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Research Paper

A compact packing humidifier for the micro humid air turbine cycle: Design method and experimental evaluation

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HIGHLIGHTS

- A compact humidifier with ceramic foam packing is designed and built.
- The performances of this humidifier are evaluated by experimental data.
- Both the steady state and dynamic performances are analyzed.
- This compact humidifier has a potential application in HAT cycle.

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ABSTRACT

The purpose of this research is to develop a compact humidifier with novel ceramic foam corrugated packing, which is conducive to the improvement of the flexibility of humid air turbine cycles, thus has a potential in commercial application. The packing size is calculated with an analytic model based on the Merkel theory and energy effectiveness-NTU function. The simplified structures of the air and water distributors are proposed according to the special characteristics of packing. The evaluation of this humidifier has been carried out by means of experimental data obtained from a mHAT system. Both the steady state performance at off-design conditions and dynamic behavior at start-up process are presented and analyzed. At nominal condition, the humidifier shows a pinch of 12 °C and a relatively pressure loss of 0.59% operating pressure. With the load decreasing from 100% to 50%, the inlet and outlet fluid temperature as well as the outlet air humid ratio will all decrease, but the maximum decrement is not more than 11%. Due to the great thermal capacitance, especially that of the water in its bottom section, a relative slow response of the humidifier has been observed.

1. Introduction

Over a long period of time, power generation technologies based on nature gas-fired gas turbines have received more attention for its compactness, flexibility, low maintenance cost and low emissions. Microturbines are very small gas turbines with outputs ranging from 30 kW to 300 kW [1]. They are considered to be promising for distributed generation and combined heat and power (CHP). However, the electric efficiency of them are still relatively low (<30%) for the low turbine inlet temperature (<900 °C), which causes a negative effect on theirs competitiveness to the internal combustion engines (ICE). A possible solution to this problem is to use more advanced cycles for the microturbines. According to Jonsson and Yan, the humid air turbine (HAT) cycle had the highest efficiency of all developed gas turbine cycles [4]. However, the HAT layout cannot be explained directly to a microturbines where the intercooling is not needed for the application of single-stage radial compressor, and then some modifications are required [5]. More recently, the thesis of optimal humidification route for microturbines is also discussed by Paepe et al. [6]. In past decade, converting the microturbine into micro humid air turbine (mHAT), by equipped with a water circuit and a humidifier to humidify the compressed air, had been experimentally verified by a few authors [7–9].

The humidifier is the key component in mHAT cycle as well as in HAT cycle. Several different types of devices have been proposed in the literature. Dalili and Westermark [10] designed a tubular humidifier which could humidify compressed air and recovery heat from the flue gas in one device. A no-packing humidifier using nozzles to inject water in the compressed air was investigated in

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Nomenclature

C	heat capacity rate ratio
C_p	specific heat at constant pressure ($kJ\cdot kg^{-1}\cdot K^{-1}$)
m	mass flow rate ($kg\cdot m^{-2}\cdot s^{-1}$)
h	specific enthalpy ($kJ\cdot kg^{-1}$)
H	enthalpy of fluid (kJ)
HTU	height of the gas-phase mass transfer unit (m)
M	molecular weight ($kg\cdot mol^{-1}$)
NTU	number of mass transfer unit
P	pressure
R	water/air mass flow ratio
T	temperature (°C)
x	humidity ratio ($kg\cdot kg^{-1}$ dry air)

Subscripts

a	air
da	dry air
i	inlet
id	ideal amount
o	outlet
v	vapor
w	water

Greek symbols

ε	energy based effectiveness

our early work [11]. The contact area was provided by the water droplets and the pressure drop could be decreased in this type of device [12]. More attention was paid to the humidifiers with the internal packing [13–15], which were most likely to be applied in commercial HAT package for the uniform air-water contact area and mature design method.

