Cooling of Compressor Air Inlet of a Gas Turbine Power Plant Using A Single Effect LiBr-Water Vapor Absorption Cycle

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ABSTRACT

LiBr-water absorption cooling system is designed to improve the performance of a gas turbine power plant in by cooling the air inlet to the compressor. The analysis were carried out for various exhaust gas turbine temperatures (150-220) °C . Results of analysis show a noticeable improvement on thermal efficiency of the gas turbine, and the cooling capacity has been getting cooler air up to 5 °C for (T_{amb}=35°C).

Keywords: Gas Turbine, Inlet Air Cooling, Absorption Refrigeration, Ejector, Regenerative Gas Turbine.

NOMENCLATURE

ARC	Absorption Refrigeration Cycle.
COP	Coefficient of Performance.
e	heat exchanger effectiveness
EES	Engineering Equation Solver.
h	enthalpy (kJ/kg)
$\dot{m}$	mass flow rate (kg/s)
P	pressure.
RGT	Regenerative Gas Turbine.
SGT	Simple Gas Turbine.
T	temperature (°C)
x	concentration (mass fraction)

SUBSCRIPT

amb	ambient.
g	generator (desorber).
LiBr	Lithium Bromide.
r	refrigerant.
ss	strong solution.
ws	weak solution.

1. NTRODUCTION

The most efficient commercial technology for central station power-only generation is the gas turbine-steam turbine combined-cycle plant. Simple-cycle gas turbines for power-only generation are available with efficiencies approaching 40%. Gas turbines have long been used by utilities for peaking capacity.

However, with changes in the power industry and advancements in the technology, the gas turbine is now being increasingly used for base-load power. The basic components of a gas turbine are compressor, a combustion chamber, and a turbine [1].

The feasibility of waste heat utilization in a process is dictated by the temperature, quantity, and availability of the waste heat source. There are a number of benefits to implementing waste heat utilization measures, the primary benefit being a reduction in the energy demand of the process. Increased energy efficiency has a number of ancillary benefits, including reducing primary energy input, reducing carbon dioxide and other emissions, and reducing operating costs. Thus waste heat utilization is an attractive improvement when feasible.
There have been numerous investigations into the feasibility of waste heat for various applications, including water desalination, air conditioning, gas turbine performance improvements, and vapor compression cycle enhancements [2].

The performance of the power plant strongly depends on ambient air temperature. Mass flow rate (kg/s) of air decreases in summer with increasing ambient air temperature for the same volumetric flow rate (m^3/s), which results in reduced power output of turbine and increased heat rate [3].

The reduction of inlet air temperature can be achieved by the application of air cooling through water atomization or installing a chiller in the inlet ducting. The use of a cooler or chiller is economically justified if the profits from the increase in power exceed the related capital and operating costs and the climate conditions for effective operation are met. Evaporative cooling, achieved by evaporation of water injected into the inlet duct, is a cost-effective way of recovering turbine capacity during high temperature and low or moderate humidity periods. This method is hindered by ambient temperatures of 10 -15 ^{o}C and above. In lower temperatures there is a higher risk of ice formation on the compressor's inlet guide vanes. Chillers, unlike evaporative coolers, are not limited by the wet bulb temperature. The possible power gain is restrained by the turbine and the capacity of the chilling device to produce coolant and heat exchange limits between coils and air [4].

Ana Paula P. dos Santos, and others, studied and compare the effect of different methods available for reducing gas turbine inlet temperature. Basically, the evaporative cooling and chilling the inlet air. Evaporative cooler and absorption chiller systems results show that when the ambient temperature is extremely high with low relative humidity (requiring a large temperature reduction) the chiller is the more suitable cooling solution. The net increment in the power output as a function of the temperature decrease for each cooling method is also obtained [5].

