Reduction of Fuel Consumption in an Industrial Glass Melting Furnace

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Abstract- Reduction of fuel consumption in glass melting furnaces can cut the cost of production, and tackle the global warming. This paper presents three independent solutions to reduce the fuel consumption in industrial glass melting furnaces. The solutions include air preheating, raw material preheating, and improving the insulation of combustion space refractory. Energy balance equations are derived and used to identify the effects of each solution. The results indicate that the three solutions reduce the fuel consumption by 9.5%, 17%, and 34%, respectively.

I. INTRODUCTION

Glass melting furnaces are energised by fossil fuels or electricity. High energy costs, tight environmental regulations, and severe competition amongst glass manufacturers have resulted in the emergence of several solutions to reduce the fuel consumption of these furnaces. In spite of the current advancements in energy reduction, there is still a long way to achieve the ultimate goals of glass production: enhancing thermal efficiency, minimising environmental impacts, and maintaining glass quality. The problem is more severe for existing furnaces operating in poor thermal conditions around the world.

A lot of research has been carried out to improve the thermal efficiency of glass furnaces. Some works [1-4] have employed simulation approaches to analyse the effect of different factors on heat consumption in glass furnaces. Other works [5-7] utilise the following innovative methods to improve the thermal performance of glass furnaces. The methods range from applying new burners and heat recovery systems for preheating combustion air and raw material [8-12], to considering new geometries of combustion space and its elements [13-15]. There are also some works that focus on advanced control techniques to achieve the optimal performance of glass furnace, e.g. [16]. A comprehensive survey on this subject is presented in [17-18].

This paper presents three independent solutions to reduce the fuel consumption in an existing 30 years old industrial glass melting furnace. The first solution implements air preheating by means of heat recovery system. The second solution exploits raw material preheating through heat exchanger. The third solution improves combustion space refractory insulation. The effect of each solution is investigated separately.

The paper is organised as follows. Section II presents the energy balance equations of furnace derived by the authors. The analysis of the thermal behaviour of the furnace under operating conditions is given in Section III. Section IV describes the following methods of energy saving in the glass furnaces: combustion air preheating, raw material preheating, and insulation of combustion space refractory. Section V investigates the effect of each method in terms of fuel reduction. Finally the concluding remarks are given in Section VI.

II. ENERGY BALANCE EQUATIONS OF FURNACE

The control volume of a glass melting plant is shown in Fig. 1. The control volume's inlets are the enthalpies of fresh air, fuel and raw material, while its outlets are glass melt, heat losses through combustion space and glass tank refractory and stack flue. The energy balance equations of the control volume as well as regenerator and raw material preheater, derived by the authors, are given in Eq. (1-3).

$$Q_{fuel} + Q_{fresh\ air} = Q_{melting} + Q_{glass\ tank\ loss} + Q_{combustion\ space\ loss} + Q_{stack\ loss} \tag{1}$$

$$Q_{flue} + Q_{fresh\ air} = Q_{preheated\ air} + Q_{regenerator\ exit} \tag{2}$$

$$Q_{regenerator\ exit} = Q_{stack\ loss} + Q_{preheated\ raw} \tag{3}$$

Combining Eq. (1-3), the stack loss is omitted and the energy balance equation of furnace is achieved (see Eq. (4)), which includes all the influencing terms in the thermal behaviour of the glass melting furnace. The terms at the left-hand side of Eq. (4) are the enthalpies of fuel, the preheated air, and the furnace flue. These determine the heat released in the combustion space. We name the result of the left-hand side terms as "heat source". On the other hand, the terms at the right-hand side of Eq. (4) are the melting heat, the enthalpy exchange of raw material, and the heat losses through combustion space and glass tank refractory. These specify the heat consumption of the furnace. We name the result of the right-hand side terms as "heat sink".

