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Performance evaluation of industrial glass furnace regenerator

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ABSTRACT

The performance of fixed matrix industrial regenerator used for waste heat recovery has been extensively investigated. The melting furnace capacity is 24 ton/day and it is equipped with two regenerators operated alternatively. The performance has been analyzed based on the first and the second laws of thermodynamics. Special attention has been paid to the effect of regenerator cleaning. Measurements have been made before and after regenerator cleaning for air and flue gas temperatures at inlet and outlet, mass flow rates of fuel and combustion air, and the composition of flue gas. It was found that the heat recovered by air is higher in the non-doghouse side. The regenerator cleaning increases the heat recovered by 0.83 and 1.97% for the non-doghouse and doghouse sides, respectively. The effectiveness during the heating period is higher than that of the cooling period. Consequently, it is recommended to use the effectiveness of the cooling period for design and selection of regenerator. The regenerator cleaning was found to increase the effectiveness during the cooling period by 0.78 and 1.56% for non-doghouse and doghouse sides, respectively. Due to regenerator cleaning, the supplied and gained exergy are increased and the second law efficiency is improved by about 3%.

1. Introduction

Glass manufacturing is an energy intensive industry. Production of glass includes six processes namely: mixing, melting, refining, forming, annealing and finishing. Melting process takes place in the melting chamber at a temperature of 1400–1500 °C and it is the most energy-intensive process [1]. Due to the high temperature in the melting chamber, the flue gas leaves the furnace at a very high temperature. Regenerators are used in majority of industrial glass furnaces to recover part of the waste energy from the flue gas and supply it to the air stream that should to be heated by burning fuel. Both of the exhaust flue gas and combustion air are passed through separate paths inside the regenerator without mixing. The regenerator checkers store the heat during the hot period from the flue gas. During the second half of the cycle, the stored energy is used to heat the combustion air. As a result, the regenerators improve the energy efficiency of the system. The efficient operation of regenerator plays an important economic role in glass plant operation.

Due to energy crises and environmental impact of fuel burning, regenerators' improvement is important for both academia and industry. A regenerator blockage prediction model based on design and operating parameters of the regenerator has been presented by Sardeshpande et al. [2]. The model has been used to estimate the actual performance of the regenerator. It has been found out that the actual performance is lower than the target performance by about 7%. Foumeny and Pahlevanzadeh [3] have evaluated the performance of baked-bed regenerator numerically using a two-dimensional model. It has been reported that the effectiveness predicted by non-plug flow model is lower than those predicted by plug flow model. Yu et al. [4] have investigated the resistance and thermal characteristics of a baked-bed regenerator. The results showed that the pressure drop across the bed increases as the bed height and fluid viscosity increase, or as the ball diameter decreases. Bauer et al. [5] have studied the heat transfer properties of six different checkers working at a limited temperature of 300 °C. It has been reported that the regenerator channels showed a considerable non-symmetrical appearance and the heat transfer depended not only on the velocity of the flow but also on the temperature differences and the resulting density difference. Clark-Monks [6] has examined the cost of regenerator efficiency and developed simple models which would help the glass maker in selecting regenerator designs based on the capital investment and efficiency. Reboussin et al. [7] have used the computational fluid dynamics code, FLUENT, to simulate a regenerator using RNG k–ε

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Nomenclature

c_p	Specific heat at constant pressure (kJ/kg. K)
$\bar{c}_P$	Mean specific heat at constant pressure (kJ/kg. K)
h	Specific enthalpy (kJ/kg)
h_f^o	Heat of formation (kJ/kg)
$\dot{m}$	Mass flow rate (kg/s)
Q	Amount of heat transfer (kJ)
$\dot{Q}$	Heat transfer rate (kW)
s	Specific entropy (kJ/kg. K)
$\dot{S}_{gen}$	Rate of entropy production (kW/K)
$\dot{S}_{destroyed}$	Rate of exergy destroyed (kW)
T	Temperature (K)
$\overline{T}$	Mean temperature (K)
x	Mass fraction (-)
$\dot{X}$	Rate of total exergy (kW)

Greek symbols

ε	Regenerator effectiveness (-)
Ψ	Specific exergy (kJ/kg)
τ	Time period (s)

Subscripts

a	Air
e	Exit
g	Gas
gen	Generation
i	Inlet
l	Leakage
min	Minimum
R	reference state
w	Wall
II	Second Law basis
0	Dead state

model. It has been concluded that the code was able to estimate the mean heat transfer coefficients with a satisfactory accuracy.