An inherent characteristic of all gas turbines (GT) is their inability to maintain constant power output as ambient temperature increases or at high elevation. Consequently, electrical generation and horsepower output are in greatest demand at high ambient temperatures. On a 35°C (95°F) day, a GT's air mass flow-rate is reduced by up to 10% and power reduced by 15% compared to its ISO performance [6].

Dayyabu Gambo Kofar-Bai and Qun Zheng, studied the effect of evaporative cooling of gas turbine power plant of some particular stations in Nigeria. Their results show that evaporative cooling of gas turbine decreases the compression work of the compressor and increases the efficiency of the station [7].

In this project, the effect of inlet air cooling by a single effect water-LiBr vapor absorption cooling system on gas turbine performance will be studied. Since, coefficient of performance (COP) of absorption refrigeration cycle (ARC) is low, with high pressure ratios in simple gas turbine (SGT) and with low pressure ratios in regenerative gas turbine (RGT).

2. REHAB SIMPLE CYCLE GAS TURBINE SPESIFICATIONS

Rehab Power Plant is located in the northern region of Jordan closed to central load area. The four-gas-turbine units are GT10 (30 MW Unit), GT11 (30 MW Unit), GT12 (100 MW Unit), GT13 (100 MW Unit). Figure (1) illustrates the simple cycle power plant (open cycle) which present the principle of operation for GT10 and GT11 and for GT12.

In a gas turbine, large volumes of air are compressed to high pressure in a multistage compressor for distribution to combustion chamber. Product gases from chamber power an axial turbine that drives the compressor and the generator before exhausting to atmosphere. The latest gas turbine designs use turbine inlet temperatures of 1500 ºc and compression ratios as high as 30:1 giving thermal efficiencies up to 35% for simple cycle gas turbine [8].

A specific gas turbine model was selected to determine the temperature and quantity of waste heat available, The GE MS5001 model used in Rehab Power Station in the northern of Jordan was selected with the following specifications:

Table 1 GE MS5001 Gas turbine specifications

Specification	Value	Unit
Rated Power	24.6	MW
Air Flow Rate	118	kg/s
Exhaust Temperature	484	°C
Efficiency	32.98	%
Pressure Ratio	10.5	

The compressor model has ambient air as an inlet; the mass flow rate at the compressor inlet was selected to be equal to the manufacturer given value of 118 kg/s for the gas turbine inlet and was kept constant. The outlet, which goes to the combustion chamber, is determined by assuming zero pressure drop at the compressor inlet, a compressor ratio of 10.5, and an isentropic efficiency of 83% [8].

The combustion chamber has two inlets, the compressor outlet and the fuel, the fuel was assumed to be pure methane at 15 °C and 1300 kPa. At full load its mass flow rate is set to match the manufacturer-specified firing temperature. Once the full load fuel rate is set in this case 6230 kg/hr, part loading is simulated by adjusting the fuel mass flow rate. The chamber is assumed to have zero pressure drops. The reactor products exit the combustion chamber and enter the turbine. The turbine's isentropic efficiency is assumed to be 85%, the pressure ratio is taken to be 10.5 and the pressure drop at the gas turbine exit is assumed to be zero. The turbine exhaust is synonymous with the exhaust of the gas turbine [8].

The gas turbine exhaust goes to a heat exchanger block, which simulates the removal of waste heat. Zero pressure drops was assumed, and the exit temperature of the block was selected to be 200 °C. This is because condensation issues might arise at temperatures lower than 200 °C, thus, 200 °C is a conservative approximation [9].

