Universidade de Aveiro Departamento de Engenharia Mecânica
2013

Ihor Sapa

Recuperação de calor residual na indústria cerâmica

Waste heat recovery in the ceramic industry

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Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Sistemas Energéticos Sustentáveis, realizada sob a orientação científica do Professor Doutor Nelson Amadeu Dias Martins, Professor Auxiliar do Departamento de Engenharia Mecânica da Universidade de Aveiro.

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agradecimentos

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palavras-chave

Recuperação de calor, Calor residual, Tecnologias de recuperação de calor, Indústria cerâmica

resumo

Este trabalho tem como objetivo principal constituir um contributo para a sistematização e análise das diferentes opções disponíveis para a recuperação de calor residual na indústria cerâmica, através do desenvolvimento e aplicação de uma metodologia para a incorporação eficiente de tecnologias de recuperação de calor residual. Com base na revisão da literatura, a metodologia proposta fornece bases para a identificação e caracterização das fontes de calor residual presentes na indústria cerâmica, bem como apresenta a revisão e análise de aplicabilidade das tecnologias de recuperação de calor mais comuns e inerentes a este sector.

A demonstração e aplicação da metodologia proposta foi desenvolvida no âmbito de um estágio extracurricular numa unidade fabril portuguesa do setor cerâmico - *TopCer* - integrado no programa Galp 202020@UA.

O estudo de caso desenvolvido revelou a importância da recuperação de calor como uma das ferramentas para a melhoria da eficiência energética no sector cerâmico no sentido de obter uma vantagem competitiva.

A revisão bibliográfica sobre recuperação de calor demonstrou que esta área do conhecimento tem apresentado um crescimento significativo em termos de número de publicações quase duplicando em número de 2011 para 2012, o que ilustra o crescente interesse da comunidades científica e tecnológica por este tema.

A metodologia proposta tendo o setor da indústria cerâmica como ponto de partida, é suficientemente robusta para poder ser facilmente adaptada a outras indústrias que procuram soluções de poupança de energia através da valorização de calor residual.

keywords Waste heat recovery, Residual heat, Heat recovery technologies, Ceramic industry

abstract

This work aims to be a contribution to the systematization and analysis of the different options available for waste heat recovery in the ceramic industry, through the development and application of a methodology for incorporating efficient technologies in waste heat recovery in the industrial process. Based on a review of the literature, the proposed methodology provides the bases for the identification and characterization of waste heat sources in the ceramics industry, and presents a review and analysis of the applicability of the available technologies for heat recovery, most common and inherent in this sector.

The demonstration and application of the proposed methodology was developed at a Portuguese ceramic manufacturing unit – *TopCer* – as part of an extracurricular internship under Galp 202020@UA program.

The undertaken case study revealed the importance of heat recovery as a tool for improving energy efficiency in the ceramic sector in order to gain competitive advantage.

The literature review on the waste heat recovery has demonstrated that this area has suffered a significant increase in terms of number of publications in 2012, illustrating the growing interest of scientific communities and practitioners in the heat recovery problems.

The elaborated methodology for waste heat recovery incorporation is a rather robust instrument and, therefore, it can be easily tailored to other industries looking for energy saving solutions though consideration of waste heat recovery options.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

A – heat transfer area (m^2)

C_{DS} – specific heat of dry solid (J/(kg·ºC))

C_G – specific heat of the dry air (J/(kg·ºC))

C_S – specific heat of the drying medium (J/(kg·ºC))

$\mathrm{C_V}$ – specific heat of vapour stream (J/(kg·ºC))

C_W – specific heat of moisture (J/(kg·ºC))

$COP_{Cooling}$ – coefficient of cooling performance (%)

$COP_{Heating}$ – coefficient of heating performance (%)

H – enthalpy of heat stream (J/kg)

H_{a1} – enthalpy of inlet air (J/kg)

H_{a1_ph} – enthalpy of pre-heating inlet air (J/kg)

