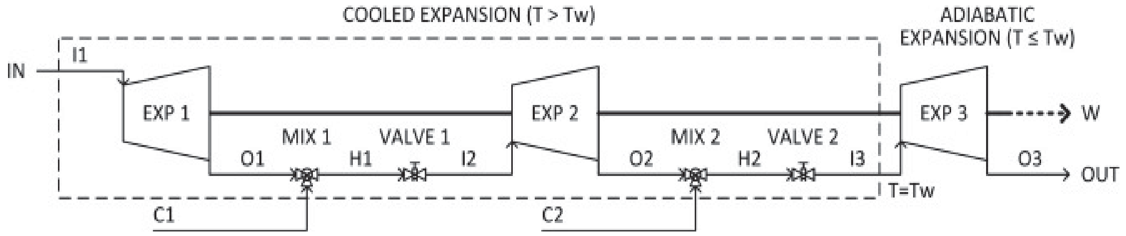

Fig. 3 Model of the improved continuous expansion model with N (number of cooled expansion steps) by Scaccabarozzi, Gatti [12].

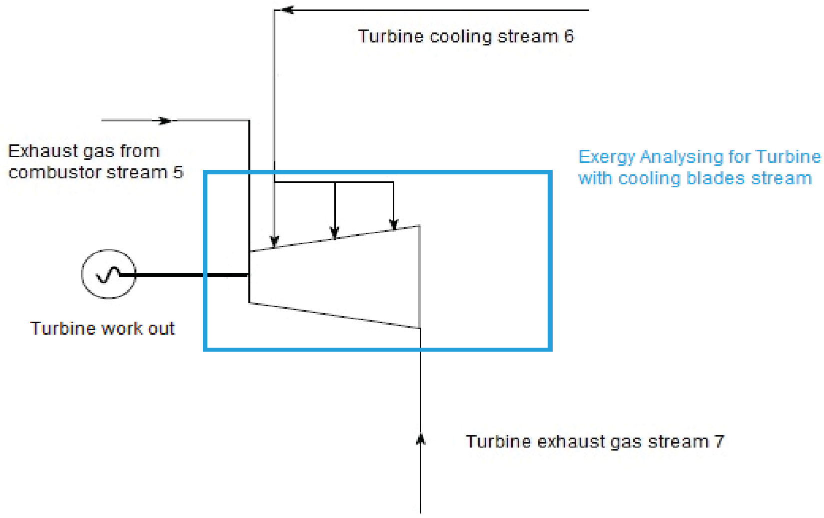

Fig. 4 NetPower Turbine with cooling blade

In this article, a new method is offered to simulate turbine with cooling blade. In order to simulate and calculate turbine parameters, the energy balance and exergy is also evaluated using this method.

3.Turbine with Cooling Blade Modeling in Aspen Plus by Exergy Analysis

The general exergy formula is following:

$$\dot{E}_{x,heat} + \sum_i m\dot{e}_{x,\iota} = \sum_e m\dot{e}_{x,e} + \dot{E}_{x,w} + \dot{I}_{dest} \tag{1}$$

The following formula can be extracted for NetPower turbine with cooling blades in Fig. 4.

$$\sum_i \dot{m}\, e_{x,i} = \sum_e \dot{m}\, e_{x,e} + \dot{E}_{x,w} + \dot{I}_{dest} \quad (2)$$

$$\sum_i m\dot{e}_{x,\imath} = \dot{E}_{x,5} + \dot{E}_{x,6} \quad (3)$$

$$\sum_e \dot{m}\, e_{x,e} = \dot{E}_{x,7} \quad (4)$$

$$\dot{E}_{x,w} = W_{gt} \quad (5)$$

$$\dot{I}_{dest} = \dot{I}_{dest\ Turbine\ with\ cooling} \quad (6)$$

$$\dot{E}_{x,5} + \dot{E}_{x,6} = \dot{E}_{x,7} + W_{gt} + \dot{I}_{dest\ Turbine\ with\ cooling} \quad (7)$$

