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Investigation of direct contact condensation for wet flue-gas waste heat recovery using Organic Rankine Cycle

Samer Maalouf *, Elias Boulawz Ksayer, Denis Clodic

Ecole des Mines de Paris, CES, 5 rue Léon Blum, Palaiseau, France

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ABSTRACT

Low-temperature flue gases (<120 °C) exiting industrial processes could be recovered for electricity generation and constitute an effective mean to reduce primary energy consumption and carbon dioxide emissions. In the wet flue gases, substantial heat can be recovered if water vapor contained in the gases is condensed. Technical options include indirect contact water vapor condensation recovery, where heat is transferred between the two fluids (typically flue gases and working fluid) using an intervening wall (typically fin-and-tube heat exchanger) and direct contact water vapor condensation recovery, which involves direct mixing between flue gases and cooling fluid (typically water) through a condensing unit. In this paper, the two recovery processes are investigated using ORC (Organic Rankine Cycle). While the indirect contact condensation is the most favorable heat recovery scheme concerning the net output power, the direct contact heat exchanger has received attention because there are no heat-transfer surfaces exposed to corrosion. In a direct contact water–vapor condensation, the inlet flue-gas wet-bulb temperature determines the operating temperature levels throughout the system and limits the circulating water temperature. The maximal net turbine power for the direct contact system is reached for a final water temperature nearby the entering wet bulb temperature of the flue gases. The temperature pinch is as low as 0.5 K, which is possible with a direct contact heat exchanger.

1. Introduction

Nowadays, more and more attention has been paid to the utilization of low-temperature flue gases (<120 °C) released from several industry sectors (cement, steel, refineries), for its potential in reducing fossil fuel consumption and alleviating environmental problems. Organic Rankine Cycle (ORC) is proposed to recover low-grade energy and transform it into power. It is a proven technology, which allows the generation of electricity from low-temperature heat sources in a far more efficient way than conventional steam cycles [1,2].

Much industrial flue gases may contain significant amount of moisture in vapor form (wet flue gases) due to many reasons such as flashing, washing, cleaning, and drying. The water dew point temperature of these flue gases could range between 55 °C and 65 °C. Therefore, a considerable amount of heat is available in the form of latent heat of water vapor in these gases and cannot be recovered if flue gases are not cooled down to temperatures lower than the flue-gas dew point. The recovery of this large amount of heat improves the overall efficiency of the recovery system [3].

An important factor influencing latent heat recovery is the corrosion problem associated to the cooling when flue gases contain sulfuric oxides (SO_x), nitric oxides (NO_x), and hydrochloric acid (HCl). However, many recovery technologies are already well developed and technically proven. Options include indirect contact condensation recovery and direct contact condensation recovery [3]. In an indirect contact condenser, the heat is transferred between the two fluids (typically flue gases and working fluid) using an intervening wall (typically fin-and-tube heat exchanger). In this case, the heat-exchanger design requires using advanced materials such as "Teflon" or equivalent coating to withstand exposure to corrosion problems. In a direct contact condenser, heat is transferred between the two fluids (typically gas and water) without an intervening wall thus there are no heat-transfer surfaces exposed to corrosion, clogging, and fouling. The two fluids move in a counter-flow direction, with one of them dispersed as small particles in a vertical column.

Many investigations were carried out about low-grade heat recovery using ORC. Comprehensive researches on appropriate working fluids for low-temperature applications have been investigated by many authors such as [4–6]. Others researchers have

* Corresponding author.
E-mail addresses: samer.maalouf@mines-paristech.fr (S. Maalouf), elias.boulawz_ksayer@mines-paristech.fr (E. Boulawz Ksayer), denis.clodic@mines-paristech.fr (D. Clodic).

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Nomenclature

CU	condensing unit
h	mass enthalpy (kJ/kg)
h_g	mass enthalpy of flue gases (kJ/kg$_{dg}$)
h_{dg}	mass enthalpy of dry flue gases (kJ/kg$_{dg}$)
h_{wv}	mass enthalpy of water vapor (kJ/kg$_{wv}$)
HEX	heat exchanger
I	irreversibility (kJ/kg)
m	mass flow rate (kg/s)
M_{dg}	molar mass of dry gases (kg/kmol)
M_{wv}	molar mass of water vapor (kg/kmol)
ORC	Organic Rankine Cycle
P_t	total pressure (Pa)
P_w	water vapor pressure (Pa)
Q	heat capacity (kJ/kg$_{dg}$)
s	mass entropy (kJ/kg K)
SC	sub-cooling (K)
T	temperature (°C)
w	humidity ratio (kg$_{wv}$/kg$_{dg}$)
W	power (kJ/kg$_{dg}$)
y	mass fraction

