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A technology comparison concerning scale dependencies of industrial furnaces. A case study of glass production.

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Abstract

Industrial furnaces are analyzed continuously to identify optimization potentials. Process data from the glass industry suggest that the size of a plant has an important influence on the specific energy consumption. This leads to incorrect results when using key performance indicators (KPIs) for comparison purposes. Therefore, the evaluation of innovative industrial technologies, as the use of microwaves, is often affected by incomplete assumptions, since economies of scale are often disregarded. A thermodynamic model for energy consumption was developed for analysing the scale dependencies on the specific energy consumption. It contains a correction factor for KPIs. This factor will be compared and validated with industrial process data from literature and databases as well as experimental data for the microwave process. The paper shows the impact of existing scale dependencies and their importance for a comprehensive technology comparison.

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Keywords: KPI; economies of scale; thermodynamic model; energy consumption; glass

1. Introduction

Nowadays, energy efficiency plays an important role in energy intensive industrial processes. The European Union set a 20% energy efficiency target by 2020 for all stages of the energy chain from production to final consumption. Therefore, energy benchmarking of industrial furnaces and their processes is a necessary task.

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Nomenclature

$\dot{H}_{F,ch}$	Chemical enthalpy of fuel	$\dot{H}_{FG,ch}$	Chemical enthalpy of flue gases
$\dot{H}_{F,cal}$	Caloric enthalpy of fuel	$\dot{H}_{FG,cal}$	Caloric enthalpy of flue gases
$\dot{H}_{A,cal}$	Caloric enthalpy of combustion air	$\dot{H}_{LF,cal}$	Caloric enthalpy of leak flue gases
$\dot{H}_{EA,cal}$	Caloric enthalpy of excess air	$H''_{G,cal}$	Caloric enthalpy of goods
$\dot{Q}_{El}$	Electric energy	$\dot{H}''_{AG,cal}$	Caloric enthalpy of auxiliary material
$\dot{H}'_{G,cal}$	Caloric enthalpy of goods	$\dot{Q}_{C}$	Heat loss through cooling
$\dot{H}'_{AG,cal}$	Caloric enthalpy of auxiliary material	$\dot{Q}_{W}$	Heat loss through walls
$\dot{Q}_{ch}$	Chemical enthalpy of non-fuel	$\dot{Q}_{R}$	Heat loss through radiation from gaps
$\dot{E}$	Other sources	$\dot{Q}_{Tr}$	Enthalpy of transformation

It is needed to identify optimization potentials and energy efficiency management strategies. An additional promising way is the development of alternative technologies. These technologies might have a chance to contribute to an energy reduction in energy intensive industries. The glass production is one of the most energy intensive industries in Europe by today resulting in high energy consumption. Glass with its many applications and products, which can be manufactured from it, plays an important role in technological processes in industry with a high consumption of glass of 60-80 kg per head of population per year [1]. Process data from the glass industry suggest that the size of a plant or the scale of operations have an important influence on the specific energy consumption. This leads to incorrect results when using key performance indicators (KPIs) for comparison purposes due to different limitations. Therefore, the evaluation of innovative industrial processes is often affected by incomplete assumptions, since economies of scale are often disregarded. Nevertheless, innovative concepts for the energy intensive glass technology sector exist. The microwave process was identified as a new and innovative technology promising a reduction of energy consumption in glass production. A comparison of those innovative technologies with conventional ones is challenging. In order to give an easy and fair comparison method, this paper presents a thermodynamic model, which was created for analyzing the scale dependencies as well as the specific energy consumption, which can be determined for different plants and sizes. This leads to a better comparison for innovative and conventional concepts with different conditions. It contains a correction factor for KPIs. This factor will be compared and validated with industrial process data from literature and databases as well as experimental data for the microwave process. Following the basic principles of a technology portfolio (TPF) analysis, the results are finally presented in a modified and streamlined portfolio matrix with five technology-based potentials for development taking into account the relevance of economies of scale applied for a case study in the field of glass production for validation purposes.