The diagram presented in Fig. 5 is used to model NetPower Turbine with cooling blades in Aspen Plus:

If we consider flow gases are mixed before interring aspen plus turbine block, then the following formula can be extracted:

$$\dot{E}_{x,heat} + \sum_i m\dot{e}_{x,\imath} = \sum_e m\dot{e}_{x,e} + \dot{E}_{x,w} + \dot{I}_{dest} \quad (8)$$

$$\sum_i m\dot{e}_{x,\imath} = \dot{E}_{x,5} + \dot{E}_{x,6} \quad (9)$$

$$\sum_e \dot{m}\, e_{x,e} = \dot{E}_{x,7} \quad (10)$$

$$\dot{E}_{x,w} = W_{gt} \quad (11)$$

$$\dot{I}_{dest\ aspen\ model} = \dot{I}_{dest\ Turbine\ aspen} + \dot{I}_{mixer} \quad (12)$$

$$\dot{E}_{x,5} + \dot{E}_{x,6} = \dot{E}_{x,7} + W_{gt} + \dot{I}_{dest\ \ aspen\ model} \quad (13)$$

If we subtract (7) and (12) then the following equation is extracted:

$$0 = \dot{I}_{aspen\ model} - \dot{I}_{dest\ Turbine\ with\ cooling} \quad (14)$$

$$\dot{I}_{dest\ Turbine\ aspen} + \dot{I}_{mixer} = \dot{I}_{dest\ Turbine\ with\ cooling} \quad (15)$$

$$\dot{I}_{dest\ Turbine\ aspen} = \dot{I}_{dest\ Turbine\ with\ cooling} - \dot{I}_{mixer} \quad (16)$$

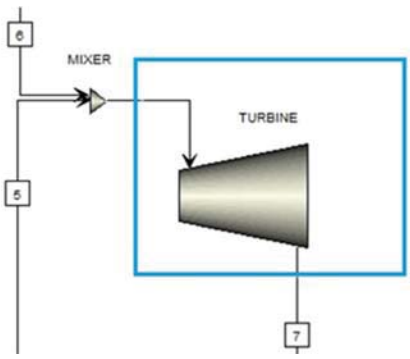

Fig. 5 Turbine block model in Aspen plus

Equations (14)-(16) show that in order to model turbine with cooling system in aspen plus, the recycled cooling stream and exhaust gas of combustion can be mixed, and an exergy destructs in mixer before interring turbine block.

Equations (14)-(16) show that destruction in aspen model turbine is less than turbine with cooling system, therefore the entropy generation in aspen model is less than turbine with cooling blades and it is extracted from (16) and in the aspen model isentropic efficiency should be more than turbine cooling blades.

$$\dot{I}_{dest\ Turbine\ aspen} = T_0 S_{gen} \quad (17)$$

In this article the isentropic efficiency is considered constant for simulation. The entropy map of turbine with cooling blades is required for accurate calculation.

The exergy analysis for turbine with cooling blades will be developed for accurate modeling of NetPower cycle in feature.

4.Recycle Gas Compression Loop

The exhaust gas exits from heat exchanger after heat recovery and loss its temperature. The flow gas inter is separation unit with water cooling to separate water from CO_2. Water is sent to water treatment unit and it can be recycled to reuse in power cycle.

The CO_2 is separated in two parts, one part as cycle by-product for cycle stability exit to sequestration unit. The other part is recycled trough four stage intercooled compressor and two intercooled pumping stages and all intercooling are with cooling water and cooling tower. The cooling water temperature is dependent to environmental condition and it is cooled on natural draft cooling tower. Table I shows the condition of cooling water for NetPower cycle:

TABLE I
CONDITION OF COOLING WATER FOR NETPOWER CYCLE

Cooling water approach temperature	7°C
Supply temperature	Normal 15°C Maximum 36°C

The recycle stream is divided into three streams:

1- 10-12% of CO_2 recycled flow is sent to turbine for cooling turbine blades. It is pumped in the final pumping stage and preheated in heat exchanger before inter turbine to increase turbine efficiency.
2- 45-50% of CO_2 flow is recycled and sent to combustion to absorb heat from combustion and control the flame temperature.
3- 38-45% of CO_2 recycle flow is mixed with high purity oxygen and produce oxidant stream and it is compressed and preheated before enter combustion for burning fuel.

