

WASTE HEAT RECOVERY AT THE GLASS INDUSTRY WITH THE INTERVENTION OF BATCH AND CULLET PREHEATING

by

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A promising option to reduce the specific energy consumption and CO₂ emissions at a conventional natural gas fired container glass furnace deals with the advanced utilization of the exhaust gases downstream the air regenerators by means of batch and cullet preheating. A 3-D computational model that simulates this process using mass and heat transfer equations inside a preheater has been developed. A case study for an efficient small-sized container glass furnace is presented dealing with the investigation of the impact of different operating and design configurations on specific energy consumption, CO₂ emissions, flue gas energy recovery, batch temperature and preheater efficiency. In specific, the effect of various parameters is studied, including the preheater's dimensions, flue gas temperature, batch moisture content, glass pull, combustion air excess and cullet fraction. Expected energy savings margin is estimated to 12-15%.

Key words: energy efficiency, waste heat recovery, batch preheating, modeling, glass industry, CO₂ emissions

Introduction

Increasing trends of fossil fuel prices during last decades and the implementation of the European emission trading scheme (ETS) is forcing glass industries to reduce CO₂ emissions mainly through fuel consumption. Currently, CO₂ certificate prices cost less than 10 €/tCO₂ while, in the future, prices are expected to elevate and the cost of glass manufacturing will be raised. Glass production is an energy intensive process, where most of the energy is consumed in the furnace, therefore, efforts are focusing on furnace energy reduction methods [1]. During the past decades, these efforts targeted on the use of recycled cullet, improvement of furnace design and combustion control, increased insulation, new process sensors and more effective regenerators.

One option to reduce the specific energy consumption and CO₂ emissions deals with the advanced utilization of the exhaust gases which have a heat content that corresponds to 25-30% of the furnace energy input [2]. The exhaust gas temperature downstream the air regenerators is in the magnitude of 400-500 °C and can reach 700 °C or higher with recupera-

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tors of air-fired furnaces while at oxygen-fired glass melting furnaces is higher than 1,100 °C. Waste heat recovery systems proposed for the glass industry include electricity generation, steam or hot water generation, thermochemical recuperation, natural gas preheating and batch/cullet preheating. The assessment of energy balance at a glass plant has shown that for a 450-500 °C heat source temperature level, ORC systems and water steam Rankine cycle systems result into an electric efficiency of 15-19% [3]. Steam or hot water can be produced through appropriate heat exchangers for internal or external (supplied to third parties) utilization, which specifically can deal with building heating and cooling or used for industrial processes in neighboring facilities [4]. Thermochemical recuperation systems use the recovered heat in order to convert natural gas to hot synthesis gas, which mainly contains CO and H₂ and has higher energy content than natural gas. The conversion reaction is highly endothermic and the installation of such a system is most appropriate for oxy-fuel or recuperative furnaces since the temperature required inside the reformer is 800-900 °C [5]. Preheating of natural gas at a temperature of about 350-400 °C has already been applied in a few industries, especially in oxy-fuel furnaces while the installation of this application leads to specific energy savings in the order of 3% [5].

Recent studies concerning energy balance modeling for all furnace parts including batch preheating investigate the effects on energy consumption of changing parameters such as cullet fraction, amount of gas, boosting heat, air excess, raw material composition, refractory insulation and cold air leakage [6] while, in another study, CFD analysis of the heat transfer from flue gas to a single granule is used to estimate the height of a pre-heater with counter-current flow [7]. Additional recent studies in the Glass Industry focus mostly on NO_x and CO₂ emission reductions by staged combustion techniques [8] or by auxiliary fuel injectors burning the excess oxygen in the combustion products [9], while NO_x emissions abatement and energy efficiency increase can be accomplished by thermo-chemical regeneration at oxy-fuel furnaces [10].

The current paper aims to further investigate, by means of modeling the batch and cullet preheating option at a conventional natural gas fired container glass furnace, the different operating and design configurations on specific energy consumption, CO₂ emissions, flue gas energy recovery, batch temperature and preheater efficiency. The novelty of the current work lies in the fact that the modeling process simulates all the mass and heat flows inside a batch preheater and calculates the amount of energy related to endothermic reactions during batch preheating such as batch moisture evaporation and soda ash dehydration. The ultimate aim is to support the European Glass Industry in confronting the challenges which occur with the 2030 climate and energy targets for a 40% emissions reduction by 2030 in comparison to 1990 levels and a minimum of 27% improvement in energy efficiency.

