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Proposal and thermodynamic analysis of a combined open-cycle absorption heat pump and thermal desalination system driven by high-humidity exhaust gas

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ABSTRACT

A combined system based on an open-cycle absorption heat pump (OAHP) and a low-temperature multi-effect evaporation (LT-MEE) water desalination process is configured, modeled, and analyzed. The system is applicable to be run by high-humidity gases, and the flue gas from the combustion of natural gas is used here. Compared with conventional absorption heat pumps, the OAHP is characterized by a gas-solution direct-contact absorber, where not only the sensible heat but also the latent heat and water vapor in flue gas are partially recovered. The OAHP-MEE system has good internal synergy, as demonstrated by a 36%–74% water production gain over the simple system when driven by flue gas with temperature of 120 °C–250 °C. With the increase of the feed-gas temperature, the combined system becomes increasingly favorable over the simple system in energy utilization and water production. For a specified feed gas condition, an optimal water recovery rate of OAHP and a maximum number of effects of MEE exist, mutually leading to a maximum water output. Using a cooler to cool the strong solution entering the absorber not only has a favorable effect on water production, but also widens the parameters' ranges, thus offering good flexibility for design and operation.

1. Introduction

According to the BP Statistical Review of World Energy [1], the global natural gas consumption reached 3542.9 billion cubic meters in 2016, accounting for 24.1% of the total primary energy consumption. Since natural gas is composed mainly of hydrocarbons, especially methane, its combustion products contain much water vapor and thus carry a large amount of latent heat. The latent heat is estimated to be about 10% [2,3] of the higher heating value of natural gas, so utilizing it efficiently is of great importance for energy conservation. The problem is that the energy level of the latent heat is usually too low to provide useful heat output through the conventional condensing method [3,4]. For example, the natural gas [5] exhaust under 10% excess air has a dew-point temperature of 57.2 °C, which releases 33.5% of latent heat (condensation heat) within 50 °C–57.2 °C, 28.8% within 40 °C–50 °C and 37.7% below 40 °C; considering the temperature difference between the exhaust gas and the fluid being heated during the heat recovery process, the amount of latent heat that can be recovered is very limited, and the temperature of the heated fluid is low, say 45 °C or lower. Clearly, more effective methods are needed for better utilization of the latent heat.

Open-cycle heat pump (OAHP) [3,4,6–14] has been considered to be a more effective way of recovering the latent heat of high-humidity gases like the natural gas exhaust than the conventional condensing method. OAHP is an absorption-based heat pump (AHP). At first glance, it seems like a conventional Type II AHP (i.e. heat transformer), as shown in Fig. 1, but in fact it is very different. Firstly, no evaporator is included in an OAHP. The water vapor absorbed in the absorber is from the humid gas, and not an evaporator as in a conventional AHP. Secondly, and more importantly, the absorber used in OAHP is a gas-solution direct-contact absorber, where the humid gas comes into direct contact with some kind of water-absorbing solution, typically LiBr-H_2O [3,12,14], $CaCl_2$-H_2O [6,8,10,11] or LiCl-H_2O [4,9] solution. Driven by the vapor pressure difference between the gas and the solution, part of the water vapor in the gas is absorbed and the latent heat is recovered at a temperature higher than the dew point of the gas, thus overcoming the limitation of the conventional condensing method [3,4] in which the condensation of water vapor occurs only when the gas temperature

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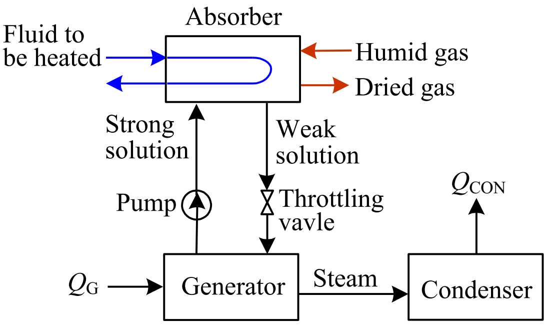
Nomenclature