The effect of pressure leakages on fixed matrix regenerator heat transfer performance has been modeled by Skiepko and Shah [8]. It has been found out that flow leakages due to the cracks in the regenerator housing have the major influence on reducing the regenerator performance. A mathematical model to investigate the performance of a fixed bed regenerator has been developed by Zarrinehkafsh and Sadrameli [9]. The model has accommodated the convection and conduction heat transfer inside the ceramic balls. A difference between measured and predicted values has been reported and has been attributed to either errors in the measured parameters or mathematical model shortage. Experiments on deposit characteristics have been carried out by Busby and Sengelow [10]. The deposition of exhaust gas components in the regenerators of glass furnaces has been investigated by Beerkens and Waal [11]. A simulated flue gas from glass furnace on a laboratory scale has been used. An equilibrium thermodynamics model has also been used to predict the nature of deposition product. Despite of the overestimation of dew point for some components, the model prediction for the composition of deposit was in close agreement with experimental results. Zanoli et al. [12] have presented an experimental study of the thermal performance of various cruciform regenerator packing. Flat and corrugated checkers have been investigated. It has been found that the heat transfer coefficient of corrugated checkers is 1.5 times that of flat checkers. Scheiblechner [13] have discussed the advantages of chimney block packing in glass furnace regenerator over straight packing. Beerkens et al. [14] have developed a model to predict the degraded thermal performance of glass furnace regenerators due to fouling caused by flue gas condensates. An annual increase in energy consumption of about 1–3% due to fouling was reported. Recently, Wołkowycki [15] have performed experimental measurements of regenerator effectiveness and reported that the regenerator effectiveness for cooling period is higher than that for the heating period. First and second laws of thermodynamics have been applied to analyze the performance of heat recovery systems. Ma et al. [16] have conducted an experimental study on heat exchanger used for industrial waste heat recovery. The analysis has been based on the heat conservation and exergy based on the operation conditions. Due to rapid increase in computers' power, Computational Fluid Dynamics (CFD) becomes a reliable tool for regenerator design. Basso et al. [17] have investigated the performance of glass furnace regenerator using FLUENT code. Instead of simulating the fluid and separately, a porous domain assumption had been introduced in which an additional source term was added to the energy equation. Verheijen et al. [18] investigated the double bass regenerator using CelSian's CFD model GTM-X. They reported that the analysis can identify the regions of corrosion rate. The second law analysis based on entropy generation and exergy as performance parameters is widely applied for different types of heat exchangers (see for example Kaluri and Basak [19], Kotcioglu et al. [20], Gheorghian et al. [21], Zhou et al. [22], Laskowski et al. [23], Bahiraei and Majd [24] and Bahiraei and Alighardashi [25]). A state-of-art review including 134 references on the use of second law for heat exchangers analysis was presented by Manjunath and Kaushik [26]. Despite the importance of second law for the assessment of heat exchanger performance, it is not applied for glass furnace regenerators.

As flue gas leave the glass furnace, some of carryover ashes is conveyed to regenerator channels. These ashes deposit forming a layer on checker paths which, in turn, affects the thermal performance of the regenerator drastically. Thus, the current study investigates the actual performance of the regenerators. Extensive experimental analysis has been conducted on a typical regenerator operating at El-Araby glass Factory located in Quesna industrial city, Egypt. Measurements of flue gas and air temperatures are carried out before and after regenerator cleaning and dust removal. These measurements are used to analyze the regenerator performance. The analysis applies the principles of both the first and the second laws of thermodynamics. The exergy and second law efficiency for flue gas and combustion air have been obtained and discussed. In addition, the experimental data presented in the current paper can be used for the validation of CFD codes.

2. Description of the glass furnace regenerator

A glass melting furnace can be regarded as a chemical reactor which converts solid–liquid state reactions to glass. All glass reactions occur at high temperature (about 1400–1500 °C) in a confined space surrounded by refractory. The general arrangement of a glass furnace is shown in Fig. 1. The regenerative heat exchanger consists of two refractory chambers. One chamber is used to absorb and store heat from flue gas, at the same time the other chamber is used to preheat the combustion air. The paths of flue gas and the combustion air through regenerator chambers are interchanged every 15 min. The directions of flows are indicated by the arrows.

Generally, the glass furnace is installed with a single raw

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