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Experimental and theoretical investigation of a novel full-open absorption heat pump applied to district heating by recovering waste heat of flue gas

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ABSTRACT

The industrial exhaust flue gas contains tremendous waste heat that cannot be efficiently recovered by conventional condensing heat exchanger. This paper proposes a novel full-open absorption heat pump for the total heat recovery of flue gas. The recovered heat is used for district heating. By applying direct-contact heat and mass transfer without solid transfer interfaces, the novel system can save considerable metallic tube or plate materials and therefore the initial investment can be reduced substantially. A prototype full-open absorption heat pump is developed and tested, achieving the *COP* (coefficient of performance) of 1.621 and the exit flue gas dew point of 36.2 °C at most. A detailed theoretical model in Eulerian–Lagrangian formulation is established, involving in conjugate heat and mass transfer and particle dynamics. The numerical simulation agrees well with the experiment results. On the basis of the validated model, three critical parameters, including excess air coefficient of the burner, moisture content of the objective flue gas and return water temperature of the district heating network, are selected to study their effects on system performances. As a controlled variable, especially, the excess air coefficient plays an important role by influencing the regeneration of the liquid absorbent in the generator. The full-open absorption heat pump outperforms the condensing heat exchanger by 19.7–178.1% in heat recovery capacity as the return water temperature increases from 40 to 55 °C.

1. Introduction

In China, more than 75% of power generation is contributed by coal-fired plants [1]. It is not realistic to replace them all by clean energy in the short term. The urgent matter is to deeply utilize the energy of the current energy systems by recovering the waste heat so as to reduce the coal consumption and CO_2 emission. In coal-fired plants, the annual waste heat exhausted along with the flue gas accounts for 50–80% of the thermal loss of coal-fired boilers and 3–8% of the global energy input of coal-fired plants, equivalent to 70 million tons of standard coal [2]. In addition to the waste heat exhausted by other industries such as lumber, metallurgy and petrochemicals, etc., it will be a great energy saving if the waste heat of the flue gas is recovered efficiently. The recovered heat can be supplied to district heating network (DHN).

The most common waste heat recovery is achieved by condensing heat exchanger (CHX) with available cooling sources (e.g. boiler return water and boiler fresh air) [3]. CHX has many types, including plate type [4], shell-and-tube type [5] and heat pipe [6], etc. Unfortunately, an unavoidable disadvantage of CHX is its strong dependence on the temperature of the cooling source. The latent heat, which usually accounts for the majority of the total heat, can be recovered only when the coolant temperature is lower than the dew point of the flue gas. Taking a common moisture content of 0.11 kg/kg for example, the dew point is 57.5 °C, quite close to the return temperature of the DHN water (45–70 °C usually); that is to say, there is no enough recovery margin for CHX.

In order to recover both the sensible and latent heat more efficiently, one alternative is to decrease the coolant temperature below the dew point of the flue gas. According to the second law of thermodynamics, extra energy input such as electricity and heat has to be paid. Either compression heat pump (CHP) or absorption heat pump (AHP) can produce low-temperature coolant. In any case, the coolant needs to cool the flue gas in CHX finally [7].

Considering the acid components in flue gas and the moisture condensation, the corrosion is a critical problem for the commonly-used metal heat exchanger. Nonmetal heat exchanger (e.g. ceramic [8] and plastic [9]) is an alternative. However, it is economically too expensive [3], especially when the desired area is big due to its low thermal conductivity.

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Nomenclature

A	heat and mass transfer area (m^2)
A_f	frontal area (m^2)
c	moisture content in gas (kg/kg overall gas); concentration of solution (kg/kg)
C_D	drag coefficient
COP	coefficient of performance
c_p	specific heat (J/kg K)
d	diameter (m)
D_v	vapor diffusivity (m^2/s)
ex	specific exergy (J/kg)
Ex	exergy (W)
g	gravitational acceleration (m/s^2)
G	volumetric flow rate (m^3/s)
h	heat transfer coefficient (W/m^2 K)
HHV	higher heating value of fuel (J/Nm^3)
J	mass transfer rate (kg/s)
k	mass transfer coefficient (m/s)
LHV	lower heating value of fuel (J/Nm^3)
$\dot{m}$	mass flow rate (kg/s)
M	molar mass (kg/mol)
Nu	Nusselt number
p	pressure (Pa)
Pr	Prandtl number
Q	heat transfer rate (W)
r	latent (J/kg); r-axial coordinate (m)
R	gas constant (J/mol K)
Re	Reynolds number
RH	relative humidity (%)
s	specific entropy (J/kg K)
Sc	Schmidt number
Sh	Sherwood number
t	temperature in Celsius (°C)
T	temperature in Kelvin (K)
t_d	dew point temperature (°C)
u	velocity (m/s)
x	x-axial coordinate (m)
y	y-axial coordinate (m)
z	z-axial coordinate (m)