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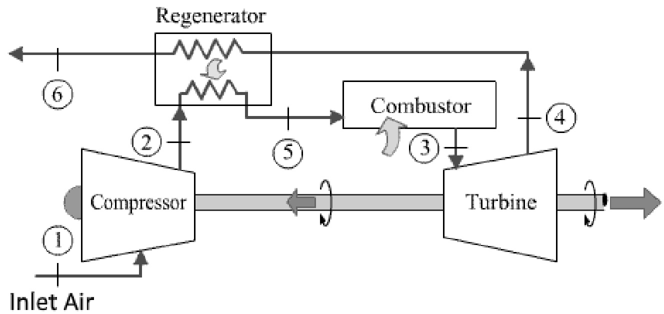

Fig. 1. Modeling and simulation of a simple gas turbine in EES

3. ABSORPTION CHILLER

Aqueous lithium bromide is used as an absorption working fluid because it is one of the best choices found among hundreds of working fluid pairs that have been considered. Aqueous lithium bromide is the preferred choice for many applications, the thermodynamic and transport properties of working fluids are considered to be good. Absorption chillers use a refrigerant-absorbent pair as a working fluid, the two most common combinations of working fluids used are ammonia/water and water/Lithium Bromide.

The absorption chiller working principle is based on single stage single effect water-LiBr that uses waste heat of exhaust gases to provide cooling of inlet air. The absorption chiller typically has a coefficient of performance (COP) between 0.4 and 1.5, based on heat input.
The required temperature level is governed by the properties of the working fluid and the operation of the other components in the chiller machine. For a typical single-effect aqueous lithium bromide machine, the desorber heat must be supplied above a temperature of approximately 90 ^{o}C. Thus, in processes where low temperature waste heat is available and cooling is desired, it often makes sense to implement an absorption chiller to increase the overall energy efficiency of the process [10].

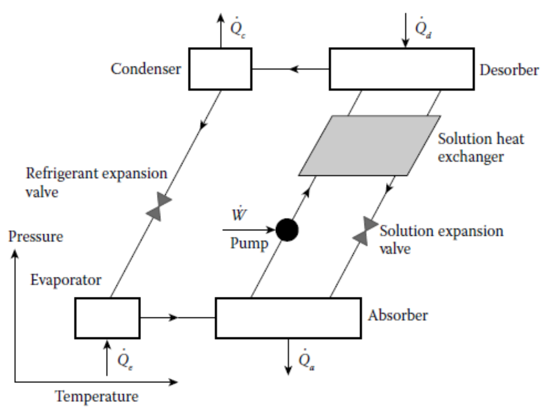

Fig. 2. Single Effect Absorption Cycle

4. MODELING OF WATER-LIBR ABSORPTION CYCLE

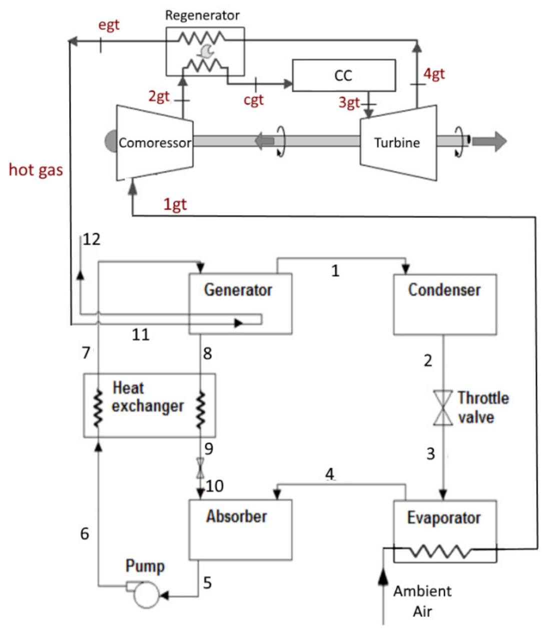

Fig. 3. Schematic diagram of the recuperated cycle with absorption inlet cooling

For A single stage vapor absorption refrigeration system based on water/lithium bromide cycle shown in the figure 2 and figure 3 . A set of operating conditions and assumptions for the cycle are as follow.