The nominal flow rate of preheated air cannot be achieved due to plugging of ports. In addition, a perfect combustion cannot practically occur, and carbon monoxide and unburned carbon particles are found in furnace flue. To compensate the described deficiencies, we multiply the heat source by a combustion efficiency factor. Comparing with the data acquired during the furnace operating condition, the combustion efficiency factor was calculated as 0.895. It is assumed that this factor remains the same in other conditions. Therefore the energy balance equation of furnace can be represented in the form of Eq. (5).

$$Q_{fuel} + Q_{preheated\ air} - Q_{flue} = Q_{melting} + Q_{glass\ tank\ loss} + Q_{combustion\ space\ loss} - Q_{preheated\ raw} \tag{4}$$

$$(Q_{fuel} + Q_{preheated\ air} - Q_{flue}) \times \mu_{combustion} = Q_{melting} + Q_{glass\ tank\ loss} + Q_{combustion\ space\ loss} - Q_{preheated\ raw} \tag{5}$$

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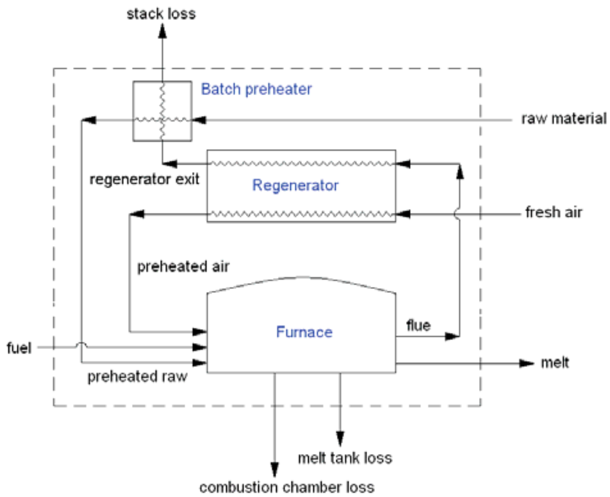

Figure 1. The control volume of a glass melting plant.

III. ANALYSIS OF FURNACE UNDER OPERATING CONDITION

In order to optimise the fuel consumption of the furnace, it is necessary to analyse the thermal behaviour of the furnace under operating condition as a benchmark. The terms involved during the operating condition are summarised in Table I. They refer to the second furnace of Abginue glass melting plant [19]. They can be classified into two groups: measured and calculated. The measured terms were acquired through the measurement devices installed in the furnace. The calculated terms were acquired through numerical simulation by the authors [19]. These terms were substituted in Eq. (5) to calculate the combustion efficiency.

TABLE I
PARAMETERS INVOLVED IN ENERGY BALANCE EQUATION OF FURNACE

Group	Parameter	Value	Source
Combustion	*fuel flow rate*	$1880\ \frac{m^3}{h}$	measured
	excess air	$20\ \%$	measured
	$ratio\ _{N_2/O_2}$	$\frac{79}{21} = 3.76$	measured
	$T_{preheated\ air}$	$1373\ K$	measured
	T_{flue}	$1801\ K$	calculated
Melting	$\dot{m}_{raw}$	$200\ \frac{ton}{day}$	measured
	$T_{preheated\ raw}$	$300\ K$	measured
	cullet percent	$0\ \%$	measured
Wall losses	U_{tank}	$5\ \frac{W}{m^2 K}$	measured
	glass tank loss	$1.62\ MW$	calculated
	$U_{chamber}$	$10\ \frac{W}{m^2 K}$	measured
	combustion space loss	$4.64\ MW$	calculated

Applying the above terms, the heat consumption associated with different components of the furnace was computed and displayed (see Fig. 2). It can be seen that 4.4 MW (20%) of total energy is consumed for glass melting and another 7.4 MW (32%) is recovered in regenerator. The rest of energy is lost through the combustion space refractory, the glass tank refractory and the stack flue as 4.6 MW (21%), 1.6 MW (7%) and 4.4 MW (20%) respectively.

