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Energy efficiency increase in a glass industry by means of waste heat recovery

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Abstract:

The paper examines the waste heat recovery potentials at a typical glass production plant by the introduction of batch preheating option. Batch and cullet preheating is a process that has been investigated for over 30 years resulting into more than 10 waste heat recovery systems applications installed on glass industrial facilities equipped with melting furnaces. Flue gases of a typical natural gas fired regenerative furnace with a temperature of approximately 450-500 °C are carrying a significant amount of energy for further exploitation. Batch and cullet preheat temperatures of about 300°C have been reported while flue gases are cooled down by 200-250 °C resulting in specific energy savings of 12-20% [1]. In addition to the reduction of the primary energy used, CO_2 emissions are decreased by 8-14% and increased glass pull rates can be achieved.

A heat recovery engineering tool has been developed for the calculation of the mass and heat flow inside a batch and cullet preheater for the glass industry. The finite volumes method was adopted to model the particulate solid as a continuum while appropriate heat transfer modules have been used for flue gases, bulk phase and ambient losses. Calculations are based on explicit scheme and are time dependent. As an output, temperature profiles and system heat fluxes are exported.

The objective of this work is to examine different design schemes for waste heat utilization taking into account raw materials and flue gas flows and characteristics, preheater geometry and components and operational requirements in order to specify the efficiency of the preheater, the amount of fuel savings and the reduction of CO_2 emissions.

Keywords:

Waste Heat Recovery, Batch Preheating, Glass Industry, CO_2 emissions

1. Introduction

Glass manufacturing is an energy intensive industry, in which most of the energy is consumed in the furnace. A typical glass furnace operates continuously at high temperatures exceeding 1500 °C in order to heat and melt the mix of raw materials. Furnace operational life lasts for about 10 years before its demolition and reconstruction. During the last decades significant efforts were made to increase productivity and efficiency and lower the emissions towards economic and environmental performance improvement by the use of recycled cullet, increased insulation, improved combustion control and more effective regenerators. It is widely accepted [1-3] that the most significant potential to reduce the specific energy consumption is the advanced utilization of the exhaust gases, having a temperature of about 400-500°C and a heat content that corresponds to 30% of the input energy at a conventional natural gas fired regenerative furnace. For the flue gases further utilization, various waste heat recovery systems have been proposed such as district heating and electricity production. Due to high investment costs, low efficiency and limited application potentials of direct heating, other concepts had been examined and proposed.

A promising option for recovering part of the waste heat, deals with batch and cullet mixture preheating which is normally supplied into the furnace at ambient temperature, having the advantage that the energy saved is directly returned to the glass production process resulting into 12-20% energy savings. Batch and cullet is preheated to about 300 °C while flue gases are cooled down by 200-250 °C. The decrease in specific energy consumption can be achieved by combining reduced fuel input and, in the case of electric boosting, reduced electricity consumption with an increased glass pull. This options results into reduced air emissions levels. In the glass manufacturing sector, 70-90% of the CO_2 emissions are related to fuel combustion, while the rest are formed due to raw materials reactions [4]. As a result, batch preheating also results into CO_2 emissions decrease. In the same way, as combustion air is reduced, NO_x emitted is also reduced [5].

Despite the fact that the first installations took place during the 80s and significant energy savings have been achieved, this specific option has not been widely utilized due to high investment costs and technical side effects that could cause serious equipment and handling problems. A major defect of the first generation systems was the evaporation of batch moisture and the dehydration of soda ash [6], resulting into the creation of agglomerations causing blocking problems of the batch flow inside the preheater. In order to avoid such problems batch preheating applications required the minimization of the water content and thus the use of cullet ratios above 50% was obligatory. Another drawback was the increased dust carry-over from both the combustion area into the regenerator and from the batch preheater to the stack since batch was completely dried. Nowadays the technology enabling the amelioration of dusting problems and the safe removal of humidity during batch preheating is developed and in the latest Best Available Techniques reference document [7] issued for the Glass Industry in 2013, batch preheating is included within the “promising technological innovations”.

2. Batch/Cullet Preheating

There are several different types of batch and/or cullet preheating systems applied in the glass industry or still in testing phase. At cullet - only preheaters, cullet is preheated by direct contact with either the flue gases or steam. At combined batch and cullet preheaters, heat can be transferred through direct or indirect contact between the batch and the hot flue gases. Batch can also be introduced inside the preheater in the form of pellets.