4.1. Operating Conditions and Assumptions

The pressure losses and heat transfer losses to the surroundings in the absorption cycle are ignored. The condensing pressure of the refrigerant of the absorption system is equal to the pressure of condensing steam at a temperature 10 °C above ambient temperature amounts 1555 kPa. The evaporator pressure of the absorption system is constant and amounts to 288 kPa. The corresponding evaporator temperature is 1.5 °C. The evaporator pressure is chosen so that the inlet air can be cooled to a temperature that is close to the required temperature for optimum operation. The concentrations of the strong and weak solutions of the absorption system are 0.62 and 0.55 respectively. The assumed values are chosen within the operating range of the Water/LiBr absorption systems and are commonly used. Minimum inlet temperature to prevent icing at the compressor inlet is 12°C. The effectiveness of the absorption system heat exchanger is 80 percent. Polytropic efficiency of compressor and turbine are 0.9 and 0.85 respectively. Combustion efficiency is 0.98 and its pressure drop is 5% of combustion chamber inlet pressure.

5. THERMODYNAMIC ANALYSIS

Following the analysis done by H. A. Al-Tahaineh, applying energy balance on all the components of the combined cycle [9].

5.1. Generator

Applying the energy equation for the desorber of the absorption system yields:

$$\mathbf{\dot{m}_g(h_{11} - h_{12}) = \dot{m}_{ws}h_8 + \dot{m}_{ss}h_1 - \dot{m}_r h_7} \quad (1)$$

Where h_{12} is the enthalpy of gas exiting the desorber $\dot{m}_g, \dot{m}_{ws}, \dot{m}_r, \dot{m}_{ss}$ are respectively the mass flow rates of gas entering the desorber, the weak solution exiting the desorber, the refrigerant exiting the desorber and the strong solution entering the desorber h_9 ,h_{10} , h_1:and are the corresponding enthalpies.

Applying the mass balance equation yields:

$$\dot{m}_{ws} = \dot{m}_{ss} + \dot{m}_r \quad (2)$$

Using the concentration–mass flow rate relation gives:

$$\dot{m}_{ws} = (x_{ss}/x_{ws})\dot{m}_{ss} \quad (3)$$

Where x_{ss} and x_{ws} are the concentrations of the strong and weak solutions respectively. Both concentrations are known and equal to 0.62 and 0.55 by using assumptions, the high pressure of the cycle, P_{high}, is equal to the condenser pressure, and the low pressure of the cycle, P_{low}, is equal to the evaporator pressure. The temperature of the outlet high-concentration mixture, T_8 can be determined as a function of its concentration and pressure using a program called Engineering Equation Solver (EES). As follows:

$$T_8 = T_{water}[P_{high}, x_{ss}] \quad (4)$$

The corresponding enthalpy of the high concentration mixture, h_8 can be determined as a function of its concentration and temperature using EES so that.

$$h_8 = h_{water}(T_8, P_8) \quad (5)$$

An equation can be written for the temperature of gas at the desorber outlet in relation to the temperature of the high concentration mixture at point 8 of the cycle (figure 3).

$$T_{12} = (T_8 + 20) \quad (6)$$

The gas pressure at the outlet of the desorber can be determined using assumption. The enthalpy of the outlet gas can be determined as a function of its pressure and temperature using EES as:

$$h_{12} = h_{AIR}(T_{12}, P_{low}) \quad (7)$$

An equation can be written for the temperature of the outlet steam in relation to the outlet high-concentration mixture at point 8 using the following assumption:

$$T_1 = (T_8 - 15) \quad (8)$$

The enthalpy of the outlet steam can be determined as a function of its pressure and temperature using EES as:

$$h_1 = h_{water}(P_{hi}, T_1) \quad (9)$$

5.2. Heat Exchanger

The effectiveness of the heat exchanger of the absorption cycle is defined as:

$$e = \frac{T_8 - T_9}{T_8 - T_6} \quad (10)$$

Where T_9 and T_6 are the temperatures of the outlet weak solution and inlet strong solution respectively. The temperatures T_6 can be determined as a function of pressure and concentration using EES as:

$$T_6 = T(P_{hi}, x_s) \quad (11)$$

Applying the energy balance equation yields:

$$\mathbf{m_{ws}(h_8 - h_9) = m_{ss}(h_7 - h_6)} \qquad (12)$$

Where h_9 and h_8 are the enthalpies of the outlet strong solution and inlet weak solution respectively. The enthalpy h_9 can be determined as a function of the temperature and concentrations of the solutions using EES as:

$$\mathbf{h_9 = h_{ss}(P_{hi}, x_{ss})} \qquad (13)$$

Equations (1 to 13) are solved simultaneously for the unknowns h_1, h_9, h_6, h_8, h_7, h_{12}, $\dot{m}_r$, $\dot{m}_{ss}$, $\dot{m}_{ws}$, T_1, T_9, T_6, T_8 and T_{12} using EES. The results were presented in figures (4-8) shown below.

6. RESULTS

From the previous analysis of the designed absorption cooling cycle. The outside air is cooled before entering the compressor and as a result the performance of the power plant will be better. The analysis were carried out for various exhaust gas turbine temperatures (150-220 °C) and the cooling capacity has been getting cooler air up to 5 °C for (T_{amb}=35°C). The results of this study are shown in Figure 3 and 4 below.

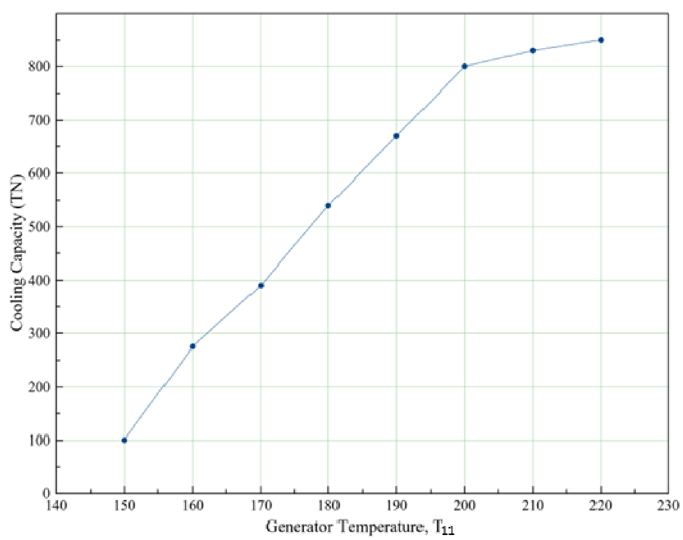

Fig. 4. Cooling capacities of chiller designs at various exhaust (generator) temperatures (T_{13})

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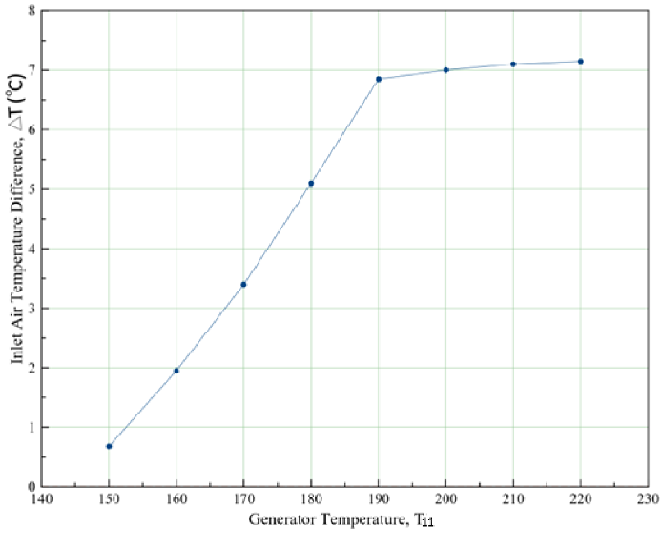

Fig. 5. Inlet air cooled °C at various exhaust temperatures (T_{13})

The inlet air cooling improves both the efficiency and the work net of the gas turbine cycle as shown in the Figures (6) and (7) below. As a result of decreasing inlet air temperature, the work net of the power plant improved by about 5.1 percent and the efficiency of the power plant improved by about 0.40 percent.