h	Specific enthalpy [kJ/kg]
H	Enthalpy [kJ]
m	Mass flow rate [kg/s]
m_w	Mass flow of fresh water produced by OAHP-MEE [kg/s]
$m_{w\mathrm{MEE}}$	Mass flow of fresh water produced by MEE [kg/s]
m_{wrec}	Mass flow of fresh water recovered from flue gas [kg/s]
n	Number of effects of MEE
p	Pressure [kPa]
p_v	Partial pressure of water vapor [kPa]
PR	Performance ratio of MEE
q_w	Specific heat consumption of water production [kJ/kg]
Q	Thermal energy; heat load [kW]
Q_{in}	Thermal energy input to OAHP by flue gas [kW]
Q_0	Thermal energy released from flue gas to the surroundings [kW]
R	Water recovery rate of OAHP from flue gas [%]
R_{wg}	Water-to-gas ratio [kg water/kg gas]
T	Temperature [°C]
TBT	Top brine temperature [°C]
T_{hs}	Saturation temperature of heating steam for MEE [°C]
v	Specific volume [m^3/kg]
W_{P}	Pumping work [kW]
x	Mass concentration of LiBr-H_2O solution [%]
α	Percentage of excess air in combustion [%]
ω	Specific humidity of flue gas [g water vapor/kg dry flue gas]
η	Heat recovery efficiency[%]
η_{P}	Adiabatic efficiency of pump [%]

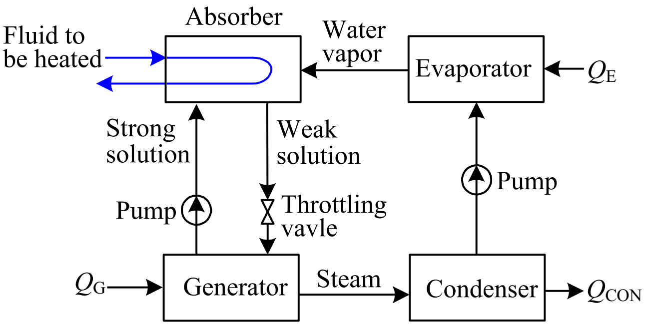
Abbreviations and subscripts

A	Absorber
AHP	Absorption heat pump
AR	Absorption refrigerator
C	Water cooler
CON	Condenser
d	Dry flue gas
dp	Dew point
f	Flue gas
E	Evaporator
G	Generator
HRSG	Heat recovery steam generator
l	Liquid water
LT-MEE	Low temperature multi-effect evaporation
max	Maximum
MEE	Multi-effect evaporation
MSF	Multi-stage flash
OAHP	Open-cycle absorption heat pump
opt	Optimal
RO	Reverse osmosis
SH	Solution heat exchanger
v	Water vapor present in flue gas
I	MEE I
II	MEE II
0	Ambient conditions
1, 2, …	States on the system flow sheet

is lower than the dew point. The diluted solution from the absorber, as done in a conventional AHP, is introduced into a generator where it is heated and then regenerated, and the steam produced is condensed in a condenser.



(a) The OAHP system



(b) The conventional AHP system (Type II)

Fig. 1. Principles of OAHP and conventional AHP (Type II) using water as the refrigerant.

Lazzarin et al. [3] may be the earliest ones who considered using OAHP in flue gas heat recovery. A case study [3] on a natural gas boiler showed that, by using OAHP, the lower-heating-value based efficiency of the boiler reached 103%–106%, which was difficult to achieve by condensing boilers. Riffat et al. [4] studied the technical feasibility, energy utilization and life-cycle cost of using OAHP for waste heat recovery of boilers, concluding that OAHP-combined systems had both energy and economy benefits over condensing heat recovery systems. Wei [6] studied theoretically the thermal performance and off-design performance of a $CaCl_2$-H_2O OAHP system, tested experimentally the performance of the absorber and generator, and proposed and modeled the configurations integrating OAHPs with humid air turbine (HAT) cycles. A case study showed that the heat recovered by OAHP was 1.6 times and the water recovered was 7.3 times higher than the conventional condensing system. In the experiment on absorber, 65.9% of water vapor in the moist gas with a specific humidity of 0.111 kg/kg and temperature of 60 °C was recovered, and simultaneously the cooling water was heated from 16 °C to 52 °C. Westerlund et al. [7] investigated experimentally the performance of an OAHP system used for both heat recovery and particle reduction of the flue gas from a biomass fired boiler, obtaining a 33%–40% reduction in particles and a 40% increase in heat production compared with an ordinary system. Experiments were carried out by Feng [8] on a high-gravity rotation-type packed absorber, and the results showed that suitable operating parameters (1.0–1.6 for solution-gas ratio and 150 for high-gravity factor in the experiments) could lead to efficient heat recovery and particle reduction simultaneously. Using LiCl as the absorbent, Song [9] studied an adiabatic counter-flow packed absorber, and predicted a payback period of 3 years when using OAHP in a 2-ton natural gas boiler. Wei et al. [10] modeled and analyzed a $CaCl_2$-H_2O OAHP system for a natural gas boiler, and made a comparison between the OAHP and two other heat recovery systems—one based on a conventional AHP and the other on an electric compression heat pump. The results