Analysis of a Gas Turbine Plant for Distributed Power Cogeneration Along with Heating, Refrigeration and Air Conditioning

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ABSTRACT

Gas turbine plants play important role in power production whenever there has been scarcity of power generated from conventional sources like oil or gas. Researchers have been trying to simulate this kind of power plants for higher outputs with improved system efficiency. In this scenario, present work attempts to study and simulate a closed cycle gas turbine power plant for different configurations. All the components are modelled and integrated to form a power generating and heating system. Parameters like compressor inlet pressure, pressure ratio and turbine inlet temperature are varied. Performance curves of the individual components and the integrated system are plotted and studied. Results obtained show the significance of pressure ratio and turbine inlet temperature. Utilization of heat from turbine exhaust shows the possibility of a cogeneration bottoming cycle that can be used for district heating, refrigeration and air conditioning applications. Also, it is found that inlet pressure of 1 bar allows both topping and bottoming cogeneration cycles to perform optimally.

Keywords: Cogeneration, District heating, Gas turbine plant, pressure ratio, vapour absorption system and air conditioning.

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INTRODUCTION

Gas turbines are one of the most suitable units for power generation when there is significant difference between the power generated and required. It is observed that for the last two or three decades, gas turbines have been playing crucial role in power sector throughout the world [1]. In order to move in this direction, Subbarao et al. [2] have proposed the utilization of gas turbine in a combined cycle power plant to meet the environmental challenges. Now-a-days, several types of gas turbines are widely used for power generation. In some cases, climatic conditions will also affect the performance of gas turbines [3]. Thus, many plants are combining the gas turbine cycle with a steam cycle to get better power output, either to produce electricity or for industrial purpose [4]. But, the efficiency and output of the gas turbine mainly depends on the ambient air temperature [5]. Previously, researchers reported that by varying the ambient temperature there is a significant change in power output of the turbine [6-9]. Few others found that by varying the inlet parameters of the turbine, efficiency of gas turbine could be changed. Moreover, increasing population in countries like India is leading to increased number of colonies in remote places and chance of gated communities that are located far away from main lines. In such cases, they may not be depending on the main power grid that involves higher transmission losses. Due to shortage of power from the power grids provided by governments, people are trying to setup their power generation sets. This falls under distributed power generation category. Diesel sets, fuel cells as well as gas turbine plants are the most suited in such cases. In this context, present work finds significance as such gas turbine plants of 100-250 kW will be able to power such colonies or communities. To meet such requirements, present work aims at studying about a combined cycle gas turbine power plant that can be used for district heating applications also. District heating tackles the issue of providing hot water to all the end users. In order to study about such plant, modelling of the components like compressor, turbine, combustor and the overall plant is done. Parameters like temperature, pressure, pressure ratio and mass flow rates are varied that help us in providing the necessary details of the gas turbine power generation system. In this present context we extended our work to produce refrigeration effect by combining gas turbine power plant with vapour absorption system. This leads to efficient performance of the system [10].Cop values are calculated by varying input parameters of combined system.

MODELLING AND METHODOLOGY

Schematic diagram of the gas turbine power plant is shown Figure 1. Working fluid enters into the compressor at low pressure and is denoted as state 1. During this operation, no heat is added, but compressor raises the pressure along with temperature. Soon after leaving the compressor, the working fluid enters into the combustion chamber, where the heat is supplied and combustion takes place at constant pressure. After the completion of combustion process, fluid enters into the turbine unit at state 3. During this operation, energy of the hot gases will be converted into work. Some amount of work output produced by the turbine is used to drive the compressor. After that, heat rejection takes place at the constant pressure in the heat exchanger. The entire process is shown in P-V and T-S diagrams as shown in Figure 2. Simulation package using C language is developed and used for analysis. Governing equations have been implemented for each and every component of the power generation system. The simulation program consists of functions to all the components like compressor, combustor, turbine and heat exchanger. The governing equations are explained in the subsequent sections.

Modelling of compressor and turbine

Compressor takes the working fluid at low pressure and compresses it to high pressure according to the compression ratio. Temperature and pressures are higher than the inlet. The outlet parameters of the compressor are obtained by usual relations,

$$p_2 = p_1 \text{ c } r^r \quad (1)$$

$$T_2 = T_1 \, x \, r^{\frac{r-1}{r}} \quad (2)$$

where r is the compression ratio.