For the packing humidifier, the compactness is an extremely important factor as well as the pressure drop. As is generally known, increasing the gas-path pressure drop between the compressor and the turbine has a negative effect on the overall cycle efficiency [16]. However, few research results have been reported about introducing a large volume in this path-way on the cycle performance. According to several authors [17,18], the recuperator thermal capacitance plays a critical role in the transient behavior of microturbines. On the other hand, the volume capacitance can usually be ignored only when the gas turbines have relatively large volume [19]. However, introducing an additional volume to the microturbines indeed increases the risk of inducing compressor deep surge especially during the emergency shutdown [20] and has a impact on the transient behaviours of the system [21]. The humidifiers are distinguished by introducing water into the compressed air under the driving force of vapor pressure, so a large air-water contact area is needed. Compared to the recuperators, they have a significantly larger thermal and volume capacitance. The impact of a volume on the shutdown and the transient behavior of mHAT is discussed in Refs. [8,22]. Therefore, a compact humidifier is beneficial to the flexibility, safe operation and decreasing installation and management costs (small volume should not be treated as a pressure vessel) of the mHAT.

In our recent work, a ceramic foam corrugated packing is developed and its heat and mass transfer performance is proved to be superior to the traditional structured packing [23]. Based on this novel packing, a compact humidifier is designed for the micro humid air turbine in this research. The design method of the column size is developed from the Merkel theory and the energy effectiveness-NTU model [24]. The structures of the air and the water distributor are simplified thanks to the excellent dispersion and wettability characteristics of the packing. The performances of the humidifier are evaluated by the experiments, including the steady state performances at design and off-design conditions and the dynamic behaviors. This compact humidifier has a strong application potential in the commercial HAT cycle.

2. Design method

2.1. Simulation of the mHAT

In order to calculate the required sizes of the humidifier, it is necessary to provide the inlet and outlet conditions of the water and the air. These conditions strongly depend on the pressure ratio and the turbine inlet temperature of the gas turbine, that means the energy and mass balance of the whole cycle should be analyzed. In our previous research, a mHAT test facility was developed from a commercial recuperated microturbine (type TG80) made by Bowman [9]. TG80 is a natural gas fired- engine with a single-stage centrifugal compressor and single-stage radial inflow turbine. Under full load condition, its output power is 80 kW and electrical efficiency is 26%. In this system, the mHAT layout proposed in [5] was used. The thermodynamic and emission performances at full- and part- load were investigated at constant rotational speed, and the impact of a aftercooler on mHAT was also evaluated by experiments. The schematic of our mHAT is shown in Fig. 1. There is no intercooler and water recovery in this system. An air-bleed system is equipped after the compressor, i.e., a part of air will be discharged in mHAT operation to match the air flow between the compressor and the turbine. Moreover, an air bypass is provided for evaluating the part flow mHAT cycle performance.

The parameters used to analyze the mHAT system are shown in Table 1. For a given microturbine, an integrated humidification system will bring several additional variables. Some constraint conditions must be set to be able to manageably analyze the whole system. These are minimum approach temperature in heat exchangers, the inlet water temperature and the minimum difference between the air wet bulb temperature and the water temperature (also be known as the pinch) in the humidifier [25]. In this work, the inlet water temperature and the pinch are selected to

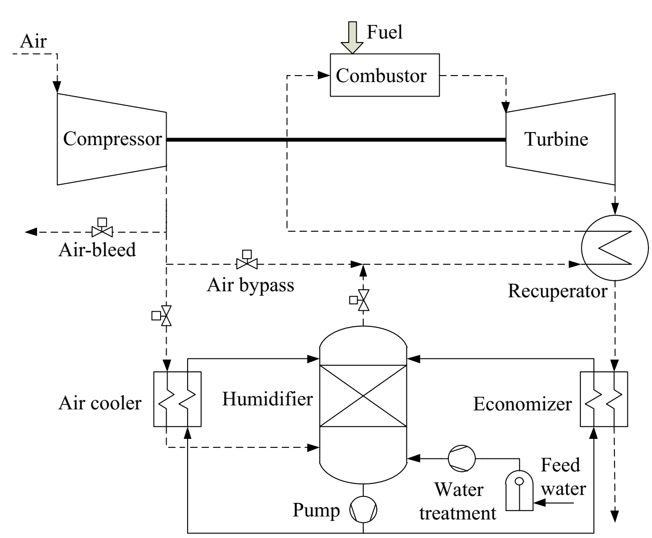

Fig. 1. Schematic of the mHAT based on a microturbine.