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Research Paper

Entransy analysis on boiler air pre-heater with multi-stage LHS unit

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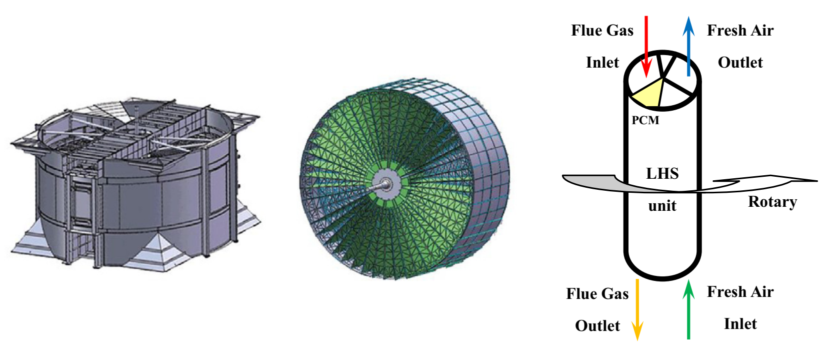
HIGHLIGHTS

- Optimum melting temperature match in air pre-heater with multi-stage LHS unit is derived with entransy analysis.
- Entransy dissipation rate in air pre-heater with LHS unit is discussed and compared with that in the case of SHS unit.
- It is concluded that air pre-heater with multi-stage LHS unit is favored, from the viewpoint of entransy analysis.
- Entransy dissipation is always reduced in the case of multi-stage LHS unit, constraining heat storage amount the same.

GRAPHICAL ABSTRACT

Sketch of rotary air pre-heater (with LHS unit). Rotary boiler air pre-heater with multi-stage LHS unit is investigated with entransy analysis. The optimum melting temperature match is derived. Entransy dissipation in the case of LHS and SHS unit is compared. It is concluded that air pre-heater with multi-stage LHS unit is favored for recovery of waste heat in flue gas, from the viewpoint of entransy analysis.



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ABSTRACT

Boiler air pre-heater with multi-stage LHS unit is investigated with entransy analysis. Optimum melting temperature match is derived. It is concluded that optimum melting temperature decreases alongside flow direction of flue gas. Optimum melting temperature at inlet increases with stage number, while that at outlet decreases. Temperature difference of PCMs in two nearby portions is the same but decreases with stage number. Entransy dissipation in LHS unit is compared with that in LHS unit. It is concluded that normalized entransy dissipation is not always reduced in LHS unit in the whole period, due to the decrease of heat transfer rate in SHS unit. However, entransy dissipation is always reduced in LHS unit, except single-stage unit, when heat storage amount is constrained. Reduction degree increases with stage number. Therefore, air pre-heater with multi-stage LHS unit is favored for recovery of waste heat in flue gas and improvement of boiler efficiency.

1. Introduction

Boiler is a common device for heat generation in industry. Chemical energy in fuel is partially transformed into thermal power in steam or hot water, as shown in Fig. 1. The ratio of thermal power output over chemical energy input is defined as boiler efficiency.

To improve boiler efficiency, waste heat in flue gas should be recovered as much as possible [1–3]. However, exhausted flue gas temperature could not be lower too much. For example, in the case of boiler generating steam at 1.6 MPa, the saturated steam

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Nomenclature

A_i	area for convective heat transfer in *i*th portion, m^2
A_0	area for convective heat transfer in air pre-heater, m^2
c	coefficient for heat transfer in portion
c_0	coefficient for heat transfer in air pre-heater
C_p	thermal capacity, $J \cdot kg^{-1} \cdot K^{-1}$
E	entransy dissipation, J·K
$\overline{E}$	normalized entransy dissipation
F	function
i	portion number
k	convective heat transfer rate, $W \cdot m^{-2} \cdot K^{-1}$
$\dot{m}$	mass flow rate of flue gas, $kg \cdot s^{-1}$
M_S	product of mass and thermal capacity of SHS material, $J \cdot K^{-1}$
n	stage number
$\dot{Q}$	heat transfer rate, W
$\overline{\dot{Q}}$	normalized heat transfer rate
t	time, s
T	temperature, K
$\overline{T}$	normalized temperature

Greek symbols

Δ	difference
$\dot{\phi}$	entransy dissipation rate, J·K
$\bar{\dot{\phi}}$	normalized entransy dissipation rate
λ	Lagrange factor
Θ	constrained heat transfer rate, W
τ	period, s