The percentage of oxidant and fuel gas should be in stoichiometric to achieve the best efficiency of plant.

III. NetPower Cycle Simulate Result Validated with IEA Report

In order to evaluate our Aspen Plus model, the results have been compared to the results of NetPower cycles presented in 2015 IEA report. Table II shows the results from our model in comparison with the data published in the IEA 2015 report. As the table shows the result is match to the IEA report and it generally validates our simulation approach and model.

There is 7.3% error in temperature of stream 8 which is cold exhaust flow form heat exchanger, this model temperature is 59.04° and IEA report is 55°. There is also a 4.4% error in temperature and 2.94% error in pressure of stream 12 which is total recycle stream from compressor, this model temperature and pressure is 41.41°C and 82.35 bar and IEA report is 43°C and 80 bars. These small variations are mainly because of the differences between the efficiencies of pumps and compressors in our simulation with IEA report as we don't have access to real pumps and compressors data for NetPower cycle.

TABLE II
RESULTS OF OUR NETPOWER MODEL IN ASPEN PLUS COMPARED WITH THE DATA PUBLISHED IN THE IEA 2015 REPORT

Pressure bar (IEA)	Pressure bar	Temp C (IEA)	Temp C	Total Flow Mmol/hr (IEA)	Total Flow Mmol/hr	Composition (% mole)										Stream
						O2 (IEA)	O2	N2 (IEA)	N2	H2O (IEA)	H2O	CO2 (IEA)	CO2	AR (IEA)	AR	
303.00	303.04	720.00	720.00	52.30	52.30	13.34	13.37	1.05	1.05	0.13	0.13	84.94	84.92	0.53	0.53	3
303.00	303.08	720.00	720.00	52.30	52.30	0.21	0.24	1.18	1.18	0.15	0.15	97.88	97.86	0.57	0.57	4
300.00	300.00	1150.00	1150.82	108.05	108.00	0.20	0.23	1.11	1.11	6.36	6.35	91.80	91.78	0.53	0.53	5
303.00	303.08	<400	398.00	11.93	11.93	0.21	0.24	1.18	1.18	0.15	0.15	97.88	97.86	0.57	0.57	6
34.00	33.99	740.00	739.98	119.99	120.00	0.20	0.23	1.12	1.12	5.74	5.73	92.41	92.39	0.54	0.54	7
33.00	33.99	55.00	59.04	119.99	120.00	0.20	0.23	1.12	1.12	5.74	5.73	92.41	92.39	0.54	0.54	8
305.00	305.04	45.00	45.65	52.30	52.30	13.34	13.37	1.05	1.05	0.13	0.13	84.94	84.92	0.53	0.53	9
305.00	305.08	50.00	50.92	64.23	64.23	0.21	0.24	1.18	1.18	0.15	0.15	97.88	97.86	0.57	0.57	10
33.00	33.99	29.00	29.00	109.62	110.00	0.21	0.24	1.18	1.18	0.15	0.15	97.88	97.86	0.57	0.57	11
80.00	82.35	43.00	41.41	109.62	110.00	0.21	0.24	1.18	1.18	0.15	0.15	97.88	97.86	0.57	0.57	12
100-120	123.51	26.00	26.00	64.23	64.23	0.21	0.24	1.18	1.18	0.15	0.15	97.88	97.86	0.57	0.57	13
100-120	123.51	26.00	26.00	45.39	45.39	0.21	0.24	1.18	1.18	0.15	0.15	97.88	97.86	0.57	0.57	14
100-120	120.00	15.00	15.00	6.92	6.92	99.50	99.50	0.20	0.20	0.00	0.00	0.00	0.00	0.30	0.30	16
7.50	7.50	275.00	275.00	34.46	34.46	20.75	20.75	77.32	77.32	0.97	0.97	0.04	0.04	0.92	0.92	17
7.30	7.50	55.00	59.04	34.46	34.46	20.75	20.75	77.32	77.32	0.97	0.97	0.04	0.04	0.92	0.92	18
33.00	33.99	29.00	29.00	3.65	3.65	0.21	0.24	1.18	1.18	0.15	0.15	97.88	97.86	0.57	0.57	19

