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Performance of humid air turbine with exhaust gas expanded to below ambient pressure based on microturbine

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ABSTRACT

A new type of HAT cycle comprising HAT and Inverted Brayton cycles, named BAHAT in this paper, is proposed to enhance the microturbine's performance. By adding an exhaust compressor after flue gas condenser, the gas expander expands to a pressure lower than ambient. Simulation and parameter optimization results show that the electricity efficiency and specific work of BAHAT are about 2 percentage points and 20% higher than that of HAT cycle respectively when turbine inlet temperature is 950 °C. The working pressure of aftercooler, humidifier and turbine hot section is only about 0.4 MPa though the optimal total pressure ratio is about 9–10. The drops of compression work and outlet water temperature of humidifier are considered the main factors to enhance BAHAT's efficiency. In addition, the exhaust compressor inlet gas temperature affects BAHAT's efficiency and water recovery ratio apparently. It is also shown that it is easy to achieve water self-support for BAHAT, mixing makeup water to the water loop before entering economizer shows the best thermodynamic performance, and air leakage to the bottom cycle influences both efficiency and water recovery ratio of BAHAT.

1. Introduction

Microturbines have come to play an important role in distributed energy systems due to its low environmental impact, compact size, multi-fuel capability and reduced O&M cost. But the low electrical efficiency, typically about 30% (LHV), is an important technical barrier to the implementation of microturbine competing to reciprocating internal combustion engine at equal power output [1–4]. To advance efficiency significantly beyond this level, say 40%, will require a substantial increase in turbine inlet temperature, this necessitating the use of ceramics in the hot-end components [5,6]. However, at present ceramic material technology is still in its infancy [6].

The efficiency of microturbine can also be augmented by humidifying the working fluid with heat recovery from microturbine exhaust. Two kinds of humidified microturbines, steam-injected cycles [7] and humid air turbine (HAT) or so called evaporative cycle [8,9], have been suggested. With steam injection, the electric efficiency of microturbine rises from 30.8% to 35.9% [7]. As to microturbine based HAT (mHAT), efficiency more than 40% was obtained in a future technology scenario even with a state-of-the-art turbine inlet temperature, 950 °C [8]. Due to the great potential of efficiency enhancement, a prototype machine for a next generation microturbine system incorporating a so called Advanced HAT (AHAT) cycle has been developed for laboratory evaluation in Hitachi Ltd. (design target of electrical output 150 kW, electrical efficiency 35% LHV) [10,11].

On the other hand, as an effective way for the simple cycle gas turbine performance enhancement, the Inverted Brayton cycle (IBC) gas turbine suggested by Frost et al. [12] has been reconsidered in the last years. By IBC, which is also named below ambient pressure discharge gas turbine (BAGT), the hot exhaust gas of gas turbine at ambient pressure is firstly expanded to below ambient pressure, then cooled and, finally, recompressed up to the ambient pressure [13]. In this process a net positive specific work can be obtained. To some extent, the IBC can be seen as an alternative to the conventional steam bottom cycle [14]. Up to present various configurations for both power production and cogeneration application have been proposed and studied [12–20]. The primary aims of these works are developing new bottom cycle arrangements and revealing the optimum operating parameters (particularly the optimum bottom cycle expansion pressures). In addition, employment of IBC at microturbine discharge is also investigated [21]. Anyhow they all reported a remarkable improvement in thermal efficiency.

In light of these works, we believe that the installation of an IBC as bottomer of a mHAT may represent a way to further increase the plant electric efficiency of a microturbine. This paper firstly proposes a new cycle configuration by integrating IBC with mHAT in which the exhaust gas of HAT is directly expanded to pressure below ambient (BAHAT). Then the performance of BAHAT cycle

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Nomenclature

AC	aftercooler
C	air compressor
CC	combustion chamber
c_{pa}	specific heat capacity of air (kJ/kg k)
c_{pg}	specific heat capacity of gas (kJ/kg k)
d	humid rate or water mass flow (kg H_2O/kg air)
EC	exhaust gas compressor
Eco	economizer
EX	expander or turbine
f	fuel to air ratio (kg fuel/kg air)
FGC	flue gas condenser
HD	humidifier
LHV	low heat value (kJ/kg)
m	mass flow (kg/s)
Q_f	fuel heat value, $Q_f = f \times$ LHV
Q_2	heat discharge to the environment
Recu	recuperater
T_3^*	turbine inlet temperature (K)
T_4^*	turbine outlet temperature (K)
T	temperature (K/°C)
ΔT	temperature difference (K/°C)
w	work based on 1 kg air
$\bar{w}$	work relative to per kJ fuel input