IV. METHODS OF SAVING ENERGY

a. AIR PREHEATING

Regenerators have been used to preheat the combustion air. Typically the flue connection is located at the end of each regenerator, and both the waste gas and combustion air pass through this connection. The heat of waste gas is transferred to refractory bricks stacked in a checker board fashion inside each regenerator. The bricks, in turn, give up their heat to the incoming combustion air on about a 15 minute reversing cycle [7]. The efficiency of a regenerative furnace is low due to the uneven distribution of hot waste gas, and the combustion air that goes through the checker pack. This fact can be explained by the fluid dynamics of the waste gas and incoming combustion air movement through the checkers. The waste gas prefers to pass through the checkers close to the flue connection as being pulled by the stack. But the incoming combustion air prefers to pass through the checkers far from the flue connection because of its momentum. Further fuel reduction could be achieved by optimising regenerators and increasing the temperature of preheated air. An example of improvement is the introduction of Superflue Regenerator [7] that has produced a 17% fuel reduction.

b. RAW MATERIAL PREHEATING

Preheating the raw material is a common way to save the energy of glass melting furnaces. The raining bed batch/cullet preheater is a heat exchanger system that preheats the glass furnace charge with hot flue gases [22]. The exhaust gases from the furnace are drawn from the flue and cooled to 973 K by mixing in ambient air [10].

Batch/cullet is fed at the top of the preheater and rains through the heat exchanger. The batch/cullet particles are deflected by internal baffles and are in direct contact with rising hot flue gases. The gases flow through a cyclone then are drawn by an induced draft fan into the stack. The hot batch reaches to 823 K, then collected and directed to the furnace charging equipment.

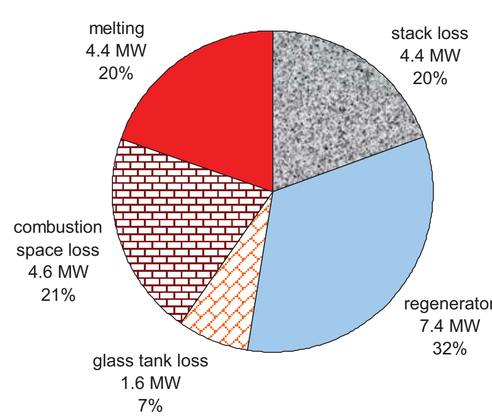

Figure 2. The portion of heat consumed in each section.

c. INSULATION OF COMBUSTION CHAMBER REFRACTORY

Conventionally AZS (Alumino-Zirconiom-Silicate) and Mullite (Alumino-Silicate) refractory are used in glass furnaces [23]. Those refractory should have some features like high insulation, good chemical stability, low thermal expansion and good creep resistance.

Heat passes through the refractory by means of conduction and leaves the outer surface of refractory by means of free convection and radiation as shown in Fig. 3. The overall heat transfer coefficient of combustion space refractory is a derived by Eq. 6., where T_i is the temperature of the internal surface of the refractory, k and t are the conductivity and the thickness of the refractory, T_o and ε_o are the temperature and the emissivity of the external surface of the refractory, h and T_∞ are the free convection coefficient and the temperature of the air surrounding the furnace and T_s and ε_s are the temperature and the emissivity of the surfaces of the refractory surrounding the furnace.

The refractory thickness cannot be increased due to structural limitations in such a wide-span furnace. But using higher quality refractory, the conductivity and emissivity can be reduced. Also a group of furnaces are double-crown type, in which the burners are in the back wall and the combustion gases pass through an opening in the furnace crown near the front wall. From this point they return to the exit port through a second chamber formed by a further crown over the roof of the furnace. By this manner, much of the heat loss from the inner surface is prevented [2].

$$\begin{aligned} Q_{refractory} &= \frac{k\, A_i\, (\overline{T}_{\mathrm{i}} - T_o)}{t} \\ &= \frac{\sigma\,(T_o^4 - T_s^4)}{\dfrac{1-\varepsilon_o}{\varepsilon_o A_o} + \dfrac{1}{F_{os} A_o} + \dfrac{1-\varepsilon_s}{\varepsilon_s A_s}} + h\, A_o\, (\overline{T}_{\mathrm{o}} - T_\infty) \qquad (6) \\ &\approx U_{refractory}\; A_{refractory}\; (\overline{T}_{refractory} - T_\infty) \end{aligned}$$