H_{a2} – enthalpy of outlet air (J/kg)

H_G – enthalpy of the dry air (J/kg)

H_{s1} – enthalpy of the feed (J/kg)

H_{s2} – enthalpy of the product (J/kg)

H_W – enthalpy of the moisture (J/kg)

h_1 – specific enthalpy at point 1 (J/kg)

h_2 – specific enthalpy at point 2 (J/kg)

h_3 – specific enthalpy at point 3 (J/kg)

h_4 – specific enthalpy at point 4 (J/kg)

h_{22} – specific enthalpy at point 22 (J/kg)

h_{44} – specific enthalpy at point 44 (J/kg)

$\dot{m}$ – mass flow rate of heat stream (kg/s)

$\dot{m}_A$ – mass flow rate of air (kg/s)

$\dot{m}_a$ – mass flow rate of dry air (kg/s)

$\dot{m}_{a1}$ – mass flow rate of inlet air (kg/s)

$\dot{m}_{a1\_ph}$ – mass flow rate of inlet pre-heating air (kg/s)

$\dot{m}_{a2}$ – mass flow rate of outlet air (kg/s)

$\dot{m}_{cl\_a1}$ – mass flow rate of inlet cooling air (kg/s)

$\dot{m}_{cl\_a2}$ – mass flow rate of outlet cooling air (kg/s)

$\dot{m}_f$ – mass flow rate of working fluid (kg/s)

$\dot{m}_{flue}$ – mass flow rate of flue gases (kg/s)

$\dot{m}_{fuel}$ – mass flow rate of fuel (kg/s)

$\dot{m}_{leaks}$ – losses of air mass flow rate due to leaks (kg/s)

$\dot{m}_{s}$ – mass flow rate of dry solid (kg/s)

$\dot{m}_{s1}$ – mass flow rate of inlet solid (kg/s)

$\dot{m}_{s2}$ – mass flow rate of outlet solid (kg/s)

Q – heat quantity of the stream (J/s)

Q_{air} – inlet air heat (J/s)

$Q_{combustion}$ – heat released during the fuel combustion (J/s)

$Q_{cooling}$ – outlet air heat in the cooling zone (J/s)

Q_{flue} – heat of the flue gases (J/s)

Q_{fuel} – inlet fuel heat (J/s)

Q_{in} – heat input (J/s)

Q_{L} – heat losses (J/s)

Q_{leaks} – heat losses by leaks (J/s)

Q_{out} – discharged heat (J/s)

Q_{rad} – heat losses by radiation (J/s)

$Q_{reaction\,\&\,ware}$ – heat used for reactions and outlet ware heat (J/s)

$Q_{tech\_process}$ – heat used for technological processes (J/s)

Q_{wall} – heat losses through the walls (J/s)

Q_{ware} – inlet ware heat (J/s)

S – entropy (J/(kg·ºC))

T_{a} – air temperature (ºC)

T_{amb} – ambient air temperature (ºC)

T_{a1} – inlet air temperature (ºC)

T_{a1_ph} – inlet pre-heating air temperature (ºC)

T_{a2} – outlet air temperature (ºC)

T_{H} – evaporation temperature (ºC)

T_{L} – condensing temperature (ºC)

T_{s1} – temperature of inlet product (ºC)

T_{s2} – temperature of outlet product (ºC)

U – overall heat transfer coefficient (W/(ºC·m^2))

W – work delivered by external source (J/s)

W_{c} – power needed for the condensation process (J/s)

W_{p} – work done by the pump (J/s)

W_{t} – power generated by the turbine (J/s)

W_{s1} – moisture in feed (kg water/kg dry solid)

W_{s2} – moisture in dried product (kg water/kg dry solid)

Ω – absolute humidity (kg water/kg dry air)

Ω_1 – absolute humidity of inlet air (kg water/kg dry air)

Ω_2 – absolute humidity of outlet air (kg water/kg dry air)