Important limitations have to be applied when installing a batch preheater. At first, the entry temperature of the flue gases must not exceed 600 °C so as to avoid the deformation of structural materials. This is also the temperature where cullet begins to stick and cause plugging problems. Although batch humidity is necessary to avoid batch de-mixing during transportation, water content of the batch needs to be reduced to a minimum as well, due to problematic water removal from the preheater. This is the reason of first generation preheating systems operating with a cullet percentage of 50% or more, where, as cullet content increases the required moisture is decreased. Well-known manufacturers of preheat systems are Interproject, Praxair (originally Edmeston), Sorg and Zippe. Some of the installed systems are described below:

Interprojekt batch preheater [5] is a direct contact heat exchanger presented in Fig. 1. Hot flue gases flow downstream the air regenerator through the preheater in several layers (8-10) of ducts which are situated horizontally across the preheater and are open at the bottom side, allowing direct contact with the batch. Flue gases pass in cross and counter flow through the preheater from the bottom with a temperature of about 400-500 °C to the top with a temperature of 200 - 250 °C. The flue gas ducts have been appropriately designed in order to minimize the pressure losses, to provide a longer residence rime of the gases inside the heat exchanger and to limit carry-over entrainment of dust. Typical flue gas velocities range between 6 and 8 m/s. Batch and cullet are mixed before entering the preheater according to a desired recipe and then conveyed to the top of the preheater. The batch moves slowly due to gravity with a typical speed of 1-3 m/h ensuring adequate heat transfer and practically no wear of the ducts and the walls. The batch is completely dried and heated to a temperature of about 300 °C. Nienburger Glas (now REXAM) has installed its first unit in 1987 in furnace no. 4 and replaced it with an improved version in 1999 using the Interprojekt system [8]. The original system was installed in a green glass regenerative furnace operating at pull rates of 260

- 310 t/d using more than 80% cullet content in the batch. The specific energy consumption was 3367 kJ/kg glass including the electric boosting, achieving an energy saving of about 16%. Another batch preheater was also installed in Nienburg furnace no. 1 which produced flint glass. This furnace was operating without electric boosting and was using lower cullet content than the green glass furnace (40-70%). The average specific energy consumption was 3870 kJ/kg glass.

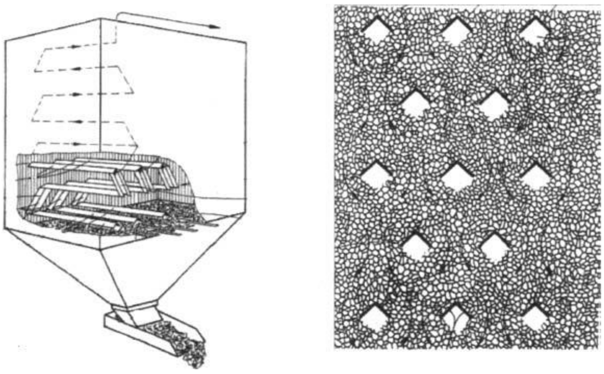


Fig. 1. Basic concept of the batch preheating system "Nienburger" type [8]

Praxair and Edmeston [9] have developed a hybrid direct cullet only preheater for oxy-fuel furnaces which is combined with an electrostatic precipitator for dust removal. External cullet from market recycling and internal cullet from defected products of the factory are treated separately. External cullet enters the pyrolizer where organic matter is vaporized after being in contact with a hot stream of flue gases and then this stream is mixed with hot flue gases from the furnace. Next step of the process deals with stream flow into an ionizer where dust particles are electrically charged and then passes through a main cullet preheater which is filled with both internal and preheated external cullet. In this main preheater, cullet is dried and further preheated while the dust particles are captured by the surface of the cullet due to an electrostatic field created by a built-in high-voltage electrode.

Sorg has also developed the so-called LoNO$_x$-Melter furnace which is combined with a direct cullet preheater. The first installation was installed at Wiegand Glass, in Steinbach, Germany. Estimated energy savings by cullet preheating is 15-20% [10] for recuperative furnaces based on 85% cullet.

Zippe has developed a cross counter flow indirect preheater in which there is no direct contact between the flue gases and the batch [6]. The system is constructed by individual heat exchange modules stacked up vertically. Compared to a direct preheater, the advantage of using closed ducts is that no chemical reactions between the flue gas and the batch occur, there are no contaminations of the flue gases and no dust carry-over. The drawbacks of this system are the decreased heat transfer rates that lead to bigger constructions and the difficulty to remove batch moisture. Due to the moisture of the descending batch, the flue gas ducts at the top of the preheater comprise a drying zone. In order to remove the steam produced, de-vaporization modules were designed and installed between the individual modules. These funnels create hollow spaces inside the preheater in which steam can be trapped and subsequently withdrawn when added to the flue gas stream. It [1] is reported that four such systems have been built in the 1990s for both regenerative and recuperative container glass furnaces. Typical height of the preheater varies between 20 - 25m and energy savings range between 12-20%.