V. RESULTS AND DISCUSSIONS

a. EFFECT OF AIR PREHEATING

The flue temperature depends on preheated air temperature, excess air and oxygen concentration of the combustion air. To express this dependency, the flue temperature is taken as a constant ratio of adiabatic flame temperature (AFT). During the operating conditions of furnace, the AFT is calculated as 2801 K while the mean flue temperature is calculated as 1801 K. The ratio of mean flue temperature to AFT is 2801/1801 = 0.615. Generalising this relation, the mean flue temperature of the furnace under other circumstances could be regarded as the product of AFT under different conditions and 0.615. Using this approach, the variation of mean flue temperature versus preheated air temperature is calculated, and shown in Fig. 4.

In order to calculate the fuel consumption under different preheated air temperatures, Eq. 5 is rearranged (see Eq. 7). In this equation the fuel mass rate is factorised from the heat source. It is assumed that the heat sink remains constant although it may change under varying air temperature.

$$\dot{m}_{fuel} = \frac{Q_{melting} + Q_{tank\ loss} + Q_{combustion\ \ space\ loss} - Q_{preheated\ raw}}{(q_{fuel} + q_{preheated\ \ air} - q_{flue}) \times \mu_{combustion}} \qquad (7)$$

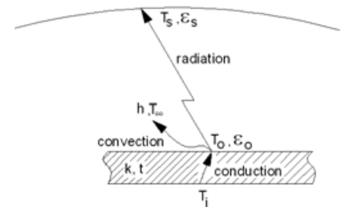

Figure 3. Through the refractory, heat transfer takes place by conduction, free convection, and radiation.

Applying Eq. (7), the absolute and relative values of fuel consumption with respect to air temperature is calculated as shown in Fig. 5. It can be seen that preheating the combustion air from 1000 to 1700 K, results in the reduction of fuel consumption from 2126 to 1700 m^3/h. If the fuel consumption under operating condition of the furnace is considered as the reference value, then the relative fuel consumption reduces from +13% to -9.5%.

b. EFFECT OF RAW MATERIAL PREHEATING

In order to calculate the fuel consumption under different raw material temperatures, Eq. 7 is again used. It is assumed that the mean flue temperature remains unchanged in comparison to the operating condition of the furnace. Therefore the lower terms of Eq. 7 would be constant. In contrast, the term $Q_{preheated\ raw}$ depends on the temperature of raw material, and therefore the heat sink varies once the raw material is preheated.

Applying Eq. 7, the absolute and relative values of fuel consumption with respect to the temperature of raw material is calculated as shown in Fig. 6. It can be seen that preheating raw material from 300 to 1000 K, the fuel consumption dramatically decreases from 1880 to 1566 m^3/h. If the fuel consumption under operating condition of the furnace is regarded as the reference value, then the relative fuel consumption reduces from 0% to -17%.

c. EFFECT OF COMBUSTION SPACE INSULATION

In order to calculate the fuel consumption under different insulations of combustion space refractory, Eq. 7 is again used. It is assumed that the mean flue temperature remains unchanged in comparison to the operating conditions of the furnace. Therefore, the lower terms of Eq. 7 would be constant. On the other hand, the term $Q_{combustion\ space\ loss}$ depends on the overall heat transfer coefficient of combustion space refractory, $U_{combustion\ space}$. Therefore the heat sink varies as the insulation of refractory is improved.

Applying Eq. 7, the absolute and relative values of fuel consumption with respect to the $U_{combustion\ space}$ are calculated as shown in Fig. 7. Decreasing the $U_{combustion\ space}$ from 16 to 2 W/m^2K, results in a sharp reduction of fuel consumption from 2372 to 1225 m^3/h. Again the fuel consumption under operating condition of the furnace is considered as the reference value, and thus decreases the relative fuel consumption from +26.2% to -34.8%.