IV. EVALUATION OF ΔTMIN FROM COMPOSITE CURVE AND GRAND COMPOST CURVE OF MULTI STREAM HEAT EXCHANGER

The composite curve of multi-steam heat exchanger is extracted for Aspen Plus MHeatX block. Fig. 6 shows the composite curve. The minimum vertical distance between hot curve and cold curve is ΔTmin. ΔTmin in this simulation is 5.3°C and this is consistent with the ΔTmin 5°C in IEA report [4].

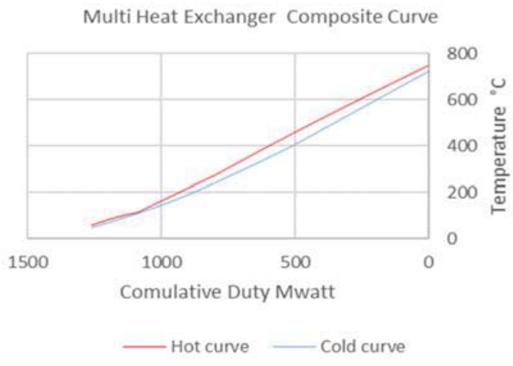

Fig. 6 Composite curve

Zone analysis for MheatX aspen plus block shows that the pinch temperature is at the 112.13° C. The heat duty between hot and cold curve in the pinch temperature is zero, therefore the grand composite curve in the pinch temperature is zero. Fig. 7 is grand composite curve of multi-stream heat exchanger.

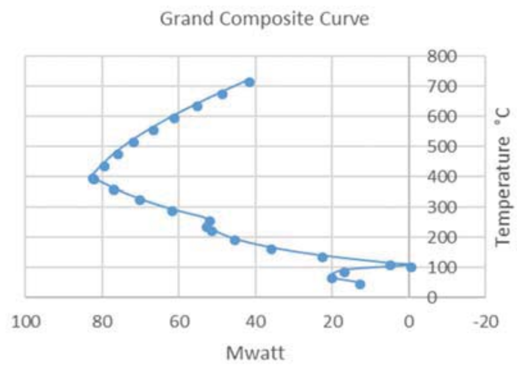

Fig. 7 Grand composite curve

V. HEAT EXCHANGER DESIGN SENSITIVITY ANALYSIS FOR NETPOWER CYCLE

In order to analyze the sensitivity of net power cycle related to designing parameters of heat exchanger the following assumption is considered:

1- Changing heat exchanger parameters with constant recycled flow rate and difference COT.
2- Changing heat exchanger parameters with constant COT and deference recycled flow rate.

In order to simplified simulations, the isentropic efficiency of cycle is considered constant for all simulations. It is necessary to add turbine with cooling blade efficiency map, compressor and pump efficiency maps for accurate simulation.

A. Sensitivity Analysis with Constant Recycled Flow Rate

The ΔTmin for heat exchanger is changed from 0°C to 20°C and diagram for power cycle efficiency related to ΔTmin is extracted in Fig. 8.

The recycled flow rate is constant so that the COT is increased with decreasing ΔTmin of heat exchanger. Fig. 9 shows COT related to ΔTmin for constant flow rate.