η_m – mechanical efficiency(%)

η_p – efficiency of pump (%)

η_{TH} – thermal efficiency

ρ – density of material (kg/m^3)

λ – latent heat of water evaporation (J/kg)

I. INTRODUCTION

1. Overview

The energy produced by the European Union (EU) meets less than half of its needs and, as a result, the EU imports around 54%: 60% of which correspond to oil imports, 26% - to gas, 13% - to solid fuels and less than 1% - to electricity and renewable energy [1]. According to the forecasts, the energy dependency will continue to increase in a context of rising and volatile energy prices caused by increased demand for hydrocarbons. The energy costs will thus represent a considerable weight for governments, businesses and households.

On the other hand, continuous raise in energy demand, increasing consumption of fossil fuels and depletion of worldwide natural resources have led to serious environmental problems such as global warming, ozone depletion and atmospheric pollution [2].

One of the alternative scenarios to the present situation resides in energy efficiency improvements that offer new opportunities to governments in the context of global economic and financial crisis along with critical environmental situation in the world. According to [3], energy efficiency is a proven and cost-effective solution. The benefits of saving energy count with (*i*) money savings; (*ii*) improvement of the security of EU energy supply; (*iii*) reduction of carbon emissions; (*iv*) creation of new business opportunities; and (*v*) a more innovative and competitive economy, through the development of energy-efficient technologies, products and services.

Currently, in the period of transformation provoked by economic and financial crisis, EU has elaborated a strategy for smart, sustainable and inclusive growth [4]. This strategy has to address all structural weaknesses of EU. One of the EU headline targets consists in meeting the "20/20/20" climate/energy goals (to reduce greenhouse gas emissions by 20%, reduce energy consumption by 20% and satisfy 20% of its energy needs from renewable sources). This would positively contribute to the energy efficiency improvement and consequently reduce energy demand without provoking a negative impact on economic growth as “energy is a necessary requirement for economic and social development” [5].

2. Problem description

During the period of 1990 – 2009, energy efficiency in Portugal decreased approximately 4% [6]. However, improvement of energy efficiency is on the top of the Portugal’s list of priorities as it contributes to many of the country’s economic, social and environmental goals and aligns with the global European objectives in the energy sector. One of the principal focuses of Portugal must be on energy savings in the energy-intensive sectors as those are responsible for the major part of energy consumption.

Industry is one of the largest energy consuming sectors in Portugal, which energy efficiency has decreased by almost 7% for 1990-2009 [6]. In 2009 industry represented 39% of total final energy consumption, 30% of which corresponded to production of non-metallic minerals [7], with 15% originated from the ceramic sector.

Ceramic industry is an energy intensive sector as it is characterized by the long-lasting operation of high-temperature kilns and furnaces [8]. Due to the elevated energy consumption during the production process, the energy cost constitutes considerable percentage of the total production costs, varying from 10% to 30% of production costs [9]. In addition, the major part of ceramic sector energy requirements are covered by fossil fuels, negatively contributing to the production of polluting emissions, such as CO_2, NO_x and SO_2, generated in the high-temperature industrial furnaces.

Implementation of energy saving technologies in ceramic industry is critical for the above mentioned reasons that deal with the elevated energy, final product cost and high pollution emissions. Besides, loss of competitiveness of the Portuguese ceramic sector caused by different factors (such as strong competition from the low cost import, mainly from the emerging economies like China; environmental regulations; elevated energy cost; competition for the substitute products; high dependency on the building sector demand and, finally, globalization, innovation and flexibility [10]) is another challenging problem that has to be covered by the energy efficiency measures.

3. Objective of the study

One of the possible ways to improve the current situation in the Portuguese (as well as European) ceramic industry resides in incorporation of waste heat recovery technologies.