Subscripts

1	inlet value in 1st portion
i	inlet value in *i*th portion; portion number
i + 1	outlet value in *i*th portion
in	inlet value in air pre-heater
L	LHS unit
m_1	melting temperature in the first portion
m_2	melting temperature in 2nd portion
m_5	melting temperature in 5th portion
m_i	melting temperature in *i*th portion
m_i+1	melting temperature in *i* + 1th portion
m_n	melting temperature in the last portion
out	outlet value in air pre-heater
S_0	initial value of SHS material
S	SHS unit

Superscripts

i	portion number
∞	infinite-stage

temperature is around 200 °C. Taking necessary temperature difference for heat transfer into consideration, flue gas temperature is usually higher than 230 °C, corresponding to larger than 10% of energy consumption (with the basis of low-level value) in exhausted flue gas emitted from boiler. Therefore, recovery of waste heat in flue gas is an important measure for boiler efficiency improvement.

Many efforts have been made to utilize the waste heat in exhausted flue gas [4–11]. Among these efforts, to recover waste heat for direct utilization in boiler is most convenient and widely adopted. As shown in Fig. 2, in air pre-heater, flue gas exhausted from boiler transfers heat to fresh air. Flue gas is cooled down and fresh air is heated up. Therefore, sensible heat in flue gas is recovered. Moreover, heated fresh air is favored for burning in boiler, i.e. save of fuel consumption. Similar benefits are also found in economizer, where flue gas is used to pre-heat water supplied to boiler. To make it compact and easy to maintenance, regenerative form is adopted [12–15], where heat of flue gas is first stored in certain material and the stored heat is later released to fresh air or water. Comparing with sensible heat storage (SHS), latent heat storage (LHS) recently proposed offers larger heat storage density and correspondingly makes it possible for compact design and less weight [16–20].

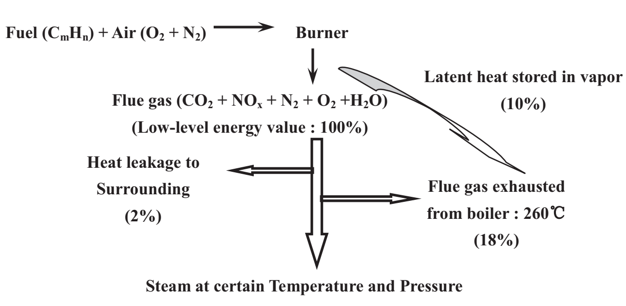

Fig. 1. Energy flow chart in boiler (with the basis of low-level energy value).

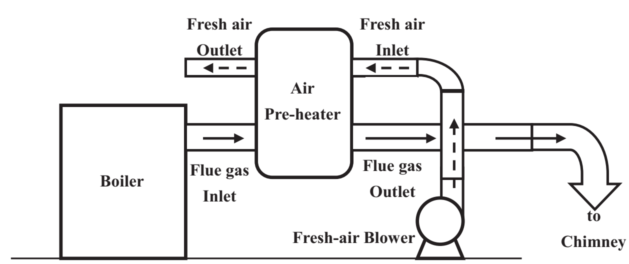

Fig. 2. Recovery of waste heat in flue gas.

Fig. 3 depicts rotary air pre-heater, which is also a LHS unit. Air pre-heater is separated into several grids. Phase change materials (PCMs) is filled in each grid. Flue gas and fresh air flow in reverse direction. When air pre-heater rotates, heat is transferred between PCMs and flue gas or fresh air intermittently. Therefore, heat is first recovered from flue gas and later released to fresh air. The main purpose is to lower flue gas temperature, which is heat storage in charging process for LHS unit. Moreover, the inlet temperature of fresh air is not always constant for air pre-heater, due to the variation in day and in season. Thus, conditions in discharging process is unstable and only charging process for LHS unit is considered in this paper [21]. Temperatures of flue gas exhausted from boiler and air pre-heater are prescribed at 260 °C and 140 °C, respectively.

Besides entropy and exergy analysis, entransy analysis is a thermodynamic tool proposed by Guo et al. to investigate or optimize heat transfer [22]. It is valid in process without heat-work conversion. Entransy is defined as potential ability of heat transfer in material with certain temperature. During heat transfer process induced by temperature difference, entransy is always dissipated. Therefore, entransy analysis corresponds to preserve heat transfer ability as much as possible, when heat transfer amount is satisfied. Of course, this is important for air pre-heater with LHS unit in charging process, because the main purpose of heat storage is to