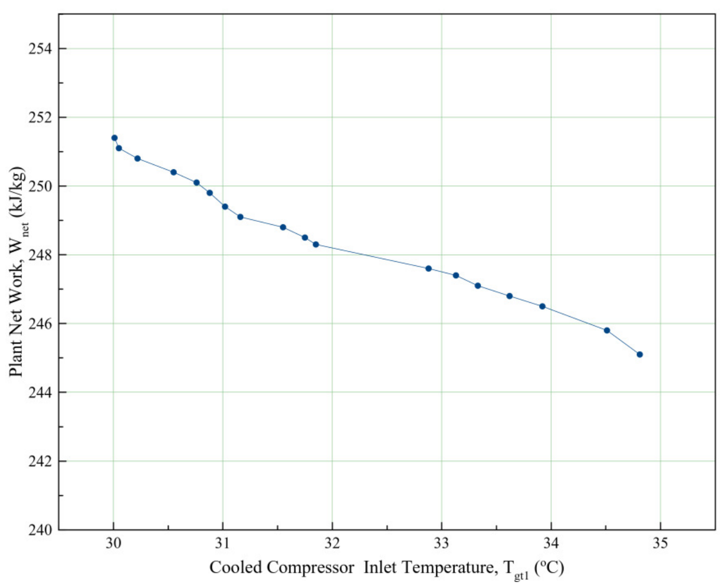

Fig. 6. Inlet cooling improves the work net of the gas turbine cycle

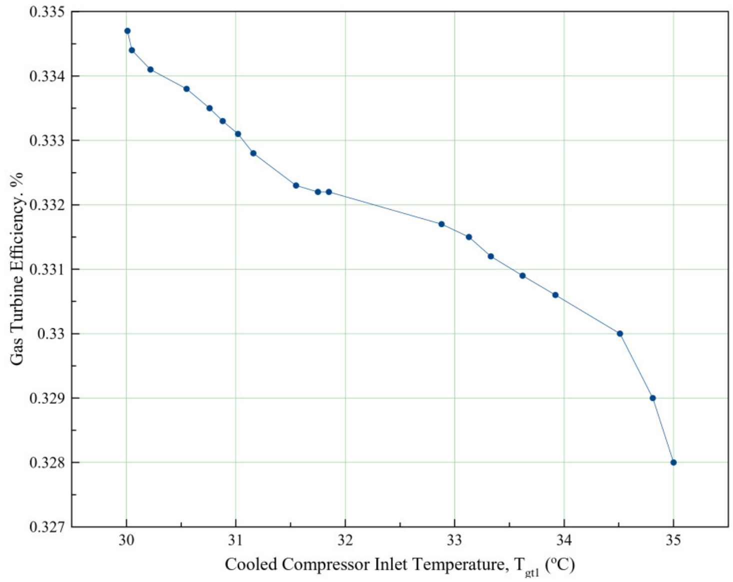

Fig. 7. inlet cooling improves the work net of the gas turbine cycle

7. CONCLUSIONS

Most of the energy lost in the gas turbine power plant is carried out with the exhaust gases which will cause a significant reduction in the work net out of the turbine and the overall thermal efficiency. On the other hand, It was shown clearly that the generated power and efficiency of the gas turbine plants affected to a high degree by the temperature of the compressor inlet air. So that they both (W_{net} and Efficiency) increase as the inlet air temperature decreases. Installing a single-stage water-LiBr absorption cooling chiller at gas turbine inlet, and running with thermal energy of exhaust gases reduces the air inlet temperature to a good degree. The results of investigation show that the compressor air inlet temperature decreases as the exhaust temperatures (T_{11}) increase. As a result the net work of the gas turbine will increase. Absorption cooling could improve efficiency by about 0.40 percent and improve the work net cycle by about 5.1 percent.

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