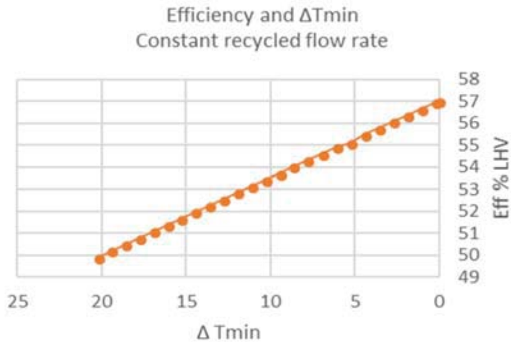

Fig. 8 Efficiency related to ΔTmin for constant recycled flow rate

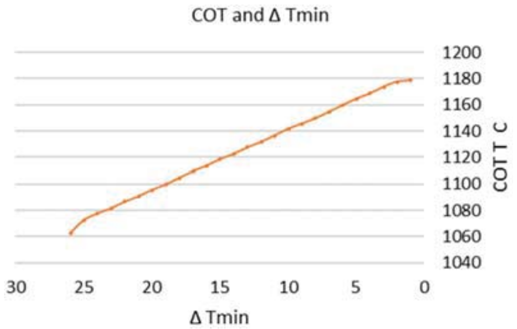

Fig. 9 Efficiency related to ΔTmin for constant recycled flow rate

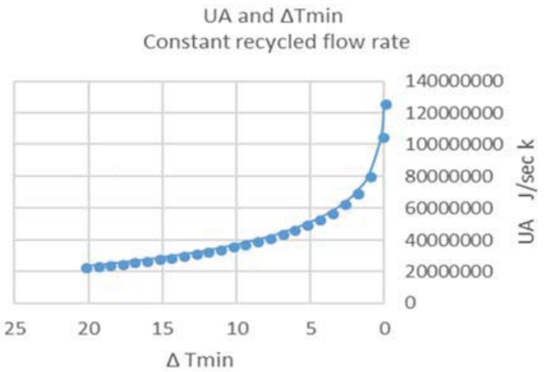

Fig. 10 Overall heat transfer coefficient UA to ΔTmin for constant recycled flow rate

Fig. 10 shows the overall heat transfer coefficient (UA) related to ΔTmin for constant flowrate. In order to decrease the ΔTmin a heat exchanger with higher overall coefficient UA needs to be designed resulting in higher capital cost (CAPEX). The diagram shows that decreasing ΔTmin to near zero increases the UA exponentially therefore capital cost will highly increase.

The required power for compressor recycle loop is constant because the recycle flow rate is constant as shown in Fig. 11.

Fig. 12 shows turbine power output is increased related to lower ΔTmin for constant flowrate. This analysis shows that lower ΔTmin without decreasing COT with more recycled flow rate, the temperature of flow gas in turbine is increased so the turbine power increased. Furthermore, the required recycle compressor loop power is constant so the cycle efficiency is increased. The material property in turbine blades is critical point of temperature design in a gas turbine. Increasing maximum allowed turbine metal temperature from 860° to 950° cause allowing the COT increases from 1150 to 1120 [4].

B. Sensitivity Analysis with Constant COT

In the constant COT simulations, the recycled flow rate will need to change related to ΔTmin of heat exchanger. For lower ΔTmin, the recycled flow rate has to increase to compensate increasing temperature of recycled flow and prevent increasing of COT. Fig. 13 shows recycle flow rate verses ΔTmin.

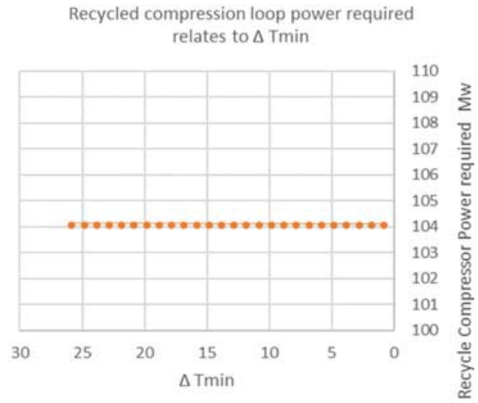

Fig. 11 The required power for recycled compression loop relates to ΔTmin in a constant recycled flow rate (the power demand is approximately constant)