3. Batch preheating calculation algorithm

In order to investigate the mass and heat flows inside a batch preheater towards its optimisation a 3 dimensional computational model was developed. The model uses the finite volumes structure using the "Euler" type approach for the batch. Each grid element is treated according to the following 4 basic categories: bulk phase, solid wall, flue gas and ambient air. As flue gases pass inside a close duct, heat is transferred to the inner duct walls by convection and radiation:

$$d\dot{q} = \left[h_{gas}\left(T_{gas} - T_s\right) + e_{Gas}\sigma\left(T_{gas}^4 - T_s^4\right)\right] A \qquad (1)$$

in which $d\dot{q}$ is the heat rate (W), h_{gas} is the convection coefficient (W m^{-2} K^{-1}), e_{gas} is the emissivity coefficient, σ is the Stefan–Boltzmann constant (σ = 5.67 * 10^{-8} Wm^{-2} K^{-4}), T_s is the solid cell temperature (K), T_{gas} is the flue gas temperature (K) and A is the surface of the cell (m^2). Flue gas convection coefficient is calculated using the correlations below:

$$h_{gas} = \frac{k_{gas} Nu}{D_H} \qquad (2)$$

$$k_{gas} = \sum_{i=1}^{n} \frac{w_i k_i}{\sum_{j=1}^{n} w_j \Phi_{i,j}} \qquad (3)$$

in which w_i is the mass fraction of the flue gas component i, k_i is the conduction coefficient of each gas (W m^{-1} K^{-1}) while $\Phi_{i,j}$ is a constant defined as :

$$\Phi_{i,j} = \frac{1}{\sqrt{8}}\left(1 + \frac{M_i}{M_j}\right)^{-\frac{1}{2}}\left[1 + \left(\frac{\mu_i}{\mu_j}\right)^{\frac{1}{2}}\left(\frac{M_i}{M_j}\right)^{\frac{1}{4}}\right]^2 \qquad (4)$$

in which, M_i is the molar mass of each component i (g mol^{-1}) and μ is the dynamic viscosity (Pa s). Nusselt number is calculated as follows:

$$Nu = 0.037\left(\mathrm{Re}^{0.75} - 180\right)\cdot \mathrm{Pr}^{0.42}\left[1 + \left(\frac{D_H}{L}\right)^{2/3}\right] \qquad (5)$$

in which Re is the Reynolds number, Pr is the Prandtl number, L is the length of the duct (m) and D_H is the hydraulic diameter of the duct. Reynolds number is defined as:

$$Re = \frac{u_{gas} D_H \rho}{\mu} \qquad (6)$$

in which u_{gas} is the flue gas velocity (m s^{-1}) and ρ is the flue gas density (kg m^{-3}). Prandtl number is:

$$\mathrm{Pr} = \frac{c_p \mu}{k_{gas}} \qquad (7)$$

in which c_p is the flue gas specific heat capacity (J kg^{-1} K^{-1}). Flue gas emissivity coefficient is calculated using the correlation below:

$$\varepsilon_{gas} = \varepsilon_{CO_2} + \varepsilon_{H_2O} - \Delta\varepsilon \qquad (8)$$

in which ε_{CO2} is the CO_2 emissivity coefficient, ε_{H2O} is the H_2O emissivity coefficient and $\Delta\varepsilon$ is the emissivity correction factor. CO_2 and H_2O are considered to be the only radiative gases. Emissivity coefficients are calculated using Leckner's correlations [11]. Equations (2) - (8) are used for the calculation of the heat transfer coefficient from the flue gases to the inner walls of a close duct. For an open-bottomed duct of a typical batch preheater, heat transfer coefficient from the flue gases to the surface of the batch is calculated with respect to empirical data ranging between 90-100 W/(m^{2}K) [12]. Between solid and bulk phase elements heat is transferred by conduction. The governing partial differential heat conduction equation in three dimensions is:

$$c_p \rho \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_z \frac{\partial T}{\partial z}\right) \qquad (9)$$

The raw material batch is considered as a mixture of solid particles surrounded by a static gas phase. The predominant heat transfer mechanism in the interior of the batch is described by conduction via the contact points located in the contact area between two particles and conduction through the air gaps. Effective thermal conductivity is determined as if the solid and fluid phases are in layers parallel to the direction of heat flow [13]. Assuming that the net heat conductivity of a mixture of solid components is given by:

$$k_s = \sum_{i=1}^{n} w_i k_{i,s} \tag{10}$$

in which n is the number of solid species in the mixture, w_i is the weight fraction of solid phase i and $k_{i,s}$ is the apparent heat conductivity of solid phase i, the heat conductivity of a multicomponent mixture is estimated by:

$$k = \varepsilon_p k_{air} + \left(1-\varepsilon_p\right) k_s \tag{11}$$

The porosity of the multicomponent mixture is given by:

$$\varepsilon_p = 1 - \frac{\rho_b}{\sum\left(w_i \rho_{s,i}\right)} \tag{12}$$

in which $\rho_{s,i}$ (kg m^{-3}) is the intrinsic density of component i and ρ_b is the density of the whole batch. Finally, a part of the initial heat potential of the flue gas escapes through the preheater's wall to the environment. The predominant heat transfer mechanism is convection. Heat loss rate to ambient is given by:

$$d\dot{q} = h_a\left(T_a - T_S\right)A \tag{13}$$

where h_a is the ambient air convection coefficient (W m^{-2} K^{-1}) and T_a is the ambient temperature (K).

