Investigation of steam injection effect and exergy analysis on ABC gas turbine cycle

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Abstract: - An air bottoming cycle (ABC) was proposed in the 1980 decade as an alternative for the conventional steam bottoming cycle. Now this cycle is being applied as a compact and simple bottoming cycle. In the gas-air heat exchanger, thermal energy of topping cycle exhaust is transferred to bottoming cycle. In fact, exhaust of topping cycle is using as a heat source for bottoming cycle. Nevertheless, lower efficiency than combined steam turbine cycles makes ABC not customary. On the other hand, attempt to increase efficiency in gas turbine was leading to wet cycles. Steam was entering in the middle parts of the cycle (between compressor and turbine).Very low additional compressor consuming work and increasing in turbine work is the main reason for higher efficiency of steam injection cycle in compare with simple cycle. In this paper, steam injection in ABC is investigated. We use both cycle benefits (steam injection and ABC).In fact, our innovation is using combination of air bottoming and wet cycles for heat recovery purpose. In this research, exergy analysis and performance improving are investigated in ABC gas turbine cycle with steam injection by using a series of computer code. In the model steam or water is injected in discharged of bottoming compressor. Corrosion reduction (in comparison with wet cycles) , performance improvement of ABC gas turbine and reducing undesirable effect of ambient temperature on efficiency of combined ABC cycle are the advantages of using this method.

Key-Words: - ABC gas turbine, steam injection, thermal efficiency, output net work

1 Introduction

In recent years, with increase in energy prices, efficient systems are interested. Power plant as a power producer is attended. During the last decades, gas turbine efficiencies were successfully improved by raising the compressor pressure ratio and the turbine inlet temperature (TIT).But it is limited and also gas turbine's exhaust has a relatively high temperature and a large mass flow, utilization of this waste heat is the most common solution. Two methods are suggested for applying the energy of flue gasses; first ,Waste heat can be recovered directly within the gas turbine by thermal recuperation, or indirectly using another working fluid (steam injection).Second method is Appling exhaust energy in a bottoming cycle as a combined cycle (gas or steam turbine) and conversion of waste heat into power.

In the case of steam bottoming, the need for a high-pressure steam generator, a steam turbine, and a condenser. Therefore, it needs large initial investment and will be feasible on a large scale. It should be mentioned that special requirements are imposed on water quality, high-pressure equipment and operators of the steam plant. An alternative ABC consists of a compressor, a heat exchanger, and an expander (Fig. 1). This subject is investigated by some authors [1-4].It operates at air

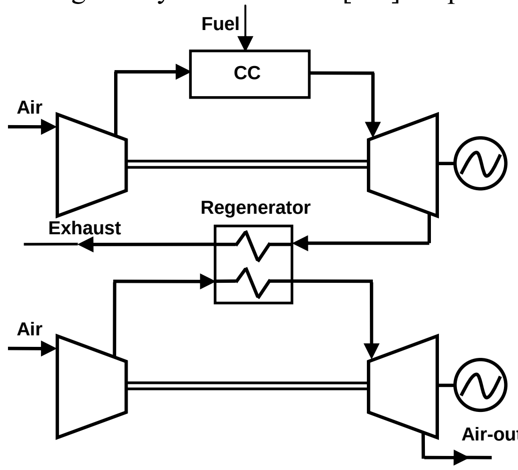

Fig.1. Gas turbine with air bottoming cycle

as a working fluid. To decrease compression low and moderate pressures and uses the ambient work, intercooling can be applied. In addition, air which leaves the bottoming cycle at a temperature of 200–270 $^{\circ}C$ can be used for process needs [5] in recent