The power of compression loop is dependent to the working flow rate so that it is required more power to compress working flow by increasing working flow. Fig. 14 shows recycled compression loop required power related to ΔTmin. These recycle data are in agreement with IEA report regarding ΔTmin [4]. The higher ΔTmin causes the lower recycle final temperature and flow rate and power generation for turbine. On the other hand, the recycle gas compressor power is decreased [4] but the overall power cycle efficiency is decrease. The following diagram approves above discussion with IEA report.

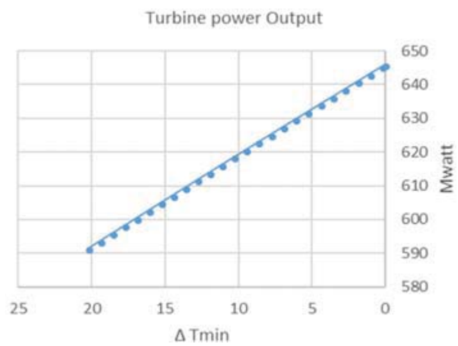

Fig. 12 Turbine power output related to ΔTmin for constant recycled flow rate

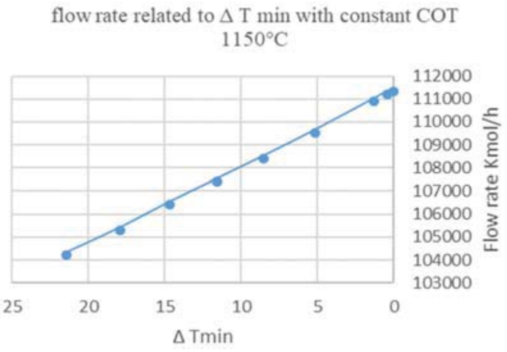

Fig. 13 Flow rate related to ΔTmin for constant COT 1150°C

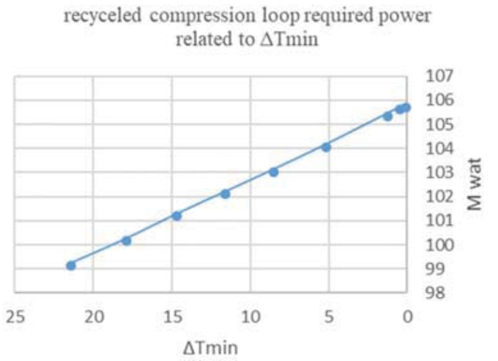

Fig. 14 Recycled compression loop required power against ΔTmin for constant COT 1150°C

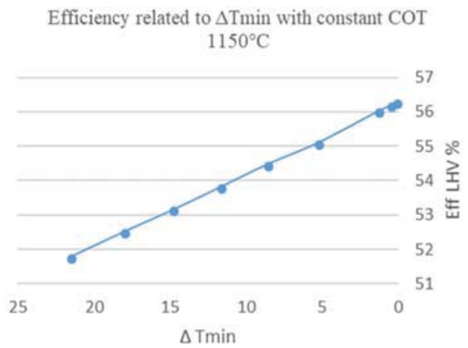

Fig. 15 Efficiency related to ΔTmin with constant COT 1150°C for constant COT 1150°C

C. Compare Sensitivity Analysis of Efficiency with COT and Recycled Flow Rate Constant

Fig. 16 shows efficiency variation related to ΔTmin with both COT and recycled flow rate constant. The cross point of two curves is happened when the two simulation COT is same 1150°C.

The COT is more than 1150°C in the lower ΔTmin for constant recycled flow rate so the efficiency is higher than other simulations with constant COT. Fig. 16 approves the higher COT causes higher efficiency.

VI. Design and Cost Analysis of NetPower Plant

The results show that to achieve higher cycle efficiency, lower ΔTmin is needed also a higher overall heat coefficient (UA).