Due to the physical batch moisture, a notable part of the flue gas heat content is used for the evaporation of the water. Soda ash absorbs water during the mixing of the batch and forms sodium carbonate monohydrate ($Na_2CO_3H_2O$) which contains 85.48% Na_2CO_3 and 14.52% water of crystallization. This chemically bound water content is released as vapor at 109°C. The dehydration of soda is an endothermic reaction and the reaction enthalpy (ΔH^o) is 3265kJ/g H_2O, which is greater than the water latent heat.

Simulation of bulk phase movement precedes the heat transfer calculations. Since batch input rate is considered constant, velocity profiles are calculated at the initial stage of the algorithm. Continuity equation is used to calculate the mass rate of the batch that flows down the preheater and velocity profiles are estimated using boundary layer equations according to Karman-Pohlhausen method [14].

Temperature in each cell of bulk phase is calculated at two stages. At the first stage, batch is considered stagnant, heat is transferred due to conduction and temporary temperature profiles are created. At the second stage, batch moves to neighboring cells and heat is transferred due to mass convection. When the second step is completed, it is assumed that each cell is thermally homogenous and final temperature profiles for the current time step are calculated.

4. Case study for batch preheater installation

A case study based on one of the most energy-efficient end-port fired regenerative container glass furnace according to [15] has been constructed. Energy balance calculations using 0 °C as reference temperature are given in Table 1. The basic data of the process without batch preheating are:

- glass pull of 260 t/d
- 83% cullet in mixture
- 2% batch humidity
- 3620 kJ/kg energy consumption
- no electric boosting

Fuel consumption corresponds to 10.9 MW. Assuming natural gas lower heating value of 46 MJ/kg and 2.6 kg of CO_2 emissions for every kg of natural gas combusted, the fuel derived CO_2 emissions are 0.205 $kgCO_2$/kg glass (53.2 tCO_2/day). The composition of the batch is: 83% cullet, 10.5% silica sand, 2% limestone, 2% dolomite and 2.5% soda ash. Limestone emits 44.8% of its mass as CO_2 while the mass loss percentage for dolomite and soda ash is 46.8% and 41.9% respectively [16]. For a glass pull of 260t/d, the process derived CO_2 emissions are 0.029 $kgCO_2$/kg glass (7.5 tCO_2/day) and overall CO_2 emissions are 0.232 $kgCO_2$/kg glass (60.3 tCO_2/day). The calculated flue gas volume flow downstream the regenerator is 14223 Nm^3/h assuming 3.5% oxygen content and its temperature is 476 °C, based on mass and energy balance of the initial configuration of the plant, as illustrated in Table 1.

Table 1. Regenerative furnace energy balance without batch preheating

Heat flows	*kW*	kJ/kg glass	%
Heat input			
Fuel	10893.5	3620.0	98.7
Batch	51.5	17.1	0.5
Air	94.1	31.3	0.9
Heat output			
Water evaporation + soda dehydration	177.7	59.1	1.6
Endothermic reactions	262.7	87.3	2.4
Heat carried by glass	4883.7	1622.9	44.2
Flue gases downstream the regenerator	3043.5	1011.4	27.6
Conduction through furnace walls	2016.8	670.2	18.2
Cooling and leakage	404.6	134.4	3.7
Regenerator losses	249.5	82.9	2.3

4.1. Configuration of the batch preheater

The proposed preheater dimensions are taken as 4.2m long, 4.7m wide while its effective height is 16.9m. Flue gases flow is split in two streams. The upper stream flows through 6 open-bottomed ducts that pass four times through the top section of the preheater. Each duct is 40cm high and 40cm wide. At the end of every passage, ducts are connected to a gas collector. The use of open-bottomed ducts is to dry the batch and remove its humidity in order to avoid the appearance of clumping downwards. Due to the open-bottomed ducts used, a free surface of batch is formed by its angle of repose which is estimated to be 45°. The second stream enters at the bottom of the preheater and flows through 7 separate and identical ducts in 14 successive layers. Unlike the open-bottomed ducts of the upper stream, closed ducts are not connected to neighboring ducts. The height of each closed duct is 70cm and its width is 40cm. The shape of the ducts is configured according to Fig. 2.