Greek symbols

λ	ratio of recovered water to added water
β	pressure ratio
η	efficiency
κ	ratio of specific heats

Subscripts

a	air
ap	approach
ex	exhaust gas
el	electrical
fp	friction and pumps
ge	generator
in	inlet
is	isentropic
mk	makeup water
out	outlet
pcs	power conversion system
rec	recovery
t	total
w	water

and the optimum operating parameters are studied. Finally, the effect of air leakage into the bottom cycle on the performance of BAHAT is investigated, and sensitivity analysis of some key parameters is conducted.

2. System configuration and thermodynamic analysis

2.1. System description

Fig. 1 shows the BAHAT cycle layout studied in this paper. The compressed air from compressor (C), after cooled in aftercooler (AC), is heated and humidified in the humidifier (HD), in which the flow rate is increased by water evaporation, and then passes through the recuperator where the saturated air is superheated by the hot gas from turbine before entering the combustor chamber (CC). After combustion with natural gas in CC, the flue gas expanded through the expander (EX) to below ambient pressure and passes hot-side of the recuperator (Recu), economizer 1 (Eco1) and Flue gas condenser 1 (FGC1) in turn. In FGC1, the flue gas is cooled to low temperature to recover some water and decrease the EC's work. Then, the flue gas is compressed to pressure slightly above the ambient by the exhaust compressor (EC) to overcome the pressure loss in Eco2, FGC2 and provide stack driven force to meet the diffusion of the emission. FGC2 is used to recover water further from the exhaust. The circulating water from the HD recovers heat in the flue gas in Eco1 and Eco2 and then humidifies the air in HD. The makeup water can be mixed within the water loop before entering economizer, before entering AC or after exiting HD, etc. In Fig. 1, the makeup water is mixed with the water from HD before entering Eco2.

As the basis for comparison, the performance of conventional HAT based on microturbine (Fig. 2) is also studied in the paper.

2.2. Thermodynamic analysis

The efficiency of the cycle can be calculated with Eq. (1).

$$\eta = \frac{w}{Q_f} = \frac{w_{EX} - w_C - w_{fp}}{Q_f} = \bar{w}_{EX} - \bar{w}_C - \bar{w}_{fp} \quad (1)$$

Generally speaking, the variations of fuel compression and pumps' works can be neglected. So the change of efficiency is decided by $\bar{w}_{EX} - \bar{w}_C$, i.e.

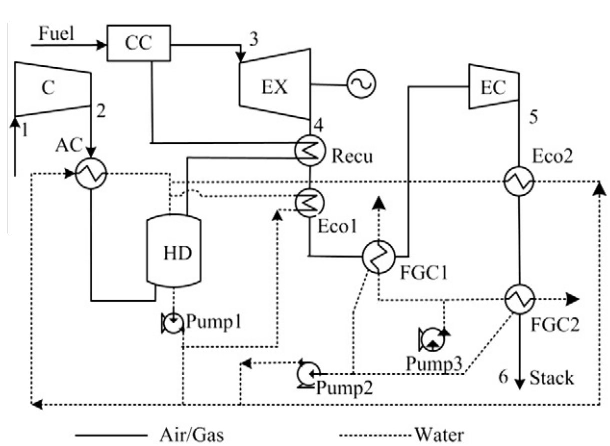

Fig. 1. Scheme of BAHAT cycle.

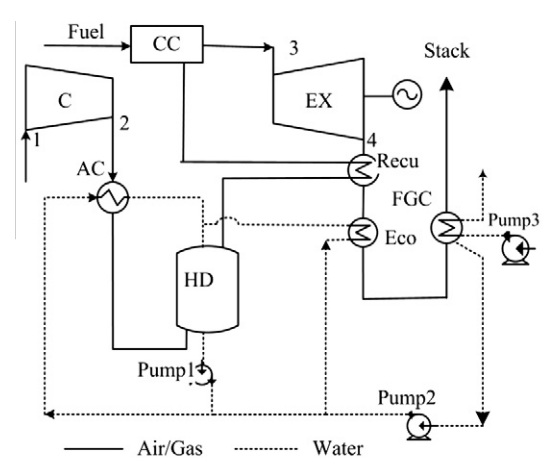

Fig. 2. Scheme of conventional HAT cycle.