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studies [6], exergy analysis of gas turbine air-bottoming combined cycle was considered and environment effect was researched.
On the other hand, attempts to improve gas cycle efficiency lead to wet cycle innovation [7-9] .wet cycles were using flue gasses energy to evaporate water which It is injected into the middle part of cycle(between compressor and turbine). The turbine work output (and hence the net work output) is increased linearly with the steam quantity that is injected, while compressor work is constant approximately and hence the net work output was increasing, It is the reason of efficiency growth. These cycles only needs a heat exchanger to achieve high performance. There are three basic types of wet cycles which are calling STIG[1], EGT[2] and HAT[3] in abbreviation. They are same in using exhaust energy to change water in to steam .Their differences are in evaporating manner and injection places. Kolev and co workers [7] and Traverso[8] were presented high wet cycle efficiencies with their innovations.
In this research, exergy analysis and performance improving are investigated in ABC gas turbine cycle with steam injection by using a series of computer code. In fact, our innovation is using combination of air bottoming and wet cycles for heat recovery purpose. Steam injection is proceeding in bottoming cycle of combined ABC in this work, so we do not encounter disadvantage of sulphur compound that makes corrosion which happened in normal gas turbine steam injection and a comparison between cycles is established.

2 Air Bottoming Cycle

Two methods for the purpose of efficiency increasing in ABC (hence overall efficiency growth in power plant) will be expressed. One of the methods is using intercooler in ABC (I-ABC).the other is convert the bottoming cycle to wet cycle which is possible to utilize wet cycle benefits while some of defects is extinct. Intercooler applying is investigated in past, but we obtain results of this method to compare our new cycles.
Operation pressures are low in ABC. Nevertheless, intercooler applying is caused overall efficiency increasing by two means. Intercooler is decreasing compressor work at first and also outlet air temperature of compressor is lessening and it helps to absorb more thermal energy from topping cycle exhaust (in the recuperator or regenerator)[1,2,3,10].

3 wet bottoming cycle

The topping exhaust gasses have high temperature after passing through the regenerator. Calculations showed the flue gasses temperature is 250–320 $°C$ in regenerator outlet that it is wasted. Thermal energy of these gasses can be used for evaporating water, and then steam is mixed with ABC compressor discharged air in a mixer. Evaporating process is done in a heat recovery steam generator (HRSG). Fig. 2 shows diagrammatically the steam injection in the air bottoming cycle gas turbine (STI-ABC) plant.

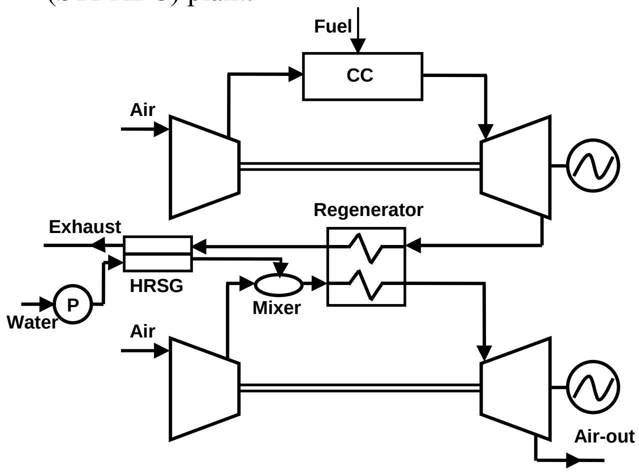

Fig.2. Gas turbine with steam injection air bottoming cycle (STI-ABC).

STIG plants have several types that are different in steam injection places [9,11,12].The steam usually is injecting in inlet or outlet of combustion chamber. If steam injects in inlet of combustion chamber the No_x production is reducing [11, 13]. Instead we encounter not burned carbon or carbon monoxide. CO_2 production is increasing [14]. Some authors offered procedures to separate the carbon compound from gasses with ion exchange and using other equipments [7, 14].
It is leading to raise cost for additional equipments and maintenance. If the steam is injected in compressor outlet of bottoming cycle, it will not be need to additional equipments because of there is no combustion product in bottoming cycle.
Corrosion and plant life reduction is an important problem in wet cycles. It makes limitation in wet cycle utilization. Alkali metals, e.g. *Na* and *K*, in the air and water will form sulphates during the combustion process. If present at sufficient partial pressures, these alkali-sulphates can condense in the temperature region 800 – 950$°C$ as droplets,

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[1]- Steam Injection Gas Turbine
[2] - Evaporating Gas Turbine
[3] - Humid Air Turbine

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deposit onto the blades and create an aggressive, corrosive environment [14]. In bottoming cycle, there is no sulphur compound that reacts with alkali metals and makes corrosion.