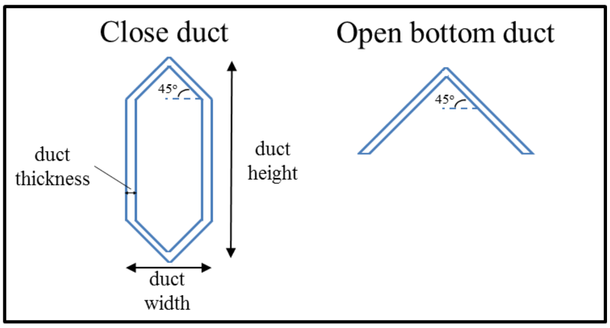


Fig. 2. Preheater ducts shape

Three cases are examined based on different configurations with effect on fuel consumption and glass pull. The same preheater configuration as described above, is used in all cases, with the same flue gases input temperature at 476 °C and inlet velocity of less than 8m/s. The water content taken as chemically bound as soda ash monohydrate corresponds to 0.35% of the dry batch mass and the free moisture content is 1.65%. The density of the batch is 1550 kg/m^3 and its porosity is 0.4. The effective heat conductivity of the batch [13, 17, 18] is $k_b = 0.528 + 0.0004T$ W/(m K), in which T is the temperature in K. When batch is moist, at temperatures less than 100 °C, the effective heat conductivity is increased by approximately 50% [19]. The heat capacity of the batch [13, 20, 21] is $c_{p,b} = 0.757\ T + 608.6$ J/(kg K) in which T is the temperature in K. The conductivity of the solid walls is $k_s = 0.0335T + 6.898$ W/(m K) and the heat capacity is $c_{p,s} = 0.304T + 376.5$ J/(kg K) in which T is the temperature in K. Ambient temperature is 20 °C and the batch is fed into the preheater at 20 °C.

The computational mesh is composed of 8340150 cells and the dimensions of each cell are dx=0.02m, dy=0.02m and dz=0.1m. The time step is set to 10 sec. Grid and time independence is achieved. The heat transfer model is also coupled with heat balance calculations for the furnace-preheater system in order to adjust the volume of the flue gases that enters the preheater and the batch throughput as specific energy consumption decreases. It is assumed that furnace wall heat losses, cooling, leakage and regenerator losses are independent of the fuel consumption and the pull rate. The energy consumed for water evaporation, endothermic reactions, batch heating and melting increases linearly as pull rate is increased. The volume of the combustion gases decrease linearly as fuel consumption decreases and process CO_2 emissions increase linearly as pull rate increases.

4.1.1. Fuel reduction case (case 1)

At the first case, glass pull is kept constant and fuel consumption is reduced. Wet batch mass enters the preheater with a rate of 3.16 kg/sec (273 t/d). The actual water content that is evaporated and escapes the preheater through the flue gases is 0.063 kg/sec (5.5 t/d). According to the model, batch is preheated to 322 °C and flue gases are cooled down to 209 °C. The total volume flow of the flue gases is reduced to 11798 Nm^3/h, where 3292 Nm^3/h pass through the upper stream and 8506 Nm^3/h pass through the lower stream. From the flue gas an amount of 1379.8 kW is recovered and the efficiency of the preheater is 55.1%. The calculated energy flows for the whole furnace-preheater system are given at Tables 2 and 3. The specific energy consumption is 2988 kJ/kg, reduced by 17.5%. Specific energy consumption is reduced as both the mass and the temperature of the exhaust gases decrease. CO_2 emissions are 0.196 kgCO_2/kg glass (51 tCO_2/day), reduced by 15.4%.

Table 2. Calculated heat input of the furnace – preheater system for reduced fuel consumption

Calculated heat input	*kW*	kJ/kg glass	%
Fuel	8991.8	2988.1	98.6
Batch	51.5	17.1	0.6
Air	77.5	25.8	0.8

Table 3. Calculated heat output of the furnace – preheater system for reduced fuel consumption

Calculated heat output	*kW*	kJ/kg glass	%
Water evaporation + soda dehydration	177.7	59.1	1.9
Endothermic reactions	262.7	87.3	2.9
Heat carried by glass	4883.7	1622.9	53.5
Flue gases downstream the batch preheater	1011.8	336.2	11.1
Conduction through furnace walls	2016.8	670.2	22.1
Cooling and leakage	404.6	134.4	4.4
Regenerator losses	249.5	82.9	2.7
Preheater losses	114.0	37.9	1.2