2. Thermodynamic model development for energy consumption

2.1. Glass production

The process of glass production consists of melting selected raw materials (the so called batch) in a glass furnace and afterwards processing the melt further to form the required product. Due to the fact that the processing technologies are very different, the melting capacities of the different furnaces are also very different and vary from some kilogram per day up to 800 and more tons per day. Most of the glass furnaces are operated in continuous processes using fossil fuels. Electricity is often used as an additional heating source, whereas fully electric furnaces are operated solely within the manufacturing of special glasses in low quantities. A very well-known type of continuously working furnaces is the glass tank furnace using regenerators with a periodic change of flame direction. [1] The operation temperature of a tank furnace lies between 1.450°C and 1.650°C and causes a high specific energy consumption in glass production. This fact is often associated with a low thermal efficiency of conventional plants. For this reason, microwave heating has been identified as a potential replacement technology for conventionally heated, gas-fired glass melting furnaces.

2.2. Model assumptions

For determining the energy consumption for any type of furnace, a thermodynamic model was developed. The model was chosen with regard to maximum versatility [2] and is shown as a sketch in Fig. 1. Energy balance models provide a good overview of energy fluxes to and from the furnace and are easy to understand. Using energy balance models is common practice in furnace design and analysis and can be used for all kinds of furnaces [3]. Energy conservation of mass $\dot{m}$ and energy $\dot{E}$ are assumed and can be written for continuous processes as

$$\sum \dot{m}_{In} = \sum \dot{m}_{Out} \tag{1}$$

and

$$\sum \dot{E}_{In} = \sum \dot{E}_{Out}. \tag{2}$$

$$\dot{H}_{LF,cal} = 5\% \cdot \sum \dot{E}_{In} \tag{3}$$

$$\dot{Q}_C = 5\% \cdot \sum \dot{E}_{In} \tag{4}$$

and

$$\dot{Q}_R = 2\% \cdot \sum \dot{E}_{In}. \tag{5}$$

Table 1 shows the temperatures used for the calculation, which are chosen from data compiled by Trier [1]. Although, all temperatures chosen represent the lowest value, it can be shown that these values by now represent the state of the art in industry compared with available data from [4].

The wall heat loss was calculated with heat transfer coefficients taken from Heiligenstaedt [5] and verified with basic heat transfer coefficient calculations based on VDI-Wärmeatlas [6]. According to [7], the theoretical energy consumption for heating and melting glass accounts for 2.045 MJ/t with a batch to be made up from 50% cullet. Further assumptions were made with

- Excess air is zero
- No auxiliary material is used
- Chemical enthalpy of non fuel is zero
- Only fuel is used for energy supply; other sources of energy are excluded
- Flue gas volume also includes gases formed by melting process

With the given assumptions and data, the required energy consumption can be calculated. By filling in the application-specific pull rate, the specific energy consumption for the setup can be calculated by the model.

2.3. Model limitations

The assumed simplifications limit general usability of the model. There are differentiations between end-fired and cross-fired furnaces. It is assumed, that all furnaces use a regenerator regardless of furnace size. In reality small scale furnaces would use neither a regenerator nor heat recovery. Geometry is, as stated above, as simplified as possible. The furnace and its regenerator are reduced to blocks. Superstructure and piping are not regarded. Losses through cooling and radiation are also simplified. But since newer furnaces require far less cooling than older furnaces with damaged refractory materials, a compromise had to be found.

Radiation losses can only be guessed. The value was chosen after example calculations for typical scenarios of radiation losses at a melting furnace. Despite these limitations the developed model is a good approach for real processes. The close approximation to real furnaces can be demonstrated in the following case study.