Batch and cullet preheating

Batch and cullet preheating deals with exhaust gas waste heat utilization to preheat the batch and cullet mixture which is normally fed into the furnace without any additional heating input. This concept returns recovered energy directly back into the melting process and is consequently not susceptible to external factors while it can be applied at the existing glass production chain without interrupting the process. Batch and cullet is preheated to about 300 °C while flue gases are cooled down by 200-250 °C. Reported energy savings for regenerative air-fired glass furnaces range between 12-20% [11] while emissions of CO₂ and NO_x are reduced in line with the energy savings [12]. Glass pull can be increased, exceeding the designed furnace capacity [5], while the energy produced through electric boosting can be

decreased [13]. Thus, 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. Investment costs depend on the size and type of the preheater, while its operating period is about 20 years and pay-back time of 2-3 years [5] and of less than 5 years has been reported [2]. Other benefits associated to the operation of a batch preheater include the reduction of furnace wall temperatures [14], the removal of SO, HCl, and HF from the waste gases, since the batch acts as a scrubbing agent at direct contact systems, and the recovery of selenium during flint glass production [2].

Despite the fact that batch preheating is a process that has been investigated for over 30 years, only a few systems are in commercial use due to technical side effects that could cause serious equipment and handling problems. A major defect of the 1st generation systems was the evaporation of batch moisture and the dehydration of soda ash [15], resulting into material clump formation that causes blocking of the batch flow inside the preheater. In order to avoid such problems, 1st generation batch preheating systems required the minimization of the water content and thus the use of cullet ratios above 50% was obligatory. Another significant drawback was the increased dust carry-over by combustion gases being in contact with the batch blanket inside the furnace. These fine particles may deposit on the regenerator surface causing fouling of the regenerator checkers [16]. Additional limitations of the current application include:

- large space requirements since the batch preheater should be close to the furnace doghouse to avoid further dusting problems and heat losses from the transport system,
- deterioration of the preheater structure due to corrosion and high temperatures, and
- odor issues in case of increased organic compound at the cullet [11].

Nowadays the technology enabling the amelioration of dusting problems and the safe removal of humidity during batch preheating is developed according to current experience.

There are several different types of batch and/or cullet preheating systems applied in the glass industry or still in pilot scale. At combined batch and cullet preheaters, heat can be transferred through direct or indirect contact between the batch and the hot flue gases while at cullet – only preheaters, cullet is preheated by direct contact with either the flue gases or steam [5]. According to the literature review, three different batch and cullet preheating systems have already been applied in the container glass industry, namely the so-called ‘Nienburger-type’ direct batch preheater, the *Zippe-type* indirect batch preheater and the *Sorg Batch-3* system. The Nienburger-type preheater is a direct contact heat exchanger developed by Interprojekt [12], presented in fig. 1. Hot flue gases flow downstream the air regenerator through the preheater in several layers 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.

Zippe Industrieanlagen GmbH has developed a cross counter flow indirect preheater in which there is no direct contact between flue gases and the batch. The system is constructed by individual heat exchange modules stacked up vertically [15]. 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 are 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 is also reported that Zippe has developed a 2nd generation advanced batch preheating system

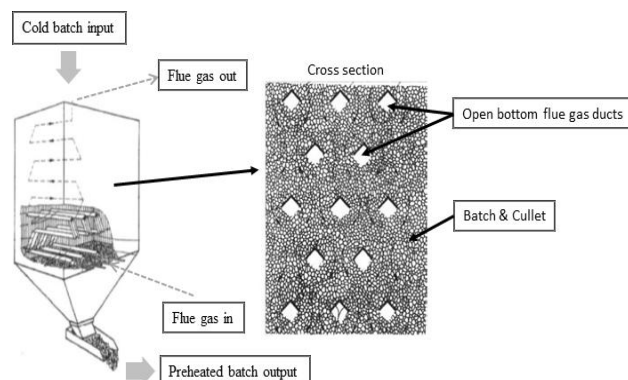


Figure 1. Basic concept of the batch preheating system Nienburger type [16]

that constitutes a hybrid between the indirect and the direct preheating system, combining both close and open-bottomed ducts [11] while a new batch preheater that can handle up to 400 tons/day was successfully commissioned for Nampak Glass in South Africa during 2015 [17]. Sorg GmbH batch preheater is part of the so called batch-3 concept which is comprised by the preheater, a charging machine that consists of multiple screw charges and a pusher and a specially designed doghouse. Sorg has installed two preheating systems at Wiegand

Glas industry between 2011 and 2013. Reported specific energy requirements have decreased by 14% while the melting capacity of the furnace has increased by 8%.

