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Novel inlet air cooling with gas turbine engines using cascaded waste-heat recovery for green sustainable energy

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ABSTRACT

Utilizing the waste heat from the exhaust of the gas turbine enhances power and efficiency combined with reducing inlet air temperature.

The system is a combination of an upper propane organic Rankine cycle ORC and a gas refrigeration lower propane cycle. The upper cycle acts as a power producer which partly runs the lower cycle. The lower propane cycle has an expander that supplies power to run its compressor in addition to cooling the inlet air to the gas turbine engine.

The effective variables are ambient temperature, gas turbine exhaust temperature, compression ratios of the upper and lower cycles, and the saturation pressure of the condenser.

The net power and overall efficiency of the integrated system at extreme conditions ($T_a = 45\ ^\circ C$ and $\Phi = 80\%$), increased by 35% and 50% respectively, due to 15 °C drop in ambient temperature.

This system is highly feasible due to its availability with hot and relatively cool ambient conditions, due to its capability to run as cogeneration and cooling system. The system matches most weathers: hot, humid and dry.

Economic evaluation showed a payback period around (1.5–2) years, which excels other cooling systems including absorption.

1. Introduction

In gas turbine power plants, the ratio of the compressor work to the turbine work is known as the back work ratio (r_w). Usually more than 50% of the turbine work is used to drive the compressor [1]. As the compressor power increases, r_w increases and the net power decreases. The compressor power usually increases with the inlet temperature and consequently the specific volume of the gas.

During summer, the ambient temperature increases which in turn reduces the net power of the gas turbine while the demand is very high. According to [2], a 1 °C increase in ambient temperature leads to a decrease in power output of approximately 0.64%.

For these reasons, many research works have been carried out on IAC (inlet air cooling) of gas turbines using several methods, such as evaporative, fogging, absorption and mechanical chillers.

Mohapatra and Sanjay [3] presented a comparison of the impact of two different methods of inlet air cooling (vapor compression and vapor absorption cooling). Vapor compression cooling improved the efficiency of the gas turbine cycle by 4.88% and work output by 14.77%, whereas vapor absorption cooling improved the efficiency by 9.47% and work output by 17.2%.

Shirazi et al. [4] presented a study of using ITES (ice thermal energy storage) system for gas turbine inlet air cooling. The study showed that the ITES system increased the power output by 11.63% and the exergetic efficiency of the system by 3.59%. The payback period was 4.72 years.

Alhazmy and Najjar [5] studied two inlet air cooling systems which are, cooling coils and water spray. The results showed that spray coolers are better than cooling coils as they have the ability of enhancing the power by 1–7% and improving the efficiency by 3%. However, spray coolers operate more efficiently during hot and dry climates. They can deliver air with 100% relative humidity which causes the air temperature to drop to wet bulb temperature.

Al-Ansary et al. [2] investigated the prospects of using a hybrid TIAC (turbine inlet air cooling) system which consists of mechanical chilling followed by evaporative cooling for a typical hot and dry region in the Saudi Arabia (KSA), near Riyadh city. The study showed that the TIAC systems are capable of boosting the