According to Fig. 2, 21% of total energy is lost trough the combustion space refractory, but here it is concluded that 34.8% energy saving can be achieved by better insulation of the refractory. The conclusion is surprising but it is reasonable. In fact, reduction of combustion space refractory loss is followed by the reduction of stack losses, and regenerator heat consumption as the fuel mass flow rate is multiplied by the lower terms of Eq. 7.

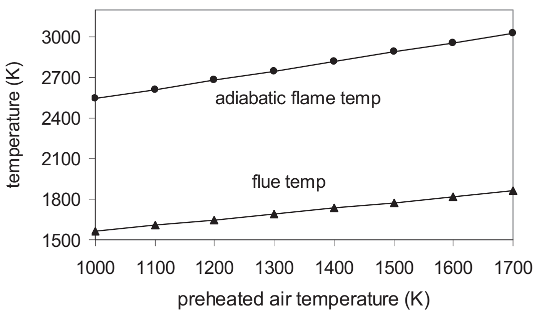

Figure 4. Variation of adiabatic flame temperature and furnace flue temperature with respect to preheated air temperature.

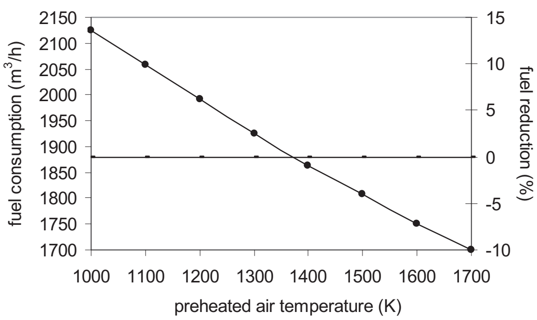

Figure 5. The absolute and relative values of fuel consumption with respect to air temperature.

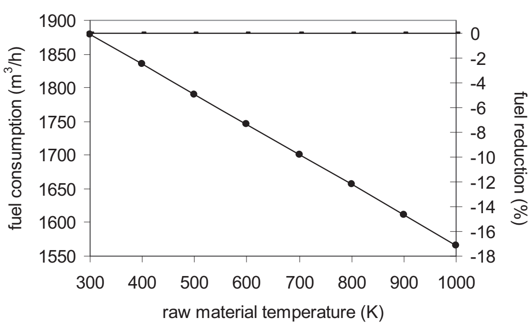

Figure 6. The absolute and relative values of fuel consumption with respect to raw material temperature.

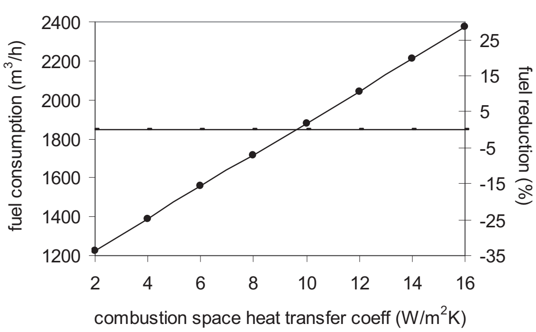

Figure 7. The absolute and relative values of fuel consumption with respect to $U_{\text{combustion space}}$.

VI. Conclusions

Simulation of glass melting furnaces can be used as a good tool to analyse the effect of different factors on the fuel consumption. In this work, the temperature of preheated air, the temperature of raw material, and the overall heat transfer coefficient of combustion space are varied over a wide range to analyse the sensitivity of fuel consumption. The results indicate that further preheating of combustion air from 1373 to 1700 K produces a 9.5% fuel reduction. Whereas preheating of raw material from 300 to 1000 K generates a 17% fuel reduction. Finally, decreasing the overall heat transfer coefficient from 10 to 2 W/m^2K results in a 34% fuel reduction. The effect of the abovementioned factors is analysed separately. A combination of different methods could be applied to achieve further fuel reduction.

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