Exhaust gases, which come out from the combustor are allowed to flow over the moving blades of the gas turbine, which leads to rotate the runner. Here hot gaseous energy is used to convert into mechanical energy. Velocity, temperature and pressure of the hot gases are

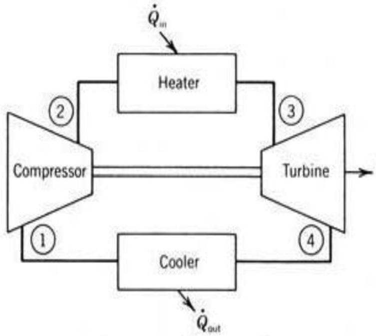

Figure 1. Schematic of a gas turbine power plant.

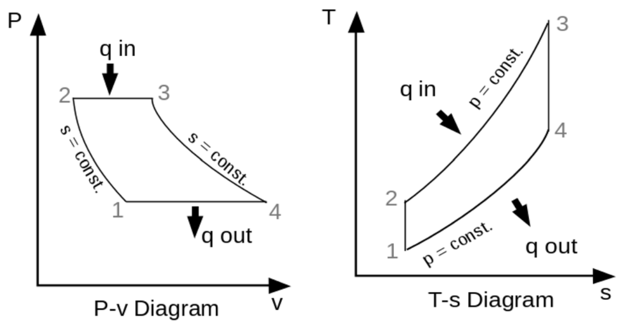

Figure 2. P-V and T-S diagram for gas turbine cycle.

sacrificed to rotate the turbine blades in order to produce shaft power. Some part of the power developed in the turbine is used to drive the compressor and remaining portion is used to drive the generator. Output pressure and temperatures are related by,

$$T_3 = T_4 \times \left(\frac{p_3}{p_4}\right)^{\frac{\gamma-1}{\gamma}} \tag{3}$$

Work output of the turbine

$$W_T = c_p \cdot T_4 \left[1 - \left(\frac{p_3}{p_4}\right)^{\frac{\gamma-1}{\gamma}}\right] \tag{4}$$

Work output of the compressor

$$W_C = c_p \cdot T_2 \left[\left(\frac{p_3}{p_4} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right] \qquad (5)$$

Modelling of combustor and heat exchangers

The governing equation for combustor is as follows,

$$Q_1 = m \bullet c_p \bullet (T_3 - T_2) \qquad (6)$$

In the heat exchanger, heat is lost from the hot gases. The outlet temperature and pressure are less than that of the inlet. The equation for heat transfer can be expressed as,

$$Q_2 = m \bullet c_p \bullet (T_4 - T_1) \qquad (7)$$

RESULTS AND DISCUSSION

Gas Turbine Cycle Performance

The objective of the simulation is to determine the overall performance of the system. Compressor work, turbine power output and overall system efficiency are described in this section for various configurations. Figure 3 describes the compressor work for various pressure ratios. With decreased pressure ratio, the compressor work is decreasing. Also, as the inlet pressure is increased, the compressor work is reducing. With these two parameters simultaneously changed, we can identify the optimum pressure ratio and at the same time, inlet pressure, at which, the compressor work is minimum can be found. Figure 4 also shows the variation of turbine output with pressure ratio. As the pressure ratio is increased, turbine power output increases. But, it may be up to a certain value. This plot gives us the pressures at which the turbine can give higher outputs. It is good to see such trend and an optimum one where the compressor work is less and turbine work is more. Effect of turbine inlet temperature (TIT) on the overall system power output is shown in Figure 4. With increased TIT, power output is increasing. There seems to be slight converging pattern and further increase in TIT may slightly decrease the power input, giving us an optimum value. On the other hand, increased inlet pressure will have reduced power output as shown in Figure 6. From Figures 3, 5, and 6 an optimum scenario of TIT and compressor inlet pressure can be obtained.

Overall efficiency of the gas turbine power plant is changing with various pressure ratios as well as inlet pressures as shown in Figure 7. For various inlet pressures and different pressure ratios, plot is made. Clearly, for an inlet pressure of 1 bar and higher pressure ratios, the performance is maximum. This solidifies the idea of open cycle gas turbine system as well, where the inlet working fluid is expected to be at atmospheric condition. In Figure 8 variation of net work obtained from the cycle with TIT is shown. With increased TIT, higher output is obtained. But, the curves seem to be closer with increments. Similarly, as the pressure ratio is increased, the output of the GT power plant is increasing up to a certain value, beyond which it is not varying more. This suggests that further increment of pressure ratio would not affect the system output. Once, the pressure ratio is optimized, TIT can be found from the plot that gives higher outputs and better efficiency. Turbine inlet temperature also plays a predominant role in system efficiency. Turbine inlet temperature is high it increases the system efficiency if it is low it reduces the efficiency of the system. Moreover higher turbine inlet temperature leads to cause some metallurgical problems so in order to get efficient performance it is necessary to maintain optimum temperature.