Evaporating gas turbine (EGT) is offered high specific work and efficiency [15]. It can improve ABC performance. Evaporating air bottoming cycle (E-ABC) is shown diagrammatically in Fig. 3. Water is injected in to a container (called evaporator). Contact between hot discharged air of compressor and injected water, makes a mixture of air and vapor with lower temperature. Increasing the differential temperature across the regenerator causes better energy recovery. Both more energy recovery and mass flow rate promotion are increasing efficiency and output turbine work in the ABC.

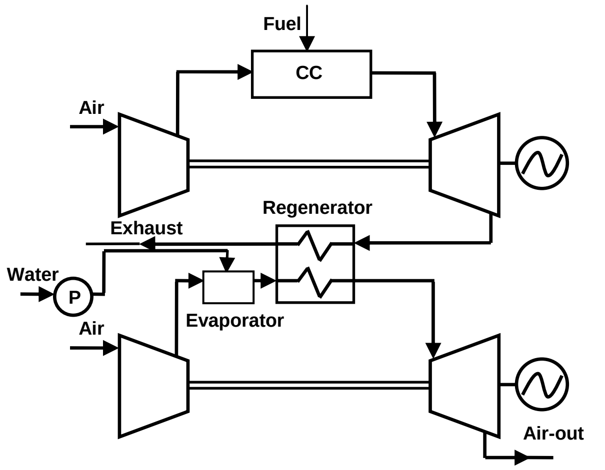

Fig.3. Gas turbine with evaporating air bottoming cycle (E-ABC).

3 Calculations

Each parts of power plant cycle were defining as a function in matlab software. Functions were calculating the parameters of their related part. Thermodynamic properties are setting as a data bank in this code. Main program was establishing communication between subprograms. This code had been validated for simple gas turbine [16]. Table 1 reports the main thermodynamic assumptions used in the present analysis:

Table 1.Main thermodynamic assumptions

Gas Turbine:	
Compressor isentropic efficiency	88%
Combustion chamber pressure drop	2%
Combustion efficiency	98%
Turbine isentropic efficiency	90%
Mechanical efficiency	99%
Regenerator Effectiveness	85%
Regenerator pressure drop (hot fluid)	2%
Regenerator pressure drop (cold fluid)	2%
Intercooler:	
Thermal Effectiveness	75%
Pressure drop	2%
Wet cycles:	
HRSG Effectiveness	75%
HRSG pressure drop (water and steam)	6%
HRSG pressure drop (flue gasses)	2%
Mixer pressure drop	0.5%
Evaporator pressure drop	0.5%
Pump hydraulic efficiency	80%

4 Results and Discussion

The comparing of the results is shown in Table 2. In the Table 2 thermal efficiency and output net work at the different cycles are compared to each other and simple gas turbine cycles.