Batch preheating simulation algorithm

A 3-D computational model is presented that simulates the mass and heat flows inside a batch preheater towards its optimisation. 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. Heat transfer mechanisms include flue gas convection and radiation with surrounding cells, solid and bulk phase conduction, solid to ambient convection and bulk phase convection due to bulk phase movement. Batch input rate is considered constant throughout the simulation period and, as a result, velocity profiles are calculated only once at the initial stage of the algorithm. Continuity equation is used to calculate the mass rate of the batch that flows down the preheater at each computational cell and velocity profiles are estimated using boundary layer equations according to Karman-Pohlhausen method [18]. As flue gases pass inside a duct, heat is transferred to the inner duct walls by convection and radiation:

$$d\dot{q} = \left[h_{gas} (T_{gas} - T_w) + \varepsilon_{gas} \sigma (T_{gas}^4 - T_w^4) \right] A \quad (1)$$

in which $d\dot{q}$ is the heat rate, h_{gas} is the convection coefficient, ε_{gas} is the emissivity coefficient, σ is the Stefan-Boltzmann constant, T_w is the solid wall temperature, T_{gas} is the flue gas temperature and A is the surface of the cell. Flue gas convection and emissivity coefficients are calculated using the correlations below:

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

$$\varepsilon_{gas} = \varepsilon_{CO_2} + \varepsilon_{H_2O} - \Delta\varepsilon \quad (3)$$

in which k_{gas} is the conduction coefficient of the flue gas, Nu is the Nusselt number, D_H is the hydraulic diameter of the duct, ε_{CO_2} is the CO_2 emissivity coefficient, ε_{H_2O} is the H_2O emissivi-

ty coefficient and $\Delta\varepsilon$ is the emissivity correction factor. Between solid and bulk phase elements heat is transferred by conduction. The governing partial differential heat conduction equation in three dimensions is:

$$c_p \rho \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left(k_x \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k_y \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(k_z \frac{\partial T}{\partial z} \right) \quad (4)$$

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 the heat flow [19]. Assuming that the net heat conductivity of a mixture of solid components is given by:

$$k_s = \sum_{i=1}^n w_i k_{i,s} \quad (5)$$

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:

$$k = \phi k_{air} + (1 - \phi) k_s \quad (6)$$

The porosity of the multicomponent mixture is given by:

$$\phi = 1 - \frac{\rho_b}{\sum (w_i \rho_{s,i})} \quad (7)$$

in which $\rho_{s,i}$ 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 walls to the environment. The predominant heat transfer mechanism is convection. Heat loss rate to ambient is given by:

$$d\dot{q} = h_{air} (T_{air} - T_w) A \quad (8)$$

in which h_a is the ambient air convection coefficient and T_a is the ambient temperature. Due to the physical batch moisture and soda ash dehydration, 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 ($\text{Na}_2\text{CO}_3 \cdot \text{H}_2\text{O}$) 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 is 3,265 kJ/gH₂O. The heat absorbed during water evaporation and soda dehydration appears as a sink of heat in subsequent calculations of the bulk phase energy equation.

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 according to an energy balance equation. The flow chart of the algorithm is presented in fig. 2.