Nowadays, waste heat recovery for energy production is a critical concern that attracts more and more attention of specialists from different areas and industries all over the world. Due to its potential in reducing the fossil fuel consumption and energy costs, increase of industry competitiveness and consequently improvement of energy efficiency of ceramic industry in the context of energy crisis, waste heat recovery constitutes the principal focus of the present work.

This work is aimed to study the opportunities of waste heat recovery in the ceramic sector. Based on the literature review results, it is expected to develop and apply a methodology that would facilitate incorporation of the waste heat recovery technologies in the ceramic industry.

4. Contribution of the study

The main contribution of the present study consists in compilation of the literature related to the waste heat recovery in ceramic industry and elaboration of the methodology for the efficient incorporation of waste heat recovery technologies in the ceramic sector. The proposed methodology can be easily adapted to other industries looking for efficient solutions in energy saving. Besides, this work reports the results of methodology application in one of the Portuguese ceramic factories located in the Centre region.

5. Thesis structure

The dissertation is organized as follows. Chapter II introduces basic notions of the waste heat recovery and performs literature review on this topic. Chapter III presents definition and classification of ceramics, provides economics and energetic analysis of ceramic industry in Portugal and describes typical manufacturing process of ceramics. Chapter IV describes a methodology for waste heat recovery incorporation in ceramic industry. This methodology is aimed to identify and characterize the waste heat sources available in ceramic sector, compare the most common waste heat recovery technologies in this industry and perform analysis of their applicability. Chapter V illustrates application of the methodology for the waste heat recovery in a Portuguese ceramic factory *TopCer*. Finally, Chapter VI outlines the conclusions and provides directions for the future research.

II. WASTE HEAT RECOVERY: CHARACTERIZATION AND OVERVIEW OF STATE OF THE ART

1. *Basic notions of waste heat recovery*

In recent years industrial processes use large quantities of fuel and electricity that in the end produce heat, much of which is released into the atmosphere or water what leads to serious environmental problems [11, 12]. The energy consumed is lost via waste heat contained in streams of hot exhaust gases and liquids, as well as through heat conduction, convection, and radiation from hot equipment surfaces and from heated product streams [13]. Waste heat recovery is a process of recovering and reusing rejected heat to replace purchased energy [14]. Figure 1 illustrates three essential components that are required for waste heat recovery : (*i*) an accessible source of waste heat; (*ii*) a recovery technology, and (*iii*) appropriate use for the recovered energy.

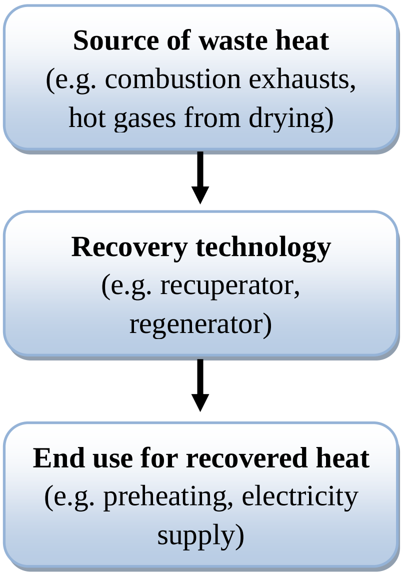


Figure 1 - Three essential components for waste heat recovery [13].

The benefits brought by incorporation of waste heat recovery technologies can be classified in two categories: direct and indirect ones [15]. Direct benefits account with improvement of efficiency of the process and reduction in the utility fuel consumption and costs. According to [11], waste heat recovery technologies are able to save up to 20% of the annual energy costs. Referring to the indirect benefits, those include reduction in thermal pollution, plant maintenance, reduction in equipment sizes (such as fans, stacks, ducts, burners, etc.) and fuel consumption [15].

Figure 2 demonstrates the simplified scheme of the material and possible energy flows for a single heat recovery process (however, generally, several processes are employed with the possibility of energy or material flows between them).