Table 2-Efficiency and specific work increases from the original simple cycle (TIT=1400°*C*, ambient temperature T_0=25°*C*, topping cycle pressure ratio R=25 and bottoming cycle pressure ratio r=6)

Cycle Type	Efficiency increase points (%)	Specific work increase (%)
ABC	7.7	19.3
I-ABC	9	22.2
STI-ABC	10.4	25.5
E-ABC	10.6	26.1

STI-ABC and E-ABC are producing more specific work than others and they are more efficient, due to better topping cycle heat recovery. Fig. 4 shows exergy balance in each cycle. The output work is same in STI-ABC and E-ABC approximately higher than I-ABC. It is due to outlet exergy from up cycle. Lowest of this parameter is related to E-ABC and highest outlet exergy from topping cycle occurs in normal ABC. I-ABC outlet exergy is lower than ABC. Intercooler causes bottoming cycle compressor discharge had lower temperature (than normal ABC), thus it can absorb more energy from flue gasses. As seen in Fig. 4, although outlet up cycle exergy is lower in both wet ABCs than I-ABC and normal ABC but part of this exergy increases output net work and other portion of exergy is consuming in irreversibilities. As in E-ABC gaseous and liquid fluids mixing, with high temperature difference is making significant irreversibility. Furthermore, increase in temperature difference in regenerator is growing irreversibility. In STI-ABC irreversibilities are occurring in HRSG *(the process of water to steam transformation) and in the mixer (air and steam mixing). For the purpose of irreversibilities reduction, new wet cycles were offered, HAT and HAWIT [8] were utilizing evaporating water process in a saturator.

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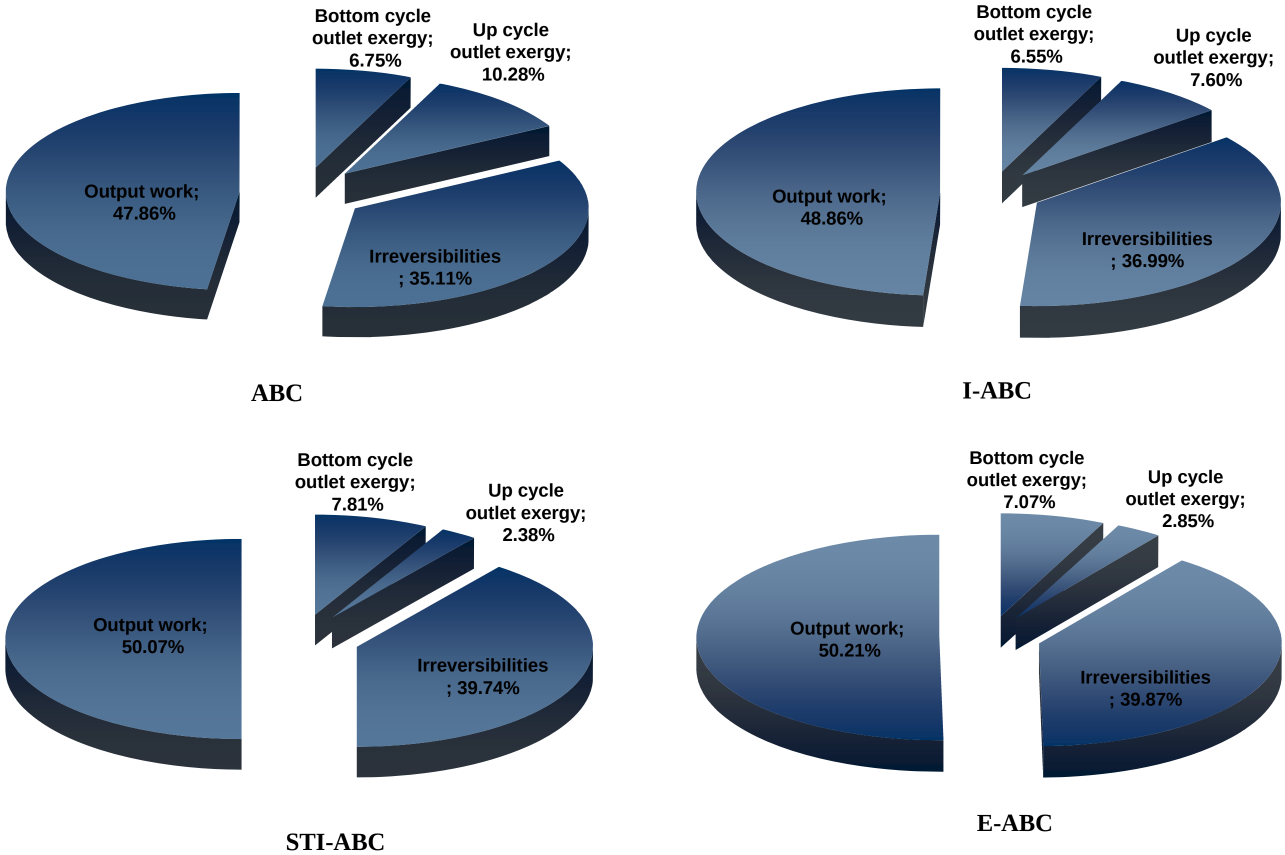