Gas Turbine Cycle with District Heating

Since the exhaust of the turbine is at higher temperature, there is a provision for bottoming cycle that can improve the system efficiency further. Present work deals with this aspect of available heat that can be used for district heating applications. Wherever this cycle is used as distributed power generation, the rejected heat can be reused for heating at the same place, improving the performance of the combined heat and power plant. The hot gases exchange heat with cold fluid that is pumped as shown. The hot water is used for various applications by the end user. Used water at low temperature is sent back to the cycle and with the use of pump, sent to the heat exchanger, as shown in Figure 8. This cycle is further extended to utilize the heat available for providing hot water to the end users. Figure 10 shows the heating capacity with change in pressure for various inlet pressures. Temperatures available at the turbine exit are taken for calculation. Since the temperature of the

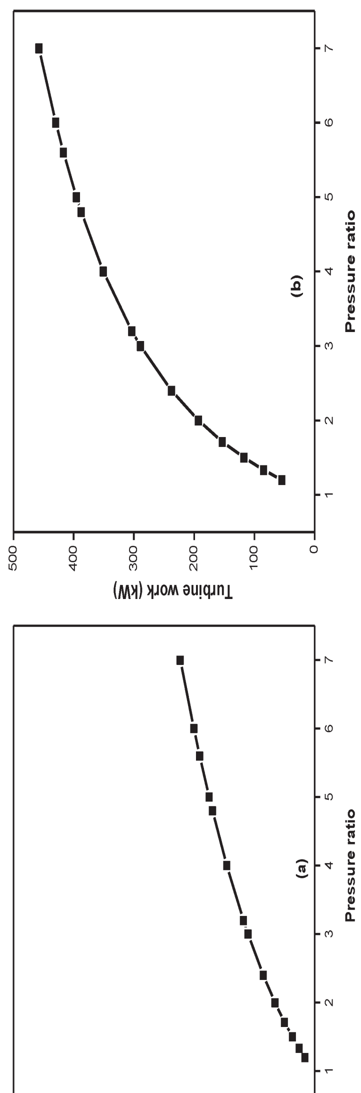

Figure 3. Compressor and turbine work for various pressure ratios.

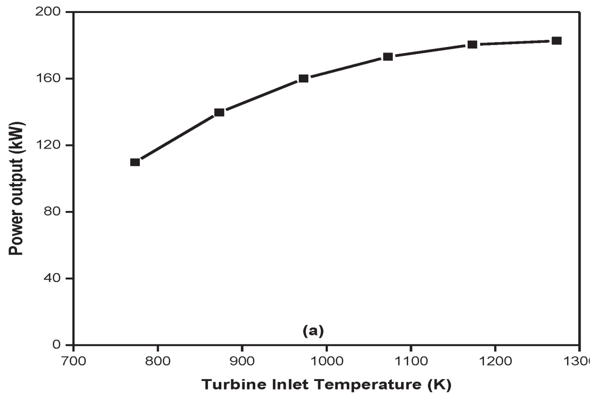

Figure 4. Influence of TIT to the system power output.

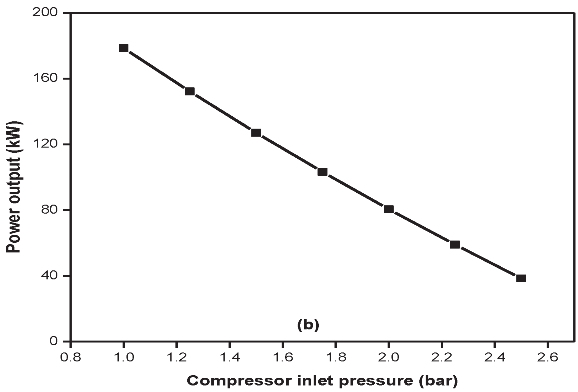

Figure 5. Inlet pressure to the power output.

working fluid at the inlet of the compressor has to be as low as possible, the heat exchanger used in the cycle should be as effective as possible, so that maximum heat is utilized in the bottoming cycle. As the pressure ratio increases, available heat reduces. For the high inlet pressure of 2 bar, more district heating is possible. In general, this heat is also taken while considering of efficiency that represents the performance of the combined cycle.