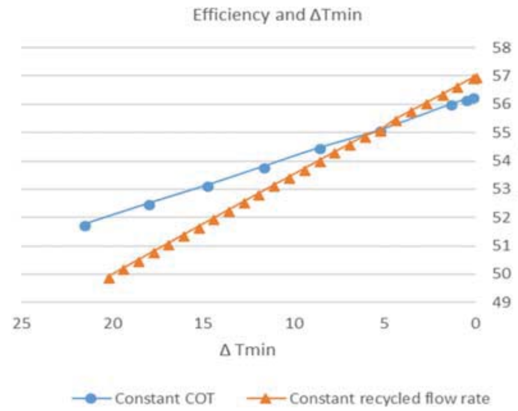

Fig. 16 Efficiency related to ΔTmin with both constant COT 1150°C and constant recycle flow rate

The following parameters are suggested for decreasing ΔTmin and increasing overall heat coefficient (UA) for multi-stream heat exchanger in NetPower cycle:

1- Increasing size of recovery heat exchanger and heat transfer area
2- Using higher conductive material to increase the overall heat coefficient
3- High efficient design of heat exchanger and consider more effective direction of flow e.g. concurrent flow
4- Using new manufacturing technologies such as printed circuit heat exchanger PCHE (as used in NetPower cycle)
5- Avoiding crossover and pinch point in multi stream heat exchanger in evaporation and condensation condition.
6- Analyzing composite curve and grand composite curve

Implementation of the above items (to achieve lower ΔTmin) increases the cost of the multi heat exchanger component in the power cycles.

The following parameters should be considered to design and evaluate cost of heat exchange for NetPower plant:

1- Heat recovery with multi-stream heat exchanger saves energy cost by reducing hot and cold utilities. The capital cost (CAPEX) of utilities and operational cost (OPEX) of utilities are reduced
2- The capital cost of heat exchanger price will increase by lower ΔTmin
3- In order to reduce pressure dropping in multi-stream heat exchanger, the CAPEX will increase but energy cost and OPEX will drop.
4- The efficiency increasing and operational energy cost reducing by lower ΔTmin.

In order to design multi-stream heat exchanger for NetPower plant, it is required to tradeoff between capital cost (CAPEX) and operational cost (OPEX) for specifying ΔTmin.

VII. Conclusion

In this article sensitivity of NetPower oxyturbine cycle is analyzed by means of process modeling in Aspen Plus software. The results show that heat exchanger design has important effects on the efficiency, capital cost, saving energy and operational cost of the cycle.

The simulation results show that the efficiency increases with lower ΔTmin in both constant COT and constant recycled flow rates. The COT shows increase by decreasing ΔTmin with constant recycled flow rate. The efficiency increases faster in constant flow rate compared to the constant COT.

The power demand for recycle compression loop was found to be highly dependent to the recycle flow rate and with constant flow rate the recycle compression loop power demand is constant. The higher ΔTmin with constant COT causes lower recycle final temperature, lower flow rate and lower turbine power output. The modelling shows that the power demand of recycle compression loop was decreased and in total, the efficiency decreased more than 1 %. These results are consistent with the results presented in the IEA 2015 report [4].

The overall heat coefficient (UA) diagram of heat exchanger related to ΔTmin shows that decreasing ΔTmin near zero causes an exponentially increase in the capital cost. The tradeoff between the capital cost and efficiency in NetPower cycle is very critical and will be justified by selecting an efficient ΔTmin.

In order to reach higher cycle efficiencies, COT will need to be increased. This shows that material property of turbine blades or turbine blades cooling strategies have critical role in increasing efficiency of NetPower Cycle. Furthermore, designing heat exchangers with higher overall heat coefficient (UA) and lower ΔTmin results in higher efficiencies in NetPower cycle. This means heat exchanger has a critical role in NetPower cycle performance and overall efficiency and therefore it is very important to invest on new heat exchanger manufacturing technologies, materials and design methods resulting in lower capital and operational cost of the cycle in near feature.

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