4.1.2. Increased pull case (case 2)

At this second case fuel consumption remains constant (10.9 MW) while batch throughput is increased. It is suggested [12] that the pull rate of a furnace is limited due to one of the following reasons: forming machine capacity, cold-end equipment handling capacity, batch plant capacity, furnace design for refining, exhaust gas pollution emissions and energy input limitations for melting. Assuming that the first four limitations don't actually restrict an increased pull, heat transfer and heat balance calculations show that glass pull reaches 344 t/d, raised by 32.3%. The wet batch mass that enters the preheater is 4.2 kg/sec (362.8 t/day). Batch is preheated to 302 °C and flue gases are cooled down to 209 °C. The total volume flow of the flue gases is 14369 Nm^3/h, where 3713 Nm^3/h pass through the upper stream and 10656 Nm^3/h pass through the lower stream. From the flue gas an amount of 1702.4 kW is recovered and the efficiency of the preheater is 55.9%. The specific energy consumption is 2736.4 kJ/kg, reduced by 24.4%. Even though fuel consumption is unchanged, specific energy consumption is reduced due to the decrease of the exhaust gas temperature and the increased glass pull. Specific CO_2 emissions are 0.184 kg CO_2/kg glass, reduced by 20.8%. The calculated energy flows for the whole furnace-preheater system are presented in Tables 4 and 5.

Table 4. Calculated heat input of the furnace – preheater system for an increased pull rate

Calculated heat input	*kW*	kJ/kg glass	%
Fuel	10895.7	2768.8	98.5
Batch	68.4	17.2	0.6
Air	94.1	23.9	0.9

Table 5. Calculated heat output of the furnace – preheater system for an increased pull rate

Calculated heat output	*kW*	kJ/kg glass	%
Water evaporation + soda dehydration	236.6	59.4	2.1
Endothermic reactions	347.6	87.3	3.1
Heat carried by glass	6461.5	1622.9	58.4
Flue gases downstream the batch preheater	1231.7	309.4	11.1
Conduction through furnace walls	2016.8	506.6	18.2
Cooling and leakage	404.6	101.6	3.7
Regenerator losses	249.5	62.7	2.3
Preheater losses	109.0	27.4	1.0

4.1.3. Combined fuel reduction and increased pull rate case (case3)

Since an increase in glass pull by 32.3% is not always possible, at this third case, glass pull is set to 286t/d, raised by 10% and wet batch mass that enters the preheater is 3.49 kg/sec (301.6 t/day). According to heat transfer and heat balance calculations the specific energy consumption is reduced by 20% and fuel consumption is reduced by 12%. Flue gases are cooled down to 210°C and batch is preheated to 313°C. The total volume flow of the flue gases is 12615 Nm^3/h, where 3425 Nm^3/h pass through the upper stream and 9190 Nm^3/h pass through the lower stream. From the flue gas an amount of 1478.9 kW is recovered and the efficiency of the preheater is 55.2%. Specific energy consumption decreases due to the increased glass pull and the reduction of the exhaust gas temperature and mass. Specific CO_2 emissions are 0.193 kgCO_2/kg glass, reduced by 17%. The calculated energy flows for the whole furnace-preheater system are presented in Tables 6 and 7.

Table 6. Calculated heat input of the furnace – preheater system combining reduced fuel consumption and increased pull rate