Gas Turbine Cycle with Refrigeration

Thermal energy released from the gas turbine enters the surroundings as waste heat. This heat can be converted into utilized form by send-

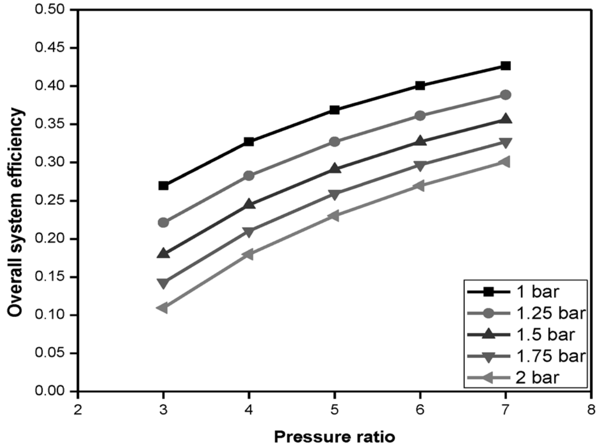

Figure 6. Efficiency for various inlet pressures.

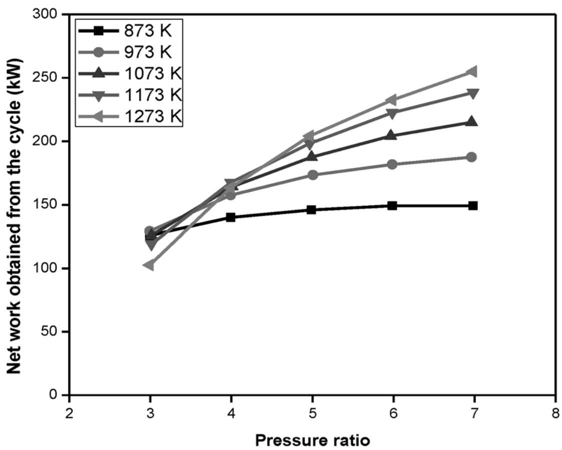

Figure 7. Effect of TIT for various pressure ratios.

ing to a refrigeration system based on vapour absorption. This not only improves the system efficiency, but also becomes more environmental friendly. Performance of the refrigeration system depends on the chemical and thermodynamic properties of working fluid used in gas turbine cycle. Present work discusses the refrigeration effect by using lithium bromide vapour absorption system. In this, water is used as refrigerant and lithium bromide as absorbent. This type of absorption system is widely used because of its properties like non-volatility and high heat of vaporization, which are very necessary for better performance. The schematic diagram of the gas turbine with vapour absorption system is shown in Figure10. In the absorber, lithium bromide absorbs the water refrigerant to form a solution of water and lithium bromide. This solution is pumped to the generator, where it is heated by taking the exhaust heat from the turbine. With the help of this heat, refrigerant gets vaporized and moves to the condenser, where it gets cooled. Lithium bromide flows back to the absorber, where it further absorbs water coming from the evaporator. COP represents the performance of the refrigeration system and its plots are made with respect to generator inlet temperature and pressure ratio. Increase in generator inlet temperature leads to increase in system COP as shown in Figure 11. This is due to the fact that concentration levels of the weak solution increases as a result of higher specific enthalpies. Trend is same for all the inlet pressures. Figure 12 shows the influence of pressure ratio on system COP. It shows that the system produces maximum COP at 1 bar. Results thus confirm that 1 bar inlet pressure itself is more suitable for a gas turbine power generation cycle, so that there is maximum benefit with respect to heating and refrigeration.

Gas Turbine Cycle with Air Conditioning

As discussed in the above section, heat from the exhaust of the turbine can also be utilized to operate an air conditioning unit by combining the gas turbine cycle with air conditioning cycle. Figure 13 represents the working of a gas turbine cycle along with air conditioning. The heat released by the turbine is taken into the conditioning unit that has compressor, condenser, evaporator and suction line. Working fluid is normally air that uses the heat available in the topping cycle. As shown in Figure 9, same heat available is used for conditioning. The overall performance of the combined cycle depends on the amount of heat that can be utilized for providing the cooling effect. This heat changes the same way as in case of heating. The only difference being the number of components and accessories required to install such units. For the capacity of 400-500 kW turbine power plants, similar or more cooling effect can be obtained from these conditioning units, which is 30% less than the exhaust heat from the turbine. Rating is possible to distinguish between the amounts of heat available to the amount of cooling effect obtained. For every 100 energy units available, 45-50 can be obtained from the gas