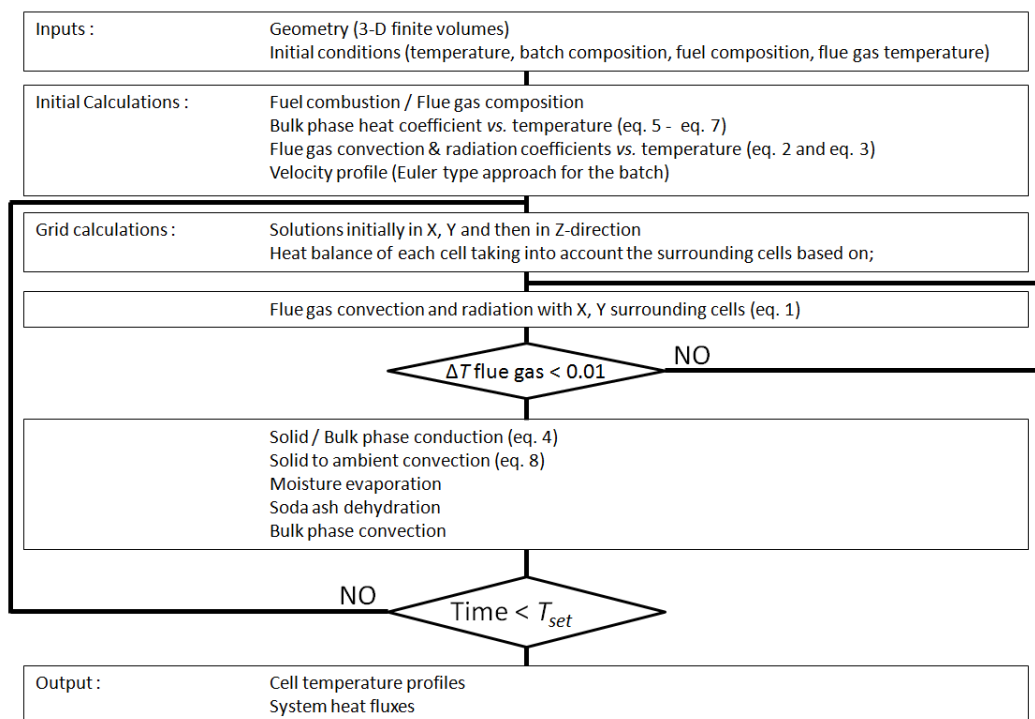


Figure 2. Model flow chart

The heat transfer model described above is also coupled with energy balance calculations for the furnace-preheater system in order to adjust the volume of the flue gases that enter the preheater as specific fuel 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 while process CO₂ emissions depend on the cullet content and the glass pull.

Case study for batch preheating installation

A case study based on a small end-fired regenerative container glass furnace has been constructed [20]. At first, furnace characteristics, that originally operates without a batch preheating system, are examined. Consequently the exhaust gases waste heat recovery potential is calculated and the configuration of a proposed batch and cullet preheater is discussed. A baseline scenario is determined according to the furnace nominal operational conditions and simulation results concerning specific energy consumption and CO₂ emissions levels after the installation of the proposed batch preheating system are presented. Subsequently, a sensitivity analysis is performed in order to evaluate the performance of the preheater under different operating conditions and estimate specific energy savings and CO₂ reduction potentials in relation to the initial operating conditions of the furnace.

The heat flows inside the furnace without batch preheating are presented in fig. 3 while the basic data of the process are:

- glass pull of 90 t/d,
- 40% cullet in mixture,
- 4% batch humidity,
- 3,833 kJ/kg energy consumption, and
- no electric boosting.

Under current pull draw, fuel consumption corresponds to 3.99 MW. Assuming that the natural gas CO₂ emission factor is 56.1 CO₂/MJ, the fuel derived CO₂ emissions are 0.215 kgCO₂/kg glass. Process derived CO₂ emissions, emitted during the calcination of limestone, dolomite and soda ash are 0.106 kgCO₂/kg glass and overall CO₂ emissions are 0.321 kgCO₂/kg glass. The calculated flue gas volume flow downstream the regenerator is 4,508 Nm³/h assuming 2% oxygen content and its temperature is 460 °C, based on mass and energy balance of the initial configuration of the plant. As a result the exhaust gases waste heat recovery potential corresponds to 826 kW.

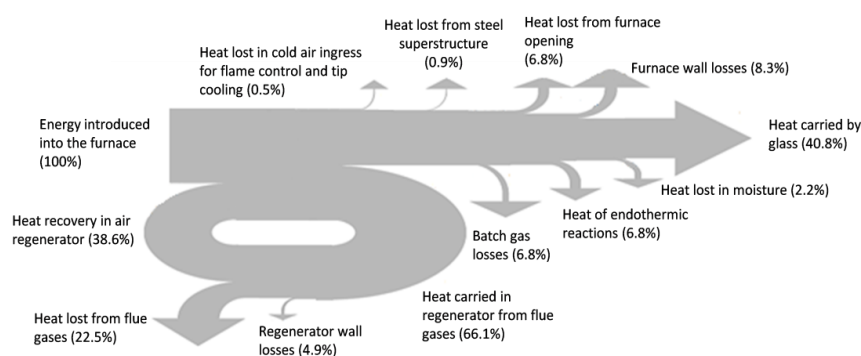


Figure 3. Sankey diagram for base case [20]

