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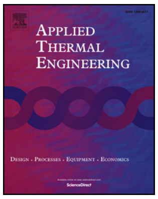

Research Paper

Conjugate heat and mass transfer study of a new open-cycle absorption heat pump applied to total heat recovery of flue gas

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HIGHLIGHTS

- A new open-cycle absorption heat pump is proposed to recover total heat of flue gas.
- A simulation work is conducted to investigate the conjugate heat and mass transfer.
- The system achieves good recovery capacity even at high cooling medium temperature.

ARTICLE INFO

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Flue gas
Open-cycle absorption heat pump
Total heat recovery
Eulerian-Lagrangian
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ABSTRACT

Industrial exhaust flue gas contains massive heat and water. Effective recovery will make positive sense for energy saving and conservation. Traditional condensing heat exchanger is restricted by coolant water temperature and corrosion problem. This paper proposes a new open absorption heat pump (OAHP). The system works on the basis of directly contacting spray heat and mass transfer occurring in three main parts, including generator, condenser and absorber. Driven by high-temperature flue gas directly from a burner, the system generates strongly concentrated LiBr solution prepared for the absorption of moisture and heat from the objective flue gas. A detailed theoretical model is established in Eulerian-Lagrangian formulation to simulate the particle dynamics and the heat and mass transfer characteristics. Extraordinary temperature profiles different from those in common heat transfer are found in the generator and are explained by the conjugate heat and mass transfer. The effects of the driving flue gas temperature and the return water temperature on system performances are studied. The OAHP system achieves excellent heat recovery capacity even at high return water temperature, indicating superiority to the condensing heat exchanger.

0. Introduction

Industrial combustion processes produce plenty of flue gas at high temperature and humidity, which contains considerable sensible and latent heat, known as waste heat. Taking the typical coal-fired boilers for example, the thermal energy contained by the exhaust flue gas accounts for 3–8% of the total energy input [1]. In China, it is estimated that the amount of water vapor brought by the exhaust flue gas reaches as high as 1.01 billion tons per year [2]. Obviously, it will be a huge waste of energy and water to discharge the heat and moisture directly into the atmosphere. Besides, the emissions of heat and moisture may lead to the humidity promotion in local regions, which does favor to the creating of haze [3,4]. As seen, the waste heat recovery of flue gas is now a critical issue referring to energy saving and conservation.

Condensing heat exchanger is the most traditional and common waste heat recovery technique, by which the flue gas is cooled below the dew point. In coal-fired power plants, low-temperature economizer (LTE), also called low-pressure economizer (LPE), is widely utilized as the low-temperature recuperative heater [5,6]. The boiler exhaust flue gas heats the feed water instead of a portion of extraction steam so that the turbine work can be promoted. Kilkovsky et al. compared various types of metallic heat exchangers used for the high-temperature heat recovery from boiler flue gas, who also mentioned some critical problems such as fouling and flow uniformity [7].

However, the total heat recovery capacity of the condensing heat exchanger strongly depends on coolant water temperature. If there is no cold enough coolant water, this method may be not applicable. In addition, the flue gas will reach or approach saturation after being processed, so the corrosion is a fatal problem, especially considering that the flue gas contains acid components [8–10]. For the corrosion-resistant nature, the ceramic heat exchanger is an alternative [11]. However, it is economically too expensive [7].

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Nomenclature

A	heat and mass transfer area (m^2)
c	water content in gas (kg/kg), 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)
g	gravitational acceleration (m/s^2)
G	volumetric flow rate (m^3/s)
h	heat transfer coefficient (W/m^2 K)
HA	heat transfer coefficient by area (W/K)
J	mass transfer rate (kg/s)
k	mass transfer coefficient (m/s)
KA	mass transfer coefficient by area (m^3/s)
L	spray tower height (m)
m	mass (kg)
$\dot{m}$	mass flow rate (kg/s)
M	molar mass (kg/mol)
n_p	particle amount in control volume
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), spray tower radius (m)
Re	Reynolds number
RH	relative humidity (%)
Sc	Schmidt number
Sh	Sherwood number
t	temperature (°C)
u	velocity (m/s)
WR	water recovery (kg/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 (°)
η	recovery efficiency
θ	horizontal angle (°)
λ	thermal conductivity (W/m K)
ρ	density (kg/m^3)
τ	time (s)

Subscripts

0	reference state
1	gas phase
2	liquid phase
CV	caloric value
env	environment
p	particle
r	*r*-axis
rec	recovery
rel	relative
sup	supply
v	vapor
z	*z*-axis

Abbreviations

ABS	absorber
CON	condenser
DFG	driving flue gas
GEN	generator
RFG	recovered flue gas
RW	return water
SSHX	solution-to-solution heat exchanger
SWHX	solution-to-water heat exchanger
WWHX	water-to-water heat exchanger

In the past decades, the promising membrane separation technology attracts more and more attentions and is widely applied to total heat recovery in HVAC (heating, ventilation and air conditioning) fields [12,13]. Recently, membrane applications in flue gas waste heat recovery have been also reported. The total heat is recovered by using selective membrane materials like nanoporous ceramic membranes [2,14,15] and dense polymer membranes [16,17], which allow water vapor to permeate only but block other non-condensable components. The main advantage of the membrane method is that it is not necessary to cool the gas below the dew point. The moisture is transferred simultaneously with the sensible heat, driven by mass transfer potential such as partial pressure difference.

The aforementioned technologies are based on non-directly contacting heat and mass transfer. Restricted by the inferior heat and mass transfer performance of gas side, whatever the solid-interface heat exchanger (metallic and ceramic) or the porous-interface membrane total heat exchanger, the heat recovery facility has to arrange a great amount of tubes or plates to obtain a considerable heat and mass transfer area and therefore achieve a considerable transfer capacity, which results in an expensive initial investment cost. In addition, the small or even micro sized flow channels may be blocked because of the corrosion and fouling.

Comparatively, the directly contacting spray method scatters the liquid phase as abundant tiny particles to obtain a considerable contacting area with the gas phase. Moreover, the submillimeter-scale hydraulic diameter (i.e. liquid particle diameter) remarkably promotes the heat and mass transfer. The material consumption and manufacture period will be reduced substantially, leading to a much lower investment cost.

Thanks to the highly hygroscopic nature of aqueous absorbent, open-cycle absorption heat pump (OAHP) is an alternative for the total heat recovery. Compared with the conventional close-cycle absorption heat pump (CAHP), there is no limitation that the evaporating temperature must be lower than the dew point of the recovered gas. Also different from CAHP, one of the condenser and evaporator is eliminated in OAHP, depending on whether the system is used for cooling or heating.

Earlier OAHP systems, generally driven by solar thermal energy, were focused on cooling application in HVAC fields, such as the cooling and dehumidification of fresh air [18–20] and the producing of low-temperature water [21,22].

As the mainly concerned heating application of OAHP in this paper, a successful practical case aimed at the timber drying in Swedish sawmills has been reported continuously for years [23–26]. Containing heat and moisture after drying process, the exhaust moist air was recovered by the OAHP, and the dry product air from the absorber returned to the timber dryer. Recently, the biomass boiler exhaust flue gas was also selected as the recovery objective [24]. By applying the OAHP technique, the energy consumption was reduced substantially; that is to say, with the same fuel consumption, the heat production of