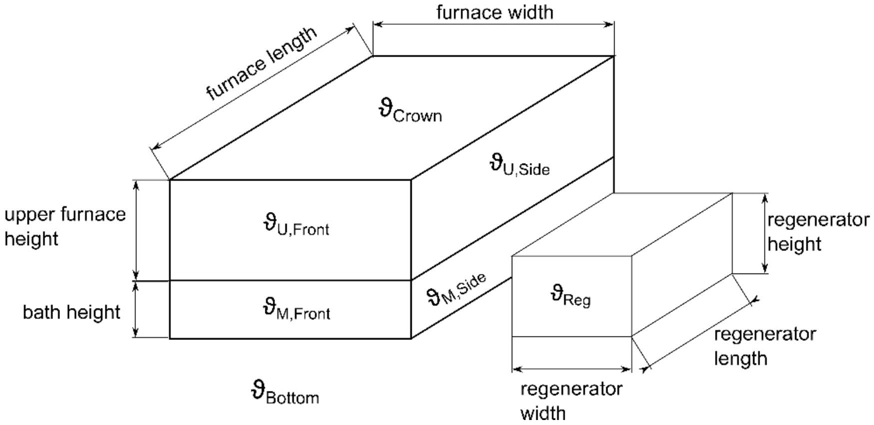

Fig. 1: Sketch of the analysed model of a glass melting furnace. The most important geometric parameters and temperatures are indicated. Explanation of temperature can be found in Table 1.

Table 1. Temperatures used for the calculation of the furnace model.

Temperature	Symbol	Value *(°C)*
Bottom of the furnace	$\vartheta_{\mathrm{Bottom}}$	150
Front- and backside of the melting bath	$\vartheta_{\mathrm{M,Front}}$	190
Sides of the melting bath	$\vartheta_{\mathrm{M,Side}}$	190
Front- and backside of the upper furnace	$\vartheta_{\mathrm{U,Front}}$	160
Sides of the melting bath	$\vartheta_{\mathrm{U,Side}}$	160
Crown	$\vartheta_{\mathrm{Crown}}$	160
Regenerator, all sides	ϑ_{Reg}	100
Environment	ϑ_{Env}	20
Flue gas temperature after leaving the system	ϑ_{FG}	550

3. Case study: Glass production

3.1. Scale dependencies of specific energy consumption in glass production

With the thermodynamic model from the previous chapter, any specific energy consumption can be calculated for a given pull rate. Comparing existing values from literature with these model data, it can be seen in Fig. 2a that the assumptions of the model underestimate the specific energy consumption slightly, but are very close to real data. Nevertheless, these data verify existing scale dependencies but they do not allow for a fair comparison of conventional and innovative technologies.

For this reason, a correction factor *(CF)* for scale dependencies in the glass production was determined based on the developed thermodynamic model and existing data from literature using the method of least square. For these data sets balancing functions were calculated. These functions are power functions according to $y = a \cdot x^{-b}$. For the literature values it can be found with *t* as pull rate in t/d that

$$\mathrm{y} = 14.427 \cdot \mathrm{t}^{-0{,}209} \tag{6}$$

and for the model values

$$y = 10.173 \cdot t^{-0.179} \tag{7}$$

Fig. 2a underlines the finding, which proves that the power function derived from literature data complies with model data concerning their practical application very well. Hence, the developed power function can be used for a reliable evaluation of a furnace and the developed model can be proven as validated. In a next step, the correction factor CF can be calculated by multiplying the specific energy consumption E_{spec} with the reciprocal of the power function y.

$$CF = E_{spec} \cdot \frac{1}{\mathrm{y}} \tag{8}$$

The CF has a typical range of

$$0 < CF \leq 2 \tag{9}$$

with two cases (case A and case B), which exist for validation purposes, as shown in Fig. 2b. Concerning case A „$CF > 1$“ it is valid, that the specific energy consumption of the assessed furnace is higher than the average comparable furnaces. Taking into account the case B „$CF < 1$“ it is valid, that the specific energy consumption of the assessed furnace is lower than average ones. Thereby, any existing or innovative furnace can be evaluated. Due to the development of a correction factor, based on data from the developed model and literature, it is possible to assess any furnace technology independent from their size or pull rate.

3.2. Potentials for development: Modified technology portfolio (TPF) analysis for glass production

Following the basic principles of a TPF analysis, which are based on [9], the results of the case study can be transferred into a streamlined technology portfolio following a three step methodology. Fig. 3a illustrates the steps with the first step consisting of the technology identification. Within this step, new technologies are identified, which may constitute a possible alternative to conventional and well established technologies with marketable products. In the long term, those new technologies should possess a functional equivalence and present a possible substitute for the state of the art technologies.