Configuration of the batch preheater

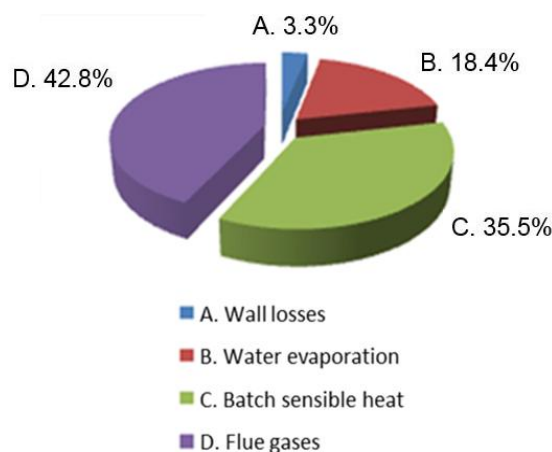
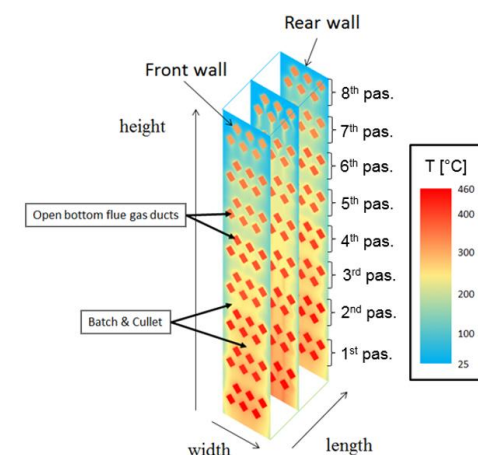
The proposed preheater dimensions used under the following simulations are taken as 2 m long, 1.9 m wide while its effective height was 10.5 m. The preheater is a direct system where a stream of flue gases arranged in multiple layers of open-bottomed ducts passes through the preheater (fig. 1). Specifically, flue gases flow in a cross-counter direction compared to the moving batch and cullet mixture through 6 ducts that pass 8 times through the preheater while at the end of every passage ducts are connected to a gas collector. The current design of the ducts ensures that the velocity of the flue gases remains less than 8 m/s. 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 was assumed of 45°. Flue gas temperature downstream the preheater is limited to 220 °C due to the risk of condensation and to ensure correct filter and stack operation. The input parameters of the model are presented in tab. 1.

At the first stage of the process, batch and cullet is mixed before entering the preheater according to the desired recipe and then conveyed to the top of the preheater. The wet batch mass enters the preheater with a rate of 103.5 t/d and moves down through the preheater due to gravity with a speed of ~1 m/h. According to simulation results, flue gases are cooled down from 460 °C to 220 °C while the batch is completely dried and preheated to 210 °C, recovering 429 kW from the flue gas stream. The total volume flow of the flue gases is re-

Table 1. Model input parameters

Parameter	Value
$c_{p,b}$ [$\text{J kg}^{-1} \text{K}^{-1}$]	$565.1 + 0.947 T$ [19, 21, 22]
$c_{p,w}$ [$\text{J kg}^{-1} \text{K}^{-1}$]	$376.5 + 0.304 T$
k_b [$\text{W m}^{-1} \text{K}^{-1}$]	$0.5798 + 0.0005 T, T < 100\text{ }^\circ\text{C}$ $0.3865 + 0.0003 T, T > 100\text{ }^\circ\text{C}$ [19, 23-25]
k_w [$\text{W m}^{-1} \text{K}^{-1}$]	$0.0335 T + 6.898$
ρ_b [kg m^{-3}]	1,550
ε_b	0.4
T_{air} [$^\circ\text{C}$]	25

of the batch preheater simulation for the base case are presented in fig. 5.

**Figure 4. Preheater energy balance for base case****Figure 5. Temperature profiles along the effective height of the preheater**

Sensitivity analysis

At the current work, a benchmark study [20] concerning a small container glass furnace without batch preheating was used in order to evaluate the performance of the proposed batch and cullet preheater, as described above, under various operating conditions. Parameters evaluated include glass pull, cullet fraction, combustion excess air, batch moisture content, flue gas temperature, air leakage as well as the preheater's dimensions. Specific energy savings and CO₂ reduction percentage presented at subsequent results are calculated in relation to the initial operating conditions of the furnace, prior to the proposed batch preheater installation.

Glass pull

At typical load variation (above 70%), the preheater's efficiency and specific energy savings percentage are reduced as glass pull rises since the amount of flue gas energy recovery potential per kg of batch decreases (fig. 6). The efficiency of the preheater peaks at 40-50% of the furnace full capacity load, while as glass pull further decreases, the preheated batch temperature increases resulting in reduced heat transfer rates and increased structural losses.

duced from 4,508 Nm³/h to 3,950 Nm³/h due to fuel consumption reduction. The specific energy consumption is 3,322 kJ/kg reduced by 13.3% compared to the original configuration of the furnace. Specific energy consumption is reduced as both the mass and the temperature of the exhaust gases decrease. CO₂ emissions are 0.293 kgCO₂/kg glass, reduced by 8.9%. The efficiency of the preheater reaches 53.9% while its energy balance is presented in fig. 4 and its efficiency reaches 53.9%. Temperature profiles