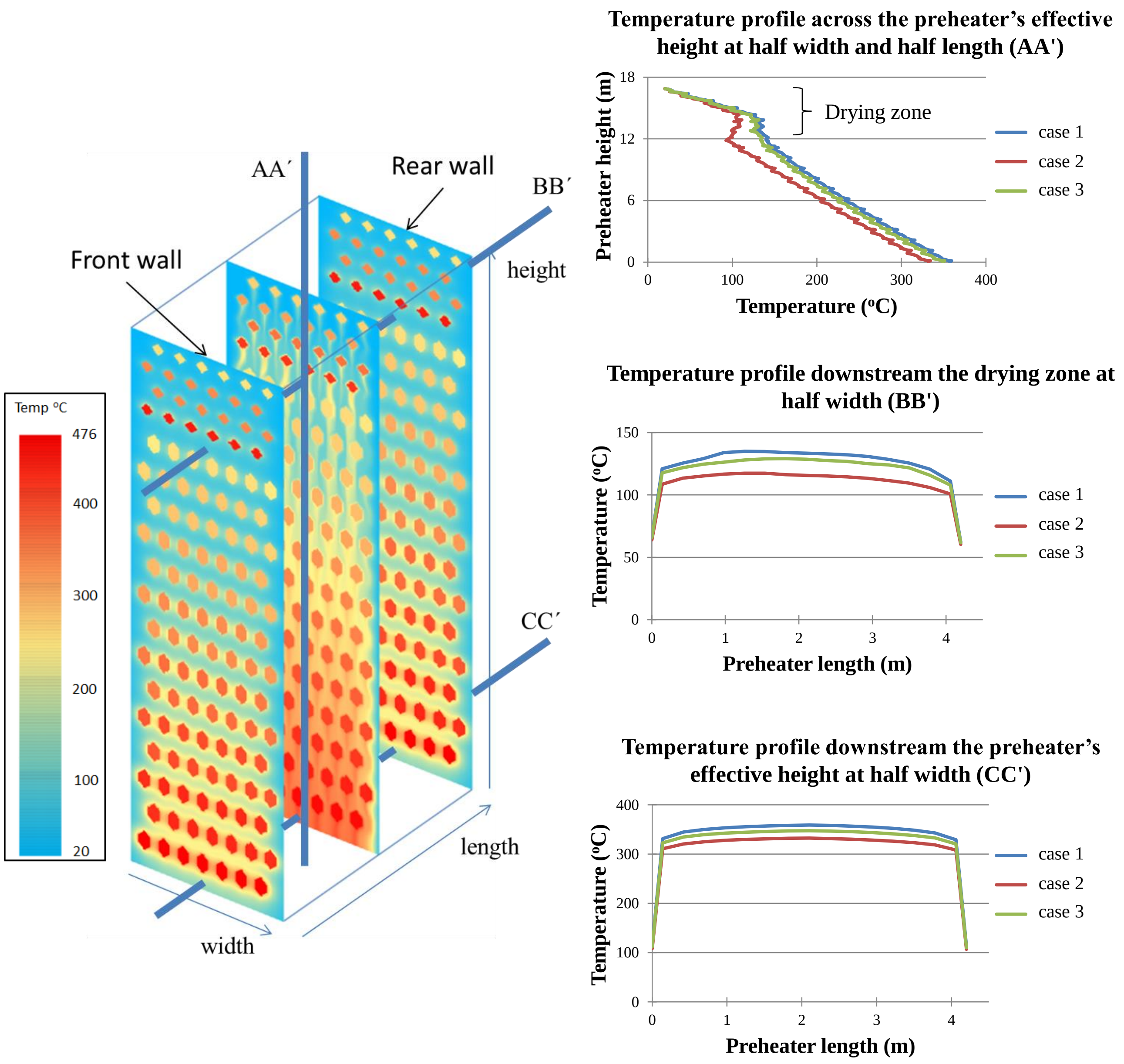
Calculated heat input	*kW*	kJ/kg glass	%
Fuel	9582.6	2894.9	98.6

Batch	56.9	17.2	0.6
Air	82.7	23.9	0.8

Table 7. Calculated heat output of the furnace – preheater system combining reduced fuel consumption and increased pull rate

Calculated heat output	*kW*	kJ/kg glass	%
Water evaporation + soda dehydration	196.7	59.4	2.0
Endothermic reactions	289.0	87.3	3.0
Heat carried by glass	5367.1	1621.4	55.2
Flue gases downstream the batch preheater	1086.4	328.2	11.2
Conduction through furnace walls	2016.8	609.3	20.7
Cooling and leakage	404.6	112.2	4.2
Regenerator losses	249.5	75.4	2.6
Preheater losses	112.0	33.8	1.2

For all three cases described above (4.1.1 – 4.1.3), the exported temperature profiles of the batch preheater are presented in Fig. 3.



Temperature profile across the preheater's effective height at half width and half length (AA')

Temperature profile downstream the drying zone at half width (BB')

Temperature profile downstream the preheater's effective height at half width (CC')

Fig. 3. Temperature profiles along the effective height of the preheater

4.2. Sensitivity analysis

At a specific batch preheating installation, the available heat content of the incoming flue gases is determined by the furnace – air regenerator operation and is considered as constant. In order to increase the temperature of the preheated batch and consequently the amount of the energy recovered, the residence time of the batch in the preheater has to be raised. Residence time can be raised by changing the preheater dimensions, as far as the batch flow is assumed constant. In the following analysis the length of the preheater was examined with respect to batch residence time.

A sensitivity analysis has been carried out where four designs of the preheater (A, B, C and D) are examined based on the regenerative container glass furnace data presented in Table 1. The length of each design A, B, C and D is 1.5m, 3m, 4.2m and 6.75m respectively, while every other designing parameter remains unchanged as described above at 4.1. Two different configurations are investigated. At the first configuration (as case 1), glass pull is kept constant at 260 t/d and fuel consumption is reduced. At the second configuration (as case 2), fuel consumption remains constant at 10.9 MW and glass pull is accordingly increased. The effect of the preheated batch temperature on the specific energy consumption is examined for both configurations and presented in Fig. 4 for each one of the four designs. The effect of an increased glass pull while energy inputs remain constant, examined at the second configuration, on the specific energy consumption is presented in Fig. 5. It is expected that, as the length of a preheater increases, the overall surface of the ducts is proportionally increased and the velocity of the batch that moves down the preheater decreases. As a result, the residence time of the batch inside the preheater increases, the efficiency of the preheater increases and the specific energy consumption of the entire glass production plant is reduced.