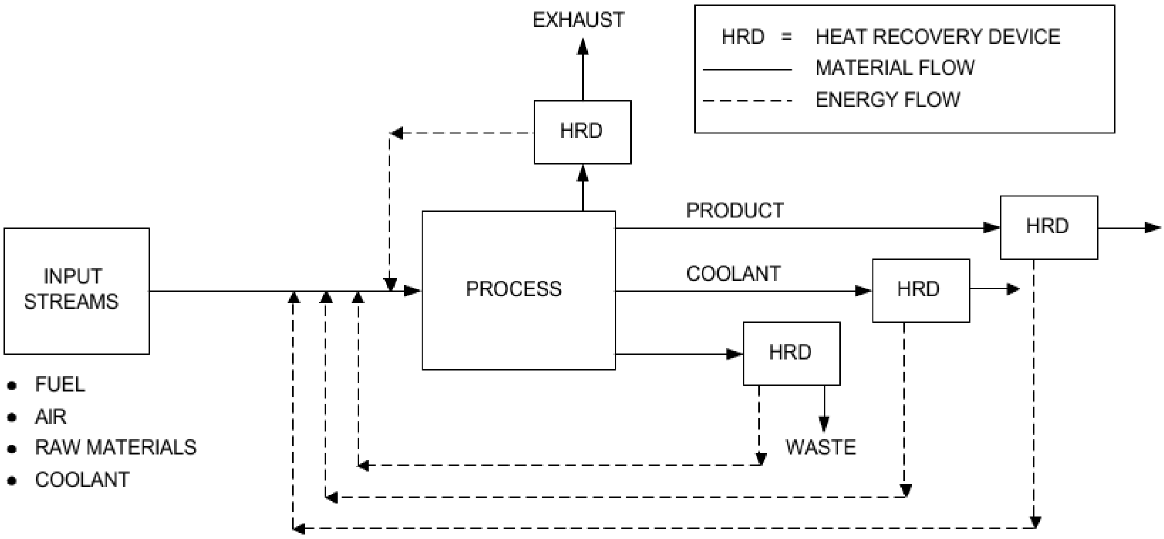


Figure 2 - Scheme of the possible single process heat recovery energy flows [11].

In accordance with the type of process, waste heat can be rejected at virtually any temperature, ranging from chilled cooling water to high temperature waste gases from an industrial furnace or kiln. Generally, waste heat recovery sources are categorized according to three temperature ranges into *low* (< 230ºC), *medium* (230ºC - 650ºC) and *high quality* (> 650ºC) waste heat sources. The waste heat temperature is one of the key factors that determine the waste heat recovery feasibility, quality and effectiveness: the higher the temperature – the higher the quality. Besides, in any heat recovery situation it is important to know the amount of heat recoverable and also its temporal availability.

There is a great variety of equipment that has been developed in order to reuse some of the waste heat: heat recuperators, regenerative heat exchangers, heat pipe heat exchangers, waste heat boilers, gas and vapour expanders, etc. This equipment must take into consideration temperature and pressure ranges, corrosiveness of the effluent and input streams, presence of materials that could foul the heat exchange surfaces, and thermal cycling [11]. The potential for heat recovery is phenomenal, however wide spread commercial acceptance still requires research and development efforts [16].

According to [17] and [18], in order to match waste heat sources with the respective heat sinks a number of criteria has to be taken into consideration. However, the authors highlight the importance of three of them: (*i*) the recovered heat can be made available at a useful temperature at the sink; (*ii*) the recovered heat can be economically transferred from the source to the sink; and (*iii*) simultaneous occurrence of the heat supply and heat demand due to the elevated cost of the heat storage.

2. Overview of state of the art

2.1. Waste heat recovery studies from Science Direct database

A search on *Science Direct* database for "*waste heat recovery*" or "*residual heat recovery*" keywords in Abstract-Title-Keywords sections of journal articles and conference proceedings (from Energy and Engineering scientific areas) resulted in a set of 316 related studies. As it can be observed from Figure 3 waste heat recovery is an area that since 2000s has gained popularity among scientific communities, with disruptive increase in number of publications that occurred in 2012.