Fig.4. Exergy analysis for various type of ABC

Complication and additional equipments are disadvantages of theses cycles. HAT and HAWIT present good performance at high pressure ratio while ABC works in low pressure ratio.

Efficiency variation relative to output net work at various pressure ratios in topping cycle are displayed for the cycles in Fig.5. STI-ABC and E-ABC have the highest efficiency. In lower pressure

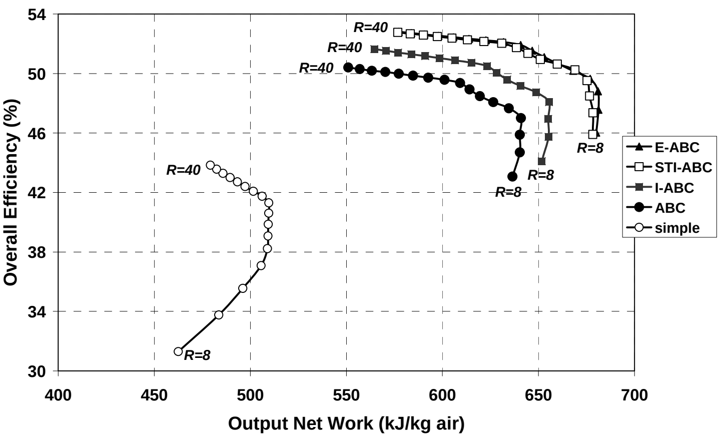

Fig.5. Efficiency variation relative to output net work at up cycle pressure ratios (TIT=1400°*C*, T_0=25°*C* and r=6)

ratios (lower than 26) E-ABC is more efficient than STI-ABC insignificantly. Although, both cycles present same efficiency and output net work, while pressure ratio growth. E-ABC efficiency average is about 2.6% higher than normal ABC and 11% higher than simple gas turbine. Output net work is increasing about 28% relative to simple gas turbine averagely. In I-ABC, efficiency is 1.1% higher than normal ABC and output net work is increasing 4.1% averagely. As seen in Fig.5 with pressure ratio increasing (each symbols indicates two units increment in the chart) efficiency is raising but we encounter work losses in high pressure ratios. In industrial application, the optimum amount of efficiency and output power have been chosen (efficiency increasing is acceptable until output net work was not decreasing).

As observed in Fig. 5, topping cycle pressure ratio increment is increasing overall efficiency in simple cycle more than ABC cycles. Thus ABC families are low sensitiveness relative to pressure ratio as compared as simple gas turbine, as seen in Fig. 6. Ambient air temperature increase has undesirable effect on simple gas turbine performance. It is decreasing thermal efficiency and output net work.