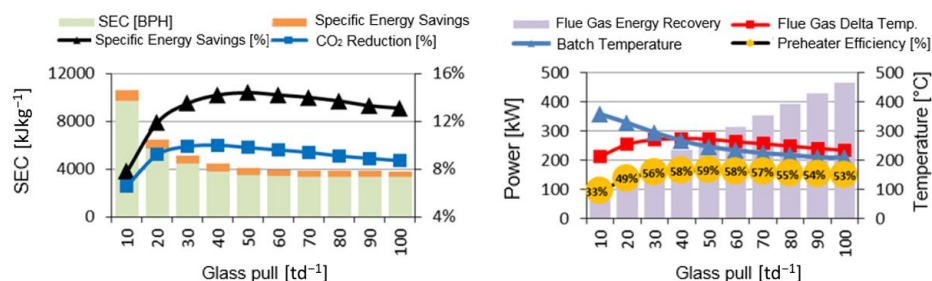


Figure 6. Effect of glass pull on the preheater's operation

Cullet content

Glass cullet is recycled glass originating from either external market recycling or internal defected products. As cullet content in the batch raises, specific energy consumption decreases resulting in reduced flue gas energy recovery potential since combustion gases flow rate is decreased. Nevertheless, an increment in the cullet content results in enhanced preheater efficiency, while the preheated batch temperature slightly rises as well (fig. 7).

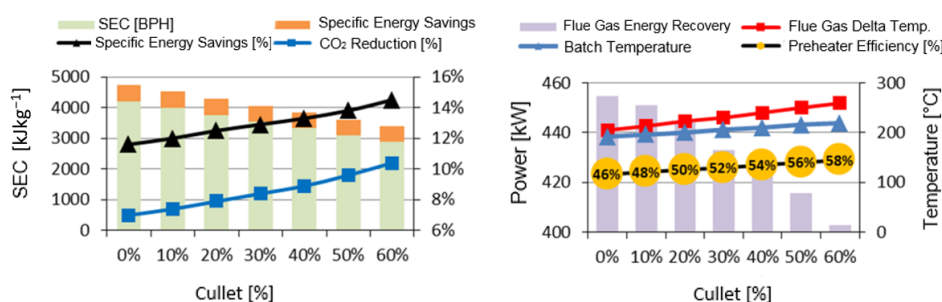


Figure 7. Effect of cullet content on the preheater's operation

Excess air

The optimum excess air level for combustion is about 10% while increased excess air levels result in elevated flue gas heat losses to ambient. In relation with the preheater's operation, as flue gas oxygen percentage raises, the overall mass of the exhaust gases coming into the preheater and the specific energy savings percentage increase although the efficiency of the preheater drops (fig. 8).

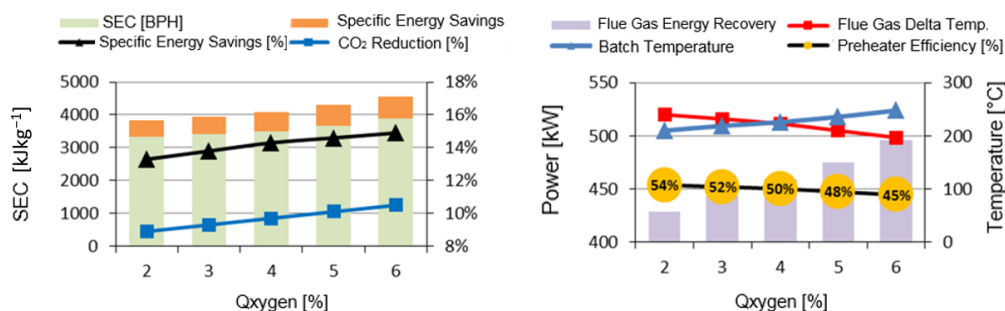


Figure 8. Effect of flue gas oxygen percentage on the preheater's operation

Batch moisture

Batch is normally sprayed with water before entering the furnace in order to avoid batch de-mixing during transport, improve melting kinetics, ensure glass quality consistency and reduce dust carry-over [26]. Heating up the batch inside a preheater dries the batch completely and prevents moisture from entering the furnace. At the base case scenario, the energy for evaporating batch moisture inside the batch preheater accounts 34% of the overall energy transferred to the raw material mixture. According to simulations, as moisture percentage raises specific energy consumption and specific energy savings percentage both increase (fig. 9). Nonetheless, high water content may compromise the operation of the preheater since water evaporation results into the creation of agglomerations that lead to blocking problems of the batch flow inside the preheater.