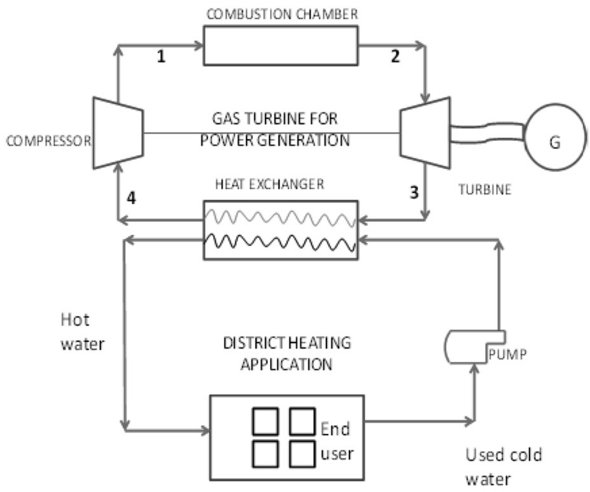

Figure 8. Gas turbine cycle with heating.

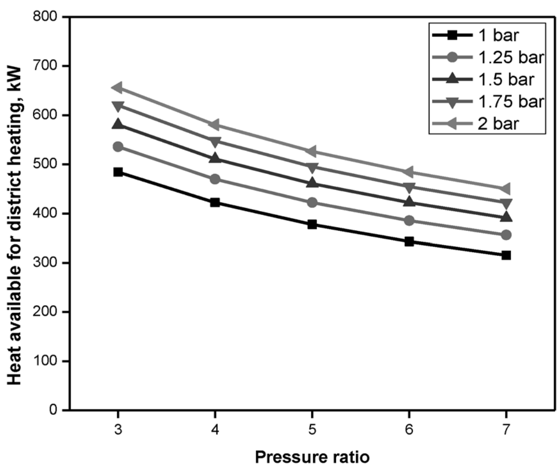

Figure 9. Heat available for district heating.

turbine power plant, based on its usual performance. In summer, refrigeration and air conditioning units can be adapted together to make the overall system producing about 75-80 units. Similarly, during winter, district heating and refrigeration units can combined raise the number of units to the same or slightly higher as shown in Figure 14. Thus, such combined cycles can be used for distributed power generation, where usual transmissions lines cannot be used.

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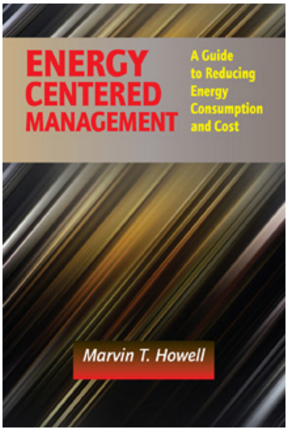

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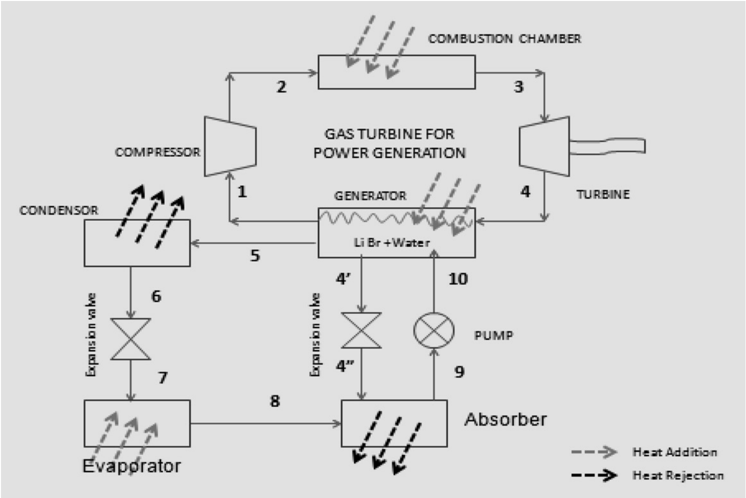

Figure 10. Gas turbine cycle with vapor absorption system.