In the case study the innovative microwave technology was identified as a possible substitute for conventional gas-fired furnaces. The melting step in a conventional furnace involves high energy requirements. The replacement by a microwave has the advantage of fast, direct and volumetric heating of the raw materials, whereby no additional air masses (as it is the case in conventional furnaces) have to be heated, and no long heating periods are necessary before starting the melting process. Production time and rate advantages can be transferred to economic benefits, since shorter production times enable higher throughput. Since only the material is heated, the energy losses in a continuous microwave heating apparatus are considerably smaller than in a conventionally fired furnace, leading to decreased energy consumption as well as reduced emissions since no fossil fuels are needed.

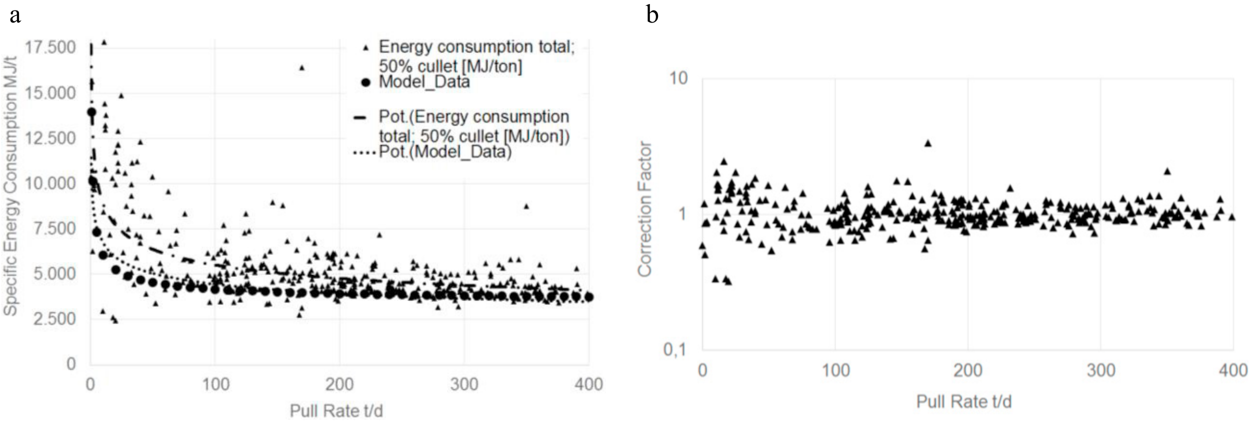

Fig. 2: (a) Development of power functions by comparing values from literature [10] and CelSian with values from the developed thermodynamic model (specific energy consumption in MJ/t depending on pull rate in t/d); (b) Determined correction factors for comparison of furnaces in the glass production with different pull rates based on the developed model.

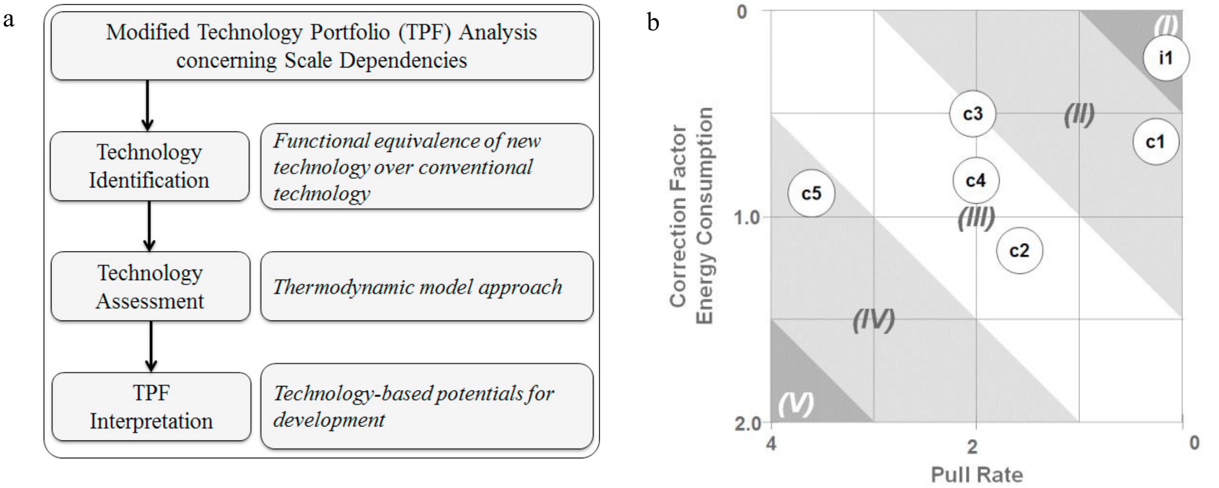

Fig. 3: (a) Methodological approach for the modified technology portfolio (TPF) analysis concerning scale dependencies; (b) Modified technology portfolio for comparison of the conventional technologies (c) and the innovative microwave technology (i) with five technology-based potentials for development from (I) very high to (V) very low.