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Nomenclature

C	cost, $
Cp	specific heat at constant pressure, kJ/kgK
CWHRS	cascaded waste heat recovery system
EES	engineering equations solver
f	fuel-air ratio
GT	gas turbine
h	specific enthalpy, kJ/kg
HE	heat exchanger
h_f	specific enthalpy of saturated liquid, kJ/kg
h_{fg}	specific enthalpy of vaporization, kJ/kg
h_g	specific enthalpy of saturated vapor, kJ/kg
IAC	inlet air cooling
LP	low pressure
LMTD	log mean temperature difference
$\dot{m}$	mass flow rate, kg/s
$\dot{m}_g$	mass flow rate of exhaust gases, kg/s
$\dot{m}_{p1}$	mass flow rate of upper propane cycle, kg/s
$\dot{m}_{p2}$	mass flow rate of lower propane cycle, kg/s
ORC	Organic Rankine Cycle
P	pressure, kPa
P_g	saturation pressure of water, kPa
P_N	net power, kW
$\dot{Q}$	heat transfer rate, kW
r_1	compression ratio of the upper cycle
r_2	compression ratio of the lower cycle
r_w	back work ratio
SFC	specific fuel consumption, kg/kJ
T	temperature, °C
T_1	inlet temperature of expander 1
T_2	exit temperature of expander 1
T_{2x}	temperature of propane after mixing
T_3	inlet temperature of the pump
T_4	temperature at the exit of the pump
T_5	inlet temperature of expander 2
T_6	exit temperature of expander 2
T_7	inlet temperature of the compressor
T_8	exit temperature of the compressor
T_9	inlet air cooled temperature to the compressor of the gas turbine
T_{10}	inlet temperature of the combustion chamber
T_{11}	turbine inlet temperature
T_{hi}	exhaust temperature of the gas turbine
T_{13}	exit temperature of the first heat exchanger (HE1)
T_a	ambient air temperature
T_{wi}	water inlet temperature
T_{wo}	water exit temperature
TIT	turbine Inlet Temperature, °C
v	specific volume, m^3/kg
$\dot{W}$	power, kW
WHR	waste heat recovery

Greek letters

ΔP	pressure drop, kPa
γ	specific heat ratio
Δh_{cc}	specific enthalpy of combustion, kJ/kg
ε	effectiveness
η	efficiency
ϕ	relative humidity
ω	humidity ratio, kg_w/kg_a

Subscripts

a	air
amb	ambient
c	compressor
exp	expander
g	gas
h	hot
HE	heat exchanger
hi	outlet stream of exhaust gases from the GT-turbine
ho	oOutlet stream of exhaust gases from HE1
i	inlet
o	outlet, overall
p	pump
p	propane
pl	propane in lower cycle
pu	propane in upper cycle
t	turbine
w	water
wi-A	water inlet of stream A
wi-B	water inlet of stream B
wo-A	water outlet of stream A
wo-B	water outlet of stream B

power output of the gas turbine by 10% or more. Furthermore, using a hybrid system with cooling towers was the most attractive option.

Pyzik et al. [6] presented a study of the effect of inlet air cooling in Poland using evaporative cooling and cooling by chillers. The results showed that the advantages of inlet air cooling in present Polish conditions are insufficient when set against the investment cost involved.

Marzouk and Hanafi [7] presented an analysis for inlet air cooling of 264 MW gas turbine plant located in Korymat, southern Egypt using evaporative and chiller cooling. The total power gained by using chillers was 117,027 MWh with a payback period of 3.3 years, whereas for evaporative cooling, 86,118 MWh of power was gained with a payback period of 0.66 year.

In this work a propane refrigeration cycle was used. In this method propane was pressurized in a compressor driven by an expander which produces low enough temperature to cool the ambient air entering the gas turbine compressor as shown in the lower propane cycle in Fig. 1. Bled air from the GT compressor instead of propane in an expander [8].

In addition to IAC, WHR (waste heat recovery) has been utilized for boosting power by steam generation. One of the methods used for WHR is the ORC (organic Rankine cycle) which partially recovers the waste heat from the evaporator of ORC to generate power from the expander. Its two main advantages are the simplicity and the availability of its components. In such a system, the working fluid is an organic substance, better adapted than water for lower heat source temperatures [9].

Jubeh and Najjar [10] presented an analysis for a CCLC (cascading closed loop cycle) with WHR from a gas turbine. The results showed that using a cascaded WHR system with gas turbine exhaust increases the efficiency of an 18 MW engine by 30%.

Najjar [11] presented a study for WHR from a gas turbine using an ORC with different working fluids. The study showed that R22 gives the highest improvement in work and efficiency with an efficiency improvement of 54.21%, but R113 was the optimum choice