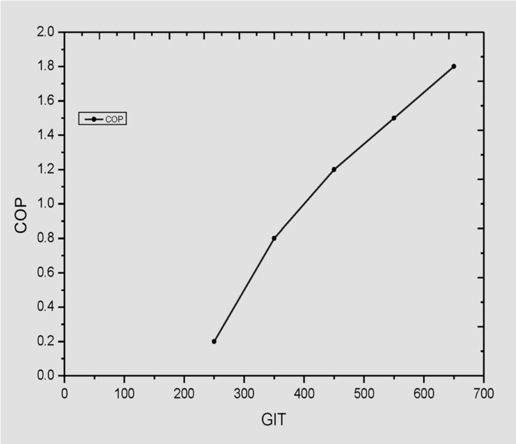

Figure 11. Effect of GIT to the system COP.

CONCLUSIONS

Components of the gas turbine power generation system are modeled based on their governing equations. Programming language 'C' is used to combine all the user defined functions that are applicable for the individual components. Parameters like pressure ratio, compressor pressure inlet, turbine inlet temperature and mass flow rates

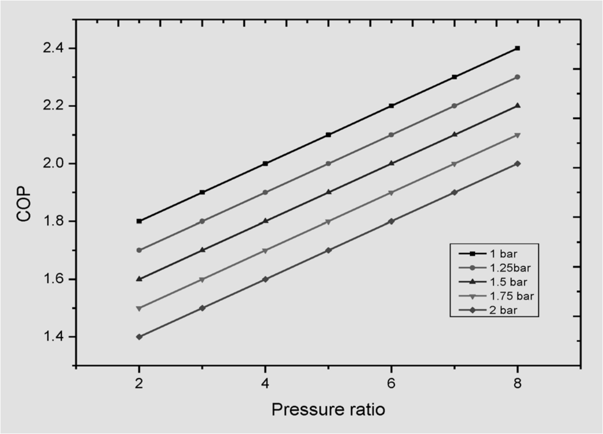

Figure 12. System COP with pressure ratios.

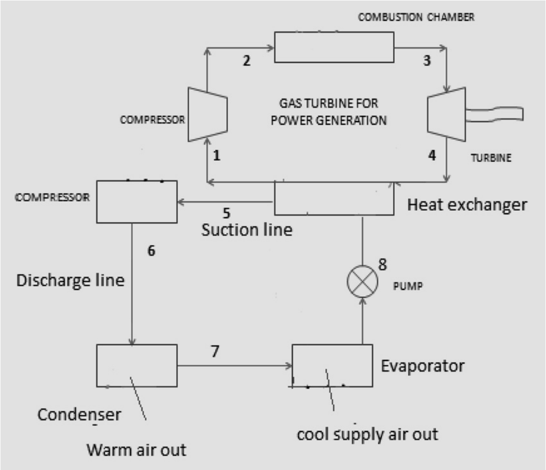

Figure 13. GT cycle with air conditioning.

are varied. Performance of the turbine is varying with inlet temperature and mass flow rate. Similarly, compressor work is changing with inlet pressure and pressure ratio. Importantly, the overall performance of the gas turbine power plant is clearly dependent on compressor inlet pressure and turbine inlet temperature. From the plots of net work output and overall efficiency drawn for different pressure ratios and inlet pressures, an optimum working condition for the power plant can be obtained. Since the temperature of the turbine exhaust is considerably

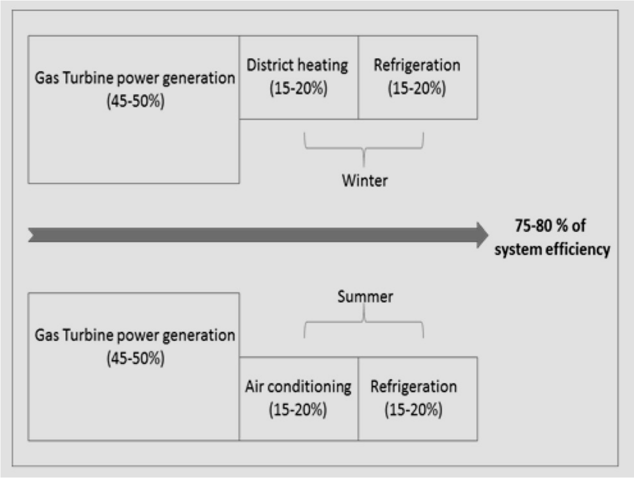

Figure 14. Efficiency of combined cycle.

high, a bottoming cycle can be added that is used for other applications as well. Increase in generator inlet temperature leads to increase in system COP. Results also show that the system produces maximum COP at 1 bar, at which GT cycle also produces maximum performance. This utilization of heat will not only improve the overall performance of the plant to about 75-80%, but also plays role in making the system more environmental friendly. Such systems are very much useful for distributed power generation.

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