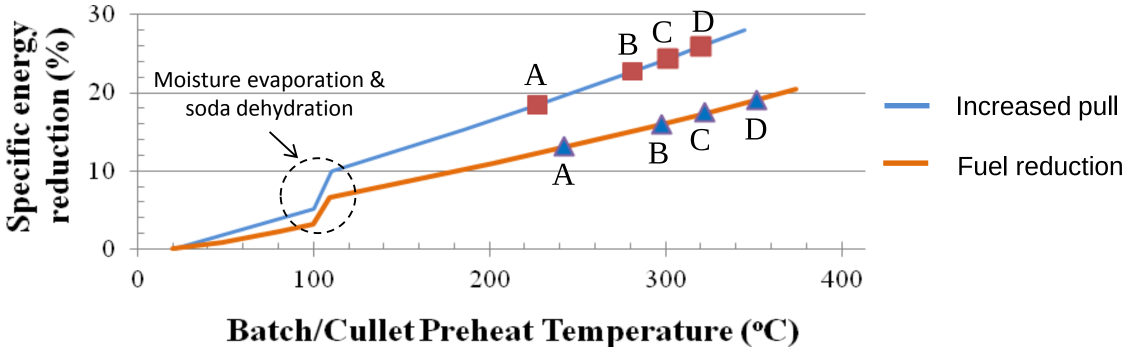


Fig. 4. Effect of preheated batch temperature on specific energy consumption in a regenerative glass furnace by examining designs A, B, C and D with varying length

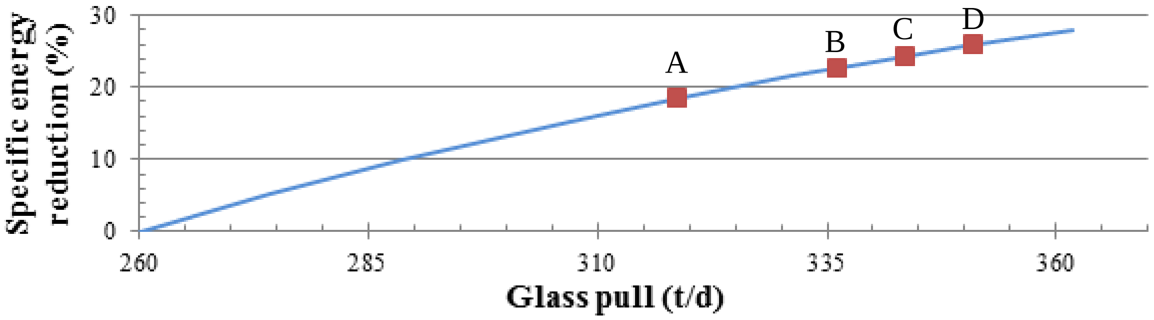


Fig. 5. Effect of increased glass pull on specific energy consumption in a regenerative glass furnace with batch preheating operating with 10.9 MW energy input by examining designs A, B, C and D with varying length

5. Conclusions

The utilization of batch preheating is still limited although the technology is now mature and problems such as dust carry-over and material plugging can be overcome according to current experience. Batch preheating is one of the best available techniques that lead in high energy savings and can increase production rates, as well as reduces CO_2 emissions.

A computational model that simulates the preheating process has been developed in order to be used to study the effect of various parameters, such as flue gas temperature, batch moisture content, preheater's dimensions etc., towards the optimization of the operation of a glass industry plant. An efficient regenerative container glass furnace has been studied, where the pull rate of the furnace is 260t/d, the energy input is 10.9MW while the specific energy consumption is 3620 kJ/kg. In the case where flue gases are cooled down from 476 °C to 209 °C and glass pull is kept constant, the specific energy consumption is reduced by 17.5% while batch is preheated to 322 °C and the efficiency of the preheater is 55.1%. Moreover, when fuel consumption remains constant, glass pull can be raised by 32.3% leading to a reduction of the specific energy consumption by 24.4% while batch is preheated to 302 °C and the efficiency of the preheater is calculated at 55.9%. In the case of both options applied with glass pull increase by 10% and use of batch preheater, a reduction of the specific energy consumption by 20% is observed while batch is preheated to 313 °C and the efficiency of the preheater is calculated at 55.2%. The results show that higher specific energy savings occur when batch preheating is combined with an increased glass pull. A sensitivity analysis indicates that an increase of the preheater's length from 4.2m up to 6.75m, leads to a further decrease in the specific energy consumption, which is reduced by 19.1% in overall when glass pull is kept constant and by 25.9% when fuel consumption remains constant and glass pull is increased.

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