One of wet cycles benefits is reducing ambient temperature undesirable effect on gas turbine

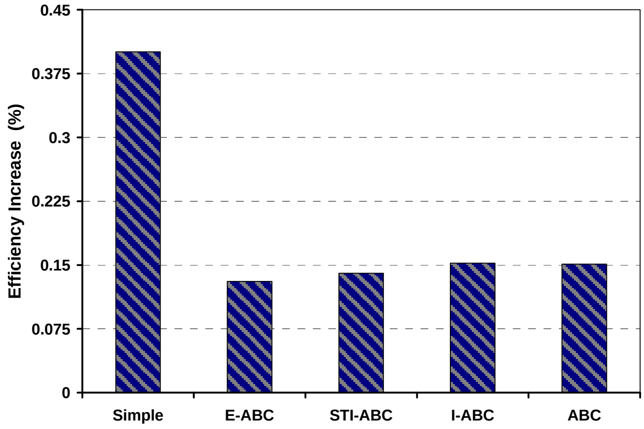

Fig.6. Percentage of efficiency increase due to pressure ratio increment within 8-40.

performance [17]. Fig.7 is showing overall efficiency against ambient temperature variation within 0-45°*C* . All the cycles lose a part of their efficiency with ambient air temperature increase. In E-ABC efficiency line gradient is less than others. Efficiency lost in ABC, I-ABC and STI-ABC is about 4.1%, 3.65% and 3.45% respectively while E-ABC efficiency lost is 3% between 0-45°*C*. Thus E-ABC has low sensitiveness relative to ambient temperature undesirable effect as compare as other ABCs..The reason is, ambient

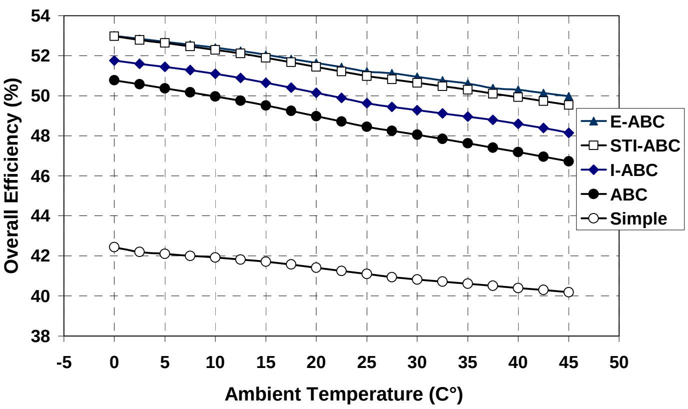

Fig.7. Efficiency variation due to ambient temperature increment 0-45°*C* . (TIT=1400°*C*, R=25 ,r=6)

temperature raising leads to increase of compressor discharged temperature and therefore, more water can be evaporated. More mass flow rate passes through the turbine thus turbine work is increasing. Fig.8 is showing efficiency rising against turbine inlet temperature (TIT). It is interesting that simple gas turbine and ABC efficiency is close to each other in lower TITs, even in 900 °*C* they present same efficiency. In this case, flue gasses have low significant temperature relatively; therefore, there is no much temperature difference between bottoming compressor outlet and exhaust gases in the regenerator for heat transfer process. Thus bottoming cycle can not work profitably and ABC using is useless. I-ABC, STI-ABC and E-ABC are better in lower TITs, but whatever TIT is raising they are presenting better efficiency than simple

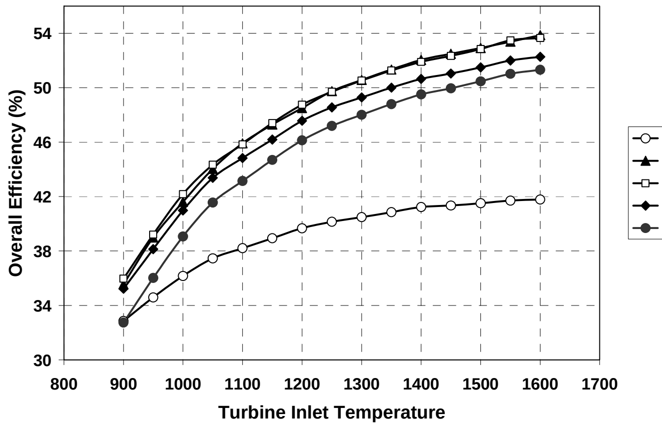

Fig.8. Efficiency variation with turbine inlet temperature (R=25 ,r=6 and T_0=25°*C*)

gas turbine. As seen in Fig.8 STI-ABC and E-ABC are showing same overall efficiency. But at a glance, E-ABC is superior to STI- ABC, because of:

- It does not need additional equipments (HRSG) like STI-ABC.
- It has lowest sensitiveness relative to pressure ratio as compared with other cycles.
- E-ABC has the greatest adjustment effect on ambient temperature undesirable effect in ABC families.