Greek symbols

η	efficiency (%)

Subscripts

cond	condensation/condenser
dg	dry gases
dp	dew point
evap	evaporation
fg	flue gases
i	components
is	isentropic
o	ambient conditions
r	working fluid
wb	wet bulb
wf	working fluid
wv	water vapor

focused on the parametric optimization and performance analysis of the ORC like [7–10]. However, these studies deal with the indirect contact condensation recovery based on sensible heat extraction from flue gases with low moisture contents, or even though, with high moisture contents [11], but cooling the gases to a minimum safe temperature in order to prevent water vapor condensation and acid formation during gas flow. The originality of this study is to extend the ORC applications to low-grade gas heat sources with high moisture contents by pointing out the effect of water vapor condensation on cycle performance using the two condensing heat recovery processes (direct and indirect heat exchange).

2. Heat load availability

In the wet flue gases, heat is available in both sensible and latent forms. The sensible heat is determined by the temperature of the flue gases and the combined heating capacities of its constituents. The latent heat is determined by the amount of water present in the flue gases in gas form [4].

The characteristics of the flue gases used in this study are tabulated in Table 1. The flue gases to be cooled are considered a mixture of water vapor (H_2O), nitrogen (N_2), oxygen (O_2), and carbon dioxide (CO_2). The CO_2 and O_2 compositions correspond to those at the "Raw Mill" exhaust in the cement plants. The water dew point is varied between 55 and 65 °C.

The enthalpy of a mixture of gases is equal to the sum of the individual partial enthalpies of the components [12]. Therefore, the mass enthalpy of flue gases can be written as follows:

$$h_g(T) = h_{dg}(T) + w \cdot h_{wv}(T) = \left(y_{O_2} h_{O_2}(T) + y_{CO_2} h_{CO_2}(T) + y_{N_2} h_{N_2}(T)\right) + w \cdot h_{wv}(T) \quad (1)$$

$$y_{O_2} + y_{CO_2} + y_{N_2} = 1 \quad (2)$$

Table 1
Flue-gas characteristics.

Composition	Molar basis	CO_2 – 15.5%, O_2 – 6.8%
Inlet temperature	T_{inlet}	120 °C
Water dew point temperatures	T_{dp}	55/60/65 °C
Corresponding wet bulb temperatures	T_{wb}	59.9/63.7/67.8 °C

where subscript "g" denotes gas, "dg" denotes dry gases, "wv" denotes water vapor, "T" is the temperature of the mixture, "w" is the humidity ratio, "y" is the dry mass fraction, and "h" represents the mass enthalpy. The mass enthalpies of the different components (O_2, CO_2, N_2 and H_2O) are calculated at the corresponding partial pressures.

The humidity ratio is calculated by:

$$w = \frac{M_{wv}}{M_{dg}} \cdot \frac{P_w}{P_t - P_w} \quad (3)$$

where "M_{wv}" and "M_{dg}" are the molar masses of the water vapor and dry gases respectively, "P_w" is the partial pressure of water vapor, and "P_t" is the total pressure.

The thermodynamic data of gases adopted in the present work are calculated using REFPROP 9.0 [13]. The ambient pressure and temperature at the specified dead reference state (P_o and T_o) are considered to be atmospheric pressure and 20 °C.

The characterization of the temperature and the available quantity of heat referred to the ambient temperature are presented in Fig. 1. The sudden breaks in slope indicate initial water dew points.

Water vapor in the flue gases is in superheated state above the initial water dew points. The cooling first reaches the initial water dew points at which condensation begins. The partial pressure of water vapor decreases continually and accompanied by a reduction in water dew point. Sensible heat recovery occurs down to water dew points. Cooling below this level increases the energy recovery rate by recovery of the latent heat.

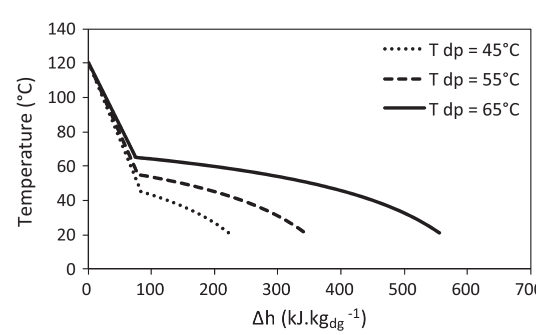

Fig. 1. Heat load availability.

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