Greek symbols

α	vertical angle (°)
β	angle of relative velocity (°)
ε	exergetic efficiency
ζ	specific enthalpy (J/kg)
η	recovery efficiency
θ	horizontal angle (°)
λ	thermal conductivity (W/m K)
ρ	density (kg/m^3)
τ	time (s)
ω	humidity ratio (kg/kg dry air)

Subscripts

0	initial state; reference state
1	gas phase
2	liquid phase
dhn	district heating network
dis	discharge
env	environment
fg	flue gas
lb	LiBr solution
ng	natural gas
p	particle
r	r-axis
rec	recovery
rel	relative
ret	return
s	sensible heat
sup	supply
w	water
v	water vapor
z	z-axis

Direct-contact heat and mass transfer provides another option for total heat recovery. Kuck improved the condensing boiler with a spray recovery system [10]. The sprayed water absorbed the total heat from the boiler exhaust flue gas in a spray tower and then released the heat and moisture to the boiler fresh air in the other spray tower. Essentially, the fresh air is pre-heated and pre-humidified by the exhaust flue gas indirectly via the water, so the fuel consumption decreased, and meanwhile the moisture content of the exhaust flue gas increased. The humidified flue gas could be recovered more easily by the boiler return water, promoting the boiler efficiency.

In recent years, a new system integrating heat pump and direct-contact heat recovery has been developed and applied. Refrigerated by CHP [11] or AHP [12], the cooling water is sprayed into the spray tower to absorb the total heat directly from the flue gas without any barriers. The recovered heat, together with the energy input of the heat pump, is used to heat the boiler return water via condenser (as well as absorber for AHP-based system). Compared with CHX which consumes abundant materials, the void spray tower without heat transfer tubes is much cheaper.

Though, the water spray recovery system assisted by heat pump has the same shortcoming as the indirect-contact CHX. Because the discharge flue gas is almost saturated, there is still corrosion risk. The only solution is to employ absorbent. The absorbent can dehumidify the flue gas to an extremely dry state; that is to say, the flue gas can be processed far from the saturation state. Besides, the low temperature requirement of absorbent is not as strict as cooling water. Even if the absorbent temperature exceeds the flue gas dew point, the latent heat recovery is possible all the same as long as the equilibrium pressure of the absorbent is below the water vapor partial pressure of the flue gas.

Just an absorber is not enough for sustainable recovery. A generator is essential to regenerate the absorbent. The generated water vapor needs to be condensed, so a condenser is also needed. Thus, a complete absorption recovery system is comprised by an absorber, a generator and a condenser basically. At least the absorber is operated in direct contact with the external flue gas under atmospheric pressure, so this new system is named open-cycle absorption heat pump (OAHP) to distinguish it from the conventional closed-cycle absorption heat pump (CAHP). Different from CAHP, the external flue gas provides the water vapor for the absorber, so the evaporator is not needed in OAHP. It should be noted that there is another type of OAHP applied to cooling, which includes evaporator rather than condenser [13].

Lazzarin et al. applied a packed absorber to recover the heat of boiler exhaust flue gas by spraying LiBr solution [14]. The diluted solution was regenerated by a burner in a direct-fired generator. Then the concentrated solution was pumped into the absorber to recover the boiler flue gas as well as the burner flue gas. The generated water vapor from the generator is condensed by boiler return water in a condenser. The flue gas was dehumidified to 10–20% RH (relative humidity), far from the dewing deadline. The efficiency in terms of gross calorific value (e.g. higher heating value) reached 0.93–0.96, while in terms of net calorific value (e.g. lower