Table 2. Values of the evaluated five conventional technologies and the innovative microwave technology.

Technology type	Pull rate *(ton/day)*	Energy consumption total *(MJ/ton)*
Conventional small scale furnace 1	0.375	8,619.0
Conventional small scale furnace 2	1.600	13,314.0
Conventional small scale furnace 3	2.000	5,326.0
Conventional small scale furnace 4	2.000	9,130.0
Conventional small scale furnace 5	3.600	8,242.0
Innovative microwave demonstrator	0.110	6,667.0

However, high temperature microwave heating has not yet been implemented for full-scale industrial processes, but is a promising technology with a high functional equivalence compared to conventional melting furnaces. Concerning economies of scale and a fair and reliable comparison of different furnaces, the relevant indicator for an evaluation is whether a technology can compete with other comparator furnaces ($CF < 1$) or not ($CF > 1$). The lower the CF and the pull rate, the higher is the technology-based potential and degree of development of the assessed furnace.

The technology assessment for the case study was carried out by applying the developed thermodynamic model from the previous chapters and determining the values for the CF as a function of the pull rate for five conventional cases and the innovative microwave. For calculating the conventional cases literature data were used, whereas for the microwave case experimental data was used, since this technology is still under development (see Table 2).

In the last step, the TPF interpretation is carried out and five technology-based potentials for development are introduced. These five potentials within the technology portfolio are adopted towards the technological development and advancement from (I) very high to (V) very low. The investigated technologies were transferred into the modified and streamlined portfolio matrix with the portfolio indicator CF and the portfolio indicator pull rate. This is contrary to standard technology portfolios, where the portfolio indicators are independent from each other. This fact was changed and simplified for this approach, since the focus is on a comparison concerning scale dependencies which are reliant directly on the pull rate and cannot be represented by independent indicators. Fig. 3b shows the assessment results for glass production. It can be seen, that the potential of development decreases with increasing pull rate. This results also in the fact, that a state-of-the-art furnace with a very high pull rate has a lower potential of development and can also be proven in the portfolio. Moreover it can be seen, that the innovative microwave technology with a very low CF can compete with conventional furnaces. Since the specific energy consumption of the innovative furnace is better than compared ones, the microwave technology is a challenging alternative to well established technologies with a very high substitution potential for the state of the art technologies although possessing a low pull rate at the current stage of development, regardless of economies of scale.

4. Conclusions

The paper shows the impact of existing scale dependencies and their importance for a comprehensive technology comparison. For determining the energy consumption for any type of furnace, a thermodynamic model was developed and a correction factor was determined for a simplified case study taking into account scale dependencies in the glass production. For validation purposes a modified technology portfolio analysis was carried out afterwards. This analysis compared the production process of glass and the results were finally transferred in a streamlined technology portfolio. Considering existing economies of scale of the examined plant sizes, it was shown within this paper that the identified microwave technology reveals promising indications to become an adequate alternative for the existing technologies. The total energy consumption can be reduced significant through the microwave technology compared to conventional systems of similar production rate. This leads also to a high emission reduction potential by the microwave technology. Considering a future "green" electricity mix, the benefits of the innovative microwave technology can be increased additionally. Nevertheless, the need of further development of this innovative technology was also shown. It should be mentioned, that the industrial scale furnaces are mostly heated with energy from fossil sources. Electrical energy is most commonly used as an additional heating source (“booster”). A more detailed comparison has to be carried out reflecting the differences in energy sources. Nevertheless, it was demonstrated that the developed thermodynamic model and the determined CF contribute to a fair and reliable comparison towards the assessment of different technologies with regard to their economies of scale.

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