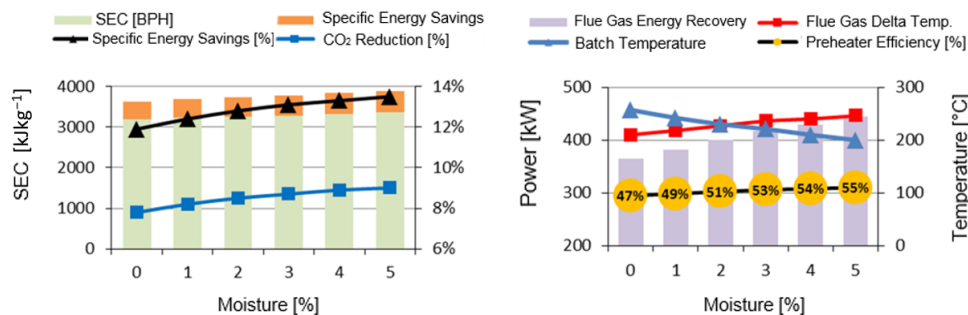


Figure 9. Effect of batch moisture content on the preheater's operation

Exhaust gas input temperature

The theoretical efficiency limit value of a regenerator ranges between 75-78%, while in practice, the efficiency of a cost effective regenerator is about 70% [27]. Simulation results indicate that specific energy savings percentage increases as flue gas temperature and mass flow downstream the regenerator increase due to reduced efficiency of the air regenerator (fig. 10).

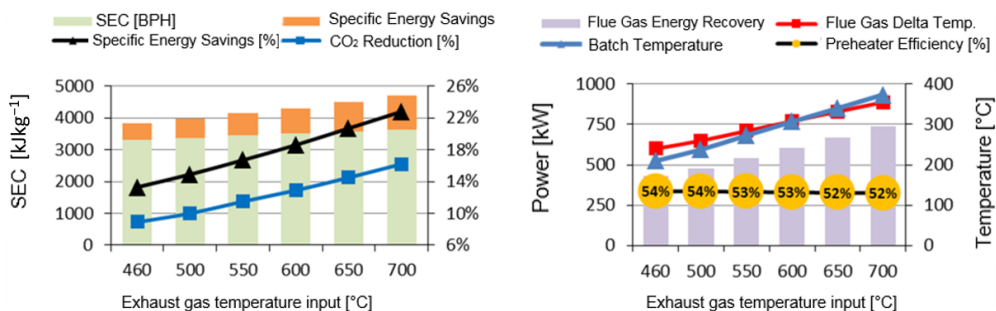


Figure 10. Effect of exhaust gas temperature input on the preheater's operation

Air leakage

Infiltration of cold air through the furnace and regenerator walls results in increased energy consumption since the requirement of preheated air from the regenerator is diminished

[28]. The amount of air leakage affects the operation of the preheater in the same way as excess combustion air levels do. In particular, as air leakage percentage increases, the overall mass of the exhaust gases entering the preheater and the preheated batch temperature increases, while the efficiency of the preheater lessens (fig. 11).

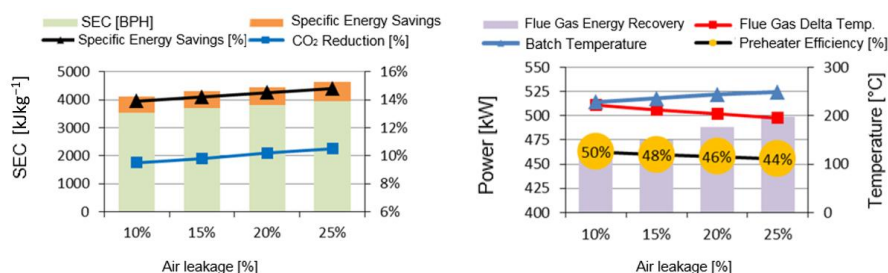


Figure 11. Effect of air leakage on the preheater's operation

Preheater's dimensions

At a certain batch preheating installation, the available heat content of the incoming flue gases is determined by the furnace – air regenerator operation. The amount of the energy recovered depends on the temperature of the preheated batch as shown in fig. 12. In order to increase the temperature of the preheated batch, the residence time of the batch inside the preheater and the overall surface of the flue gas ducts have to be raised.

A sensitivity analysis was carried out where the length and the height of the preheater are altered while glass pull is kept constant at 90 t/d, in agreement with the basic scenario, and fuel consumption is accordingly reduced. At first, the length of the preheater varies between 1-6 m while every other designing parameter remains unchanged. At the second case the length of the preheater is set to 2 m while the number of duct passages ranges between 4 and 18 passages and, as a result, the preheater height ranges between 5.6 and 23.8 m. Simulation results for each preheater configuration with respect to the flue gas temperature downstream the preheater and the temperature of the preheated batch are presented in fig. 13.