As mentioned above, E-ABC is better and so do more investigation on E-ABC for obtain optimum operation condition. we must define a pressure limitation for every turbine inlet temperature while overall efficiency increases

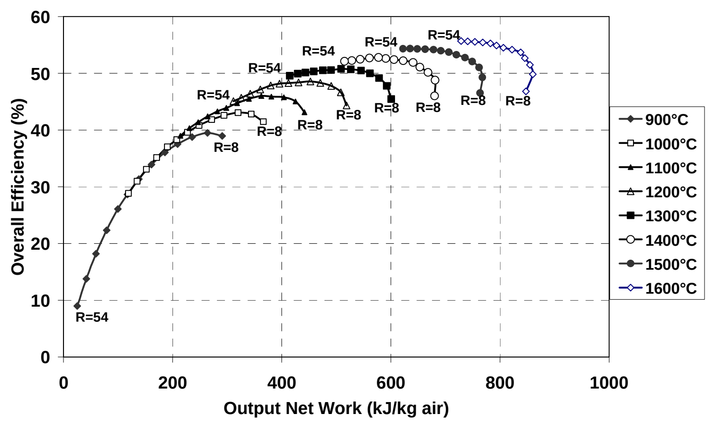

Fig.9. E-ABC efficiency variation with output net work at up cycle pressure ratio 8-54 in various TITs

and output net work does not decrease. In E-ABC, pressure ratios within 20-30 are recommended for TIT higher than 1200°*C*.They are shown in Fig.9.As observed in Fig.10, in higher turbine inlet temperature, pressure ratio increment raises efficiency insignificantly. After 30 pressure ratio, efficiency increase is stopped approximately.

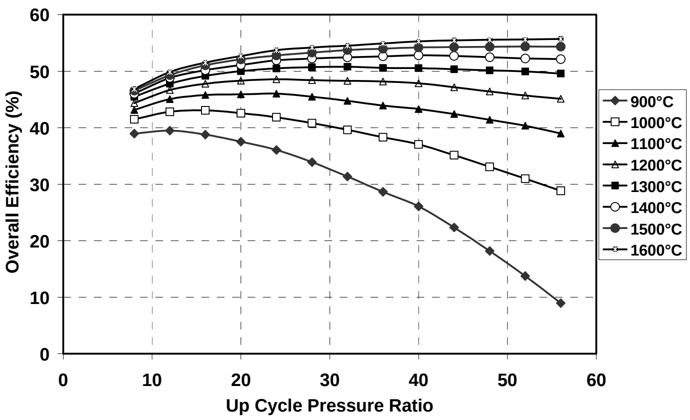

Fig.10. E-ABC efficiency variation with up cycle pressure ratio in various TITs

5 Conclusion

Wet cycles E-ABC and STI-ABC present higher efficiency (2.5-3.5%) than normal ABC. Efficiency of these cycles is about 10-12 percent higher than simple gas turbine and output net work increases 20-35 percent relative to simple gas turbine. Corrosion eventuality is less than normal wet simple gas turbine cycles. Apply of ABC and its family is not recommended in low up turbine inlet temperatures although, efficiency is raising shortly in I-ABC, STI-ABC and E-ABC in these temperatures. E-ABC is superior than STI- ABC, because of not needing to additional equipment, low sensitiveness relative to pressure ratio and ambient temperature. Finally, E-ABC is a proper idea to improve ABC performance.

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