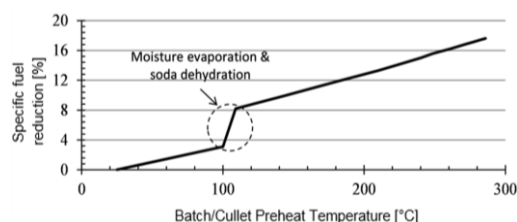


Figure 12. Effect of preheated batch temperature on specific energy consumption

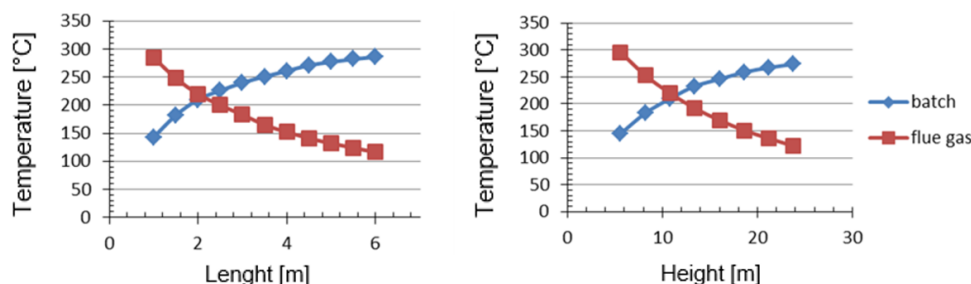


Figure 13. Effect of preheater's length and height on batch and flue gas temperature

Conclusions

Batch and cullet preheating is one of the best available techniques that leads in improved energy efficiency and reduced CO₂ emissions. Over the past 30 years more than 10 preheating systems have been installed resulting in specific energy savings of 12-20% while problems such as dust carry-over and material plugging can be currently overcome.

A computational model that simulates the mass and heat flows inside a batch and cullet preheater has been developed. The model can be used as a predictive tool for the quantification of potential reduction of fuel consumption and respective CO₂ emissions reduction aiding the designer to evaluate the performance of a preheater and maximize its efficiency with respect to flue gas exhaust gas temperature limitations and furnace operational characteristics.

An efficient regenerative container glass furnace has been studied, where the pull rate of the furnace is 90 t/d, the energy input is 3.99 MW and the specific energy consumption is 3,833 kJ/kg. In the case where flue gases are cooled down from 460 °C to 220 °C the specific energy consumption at the furnace is reduced by 13.3%, CO₂ emissions are reduced by 8.9% while batch is preheated to 210 °C and the efficiency of the preheater is 53.9%. The effect of various parameters is studied, including glass pull, cullet fraction, combustion air excess, batch moisture content, flue gas temperature and air leakage. The results focus on the variation of specific energy consumption of the entire furnace – preheater system, CO₂ emissions reduction, batch preheater efficiency, preheated batch and exhaust gas temperature downstream the batch preheater. Simulations indicate that the inefficiency of the regenerator, the increased batch moisture content or the increased air leakage that lead in specific energy consumption increase can be partially balanced by the use of a preheater. In addition, a sensitivity analysis of the preheater's dimensions shows that increasing the preheater's dimensions results in a logarithmic increase of the preheated batch temperature and a logarithmic decrease of the flue gas temperature downstream the preheater.

Results demonstrate that there is potential towards achieving significant energy savings of 12-15% and respective CO₂ emissions reduction so that the European Glass industry may support the goals imposed by the 2050 European Low Carbon Economy Roadmap while maintaining its competitiveness. Future work concerns the application of the suggested process alteration and its replication to EU Glass Industry so as to sustain the EU 2050 Low Carbon Economy goal for an 80% emissions reduction in comparison to 1990 levels. In addition, the specific batch preheating process is significant as to its replication potential because it is suited as promising for heat recovery and melting capacity increase according to the latest Reference Document for the glass industry under the Industrial Emissions Directive [27]. The continuation of the current work concerns industrial testing of the model and additional energy efficiency improvement for the EU Glass Industry. The approach on the Waste Heat Recovery suggested, recognizes the importance of research and innovation for the development of more cost-competitive technologies, urged by the increasing average capital costs of the energy system as acknowledged by the European Commissions' Energy Roadmap [29].

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Nomenclature

A	– surface, [m ²]
c_p	– specific heat capacity, [Jkg ⁻¹ K ⁻¹]
$d\dot{q}$	– heat rate, [W]
D_H	– hydraulic diameter of the duct, [m]
h	– convection coefficient, [Wm ⁻² K ⁻¹]
k	– conduction coefficient, [Wm ⁻¹ K ⁻¹]
Nu	– Nusselt number, [–]
T	– temperature, [K]
w	– weight fraction, [–]

Acronyms

BPH	– batch preheating
SEC	– specific energy consumption

Greek symbols

ε	– emissivity coefficient, [–]
$\Delta\varepsilon$	– emissivity correction factor, [–]
ρ	– density, [kgm ⁻³]
σ	– Stefan-Boltzmann constant, [Wm ⁻² K ⁻⁴]
φ	– batch porosity, [–]

Subscripts

air	– ambient air
b	– batch
gas	– flue gas
s	– solid particle
w	– solid wall

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