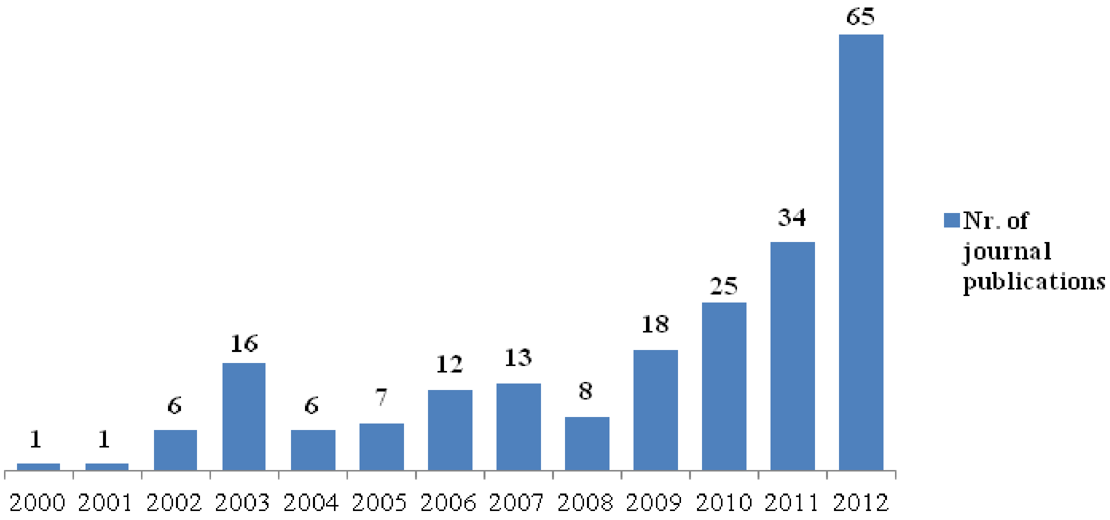


Figure 3 – Evolution of number of journal publications about waste/residual heat recovery since 2000.

Referring to the scientific journals that publish articles on the topic, *Applied Thermal Engineering* and *Energy* are the leaders among them. However, there is a considerable amount of studies related to the waste/residual heat recovery present in such journals as *Energy Conversion and Management*, *Renewable and Sustainable Energy Reviews*, *Applied Energy*, *Renewable Energy*, among the others.

A large number of scientific articles dedicated to the residual heat recovery problem is centered over description and/or testing of equipment, models, systems and methods developed by researchers for waste heat recovery. Among the proposed equipment one can find adaptive generalized predictive controller for waste heat recovery power plants with Organic Rankine Cycles (ORCs) [19], electrochemical reactor for wastewater treatment along waste heat recovery and hydrogen production [20], water driven steam injector to recover waste heat in various industries [21], waste heat recovery apparatus that uses truck exhaust gas for road maintenance purposes [22], etc. The models elaborated by investigators for use of waste heat count with model of waste heat recovery boiler [23], dynamic models for ORCs [24], model of adsorption cooling system for automobile waste heat recovery [25]. Some examples of the systems for utilization of waste heat include advanced generator absorber heat exchanger cycle [26], waste heat recovery sub-system for power generation system based on Rankine cycle [27], heat recovery system that uses endothermic heat of reaction [28], liquid metal based thermoelectric generator system for waste heat recovery [29], waste heat recovery system for district heating [30]. The authors that work at waste heat recovery also propose different methods and methodologies that can be used, for example, in order to reduce energy loss in the conventional two-step processing of phosphoric acid wastes [31] or to target and design waste heat recovery industrial zones comprised of multiple plants [32].

A considerable amount of scientific effort has been directed to determine optimum operation conditions of equipment used to recover residual heat as well as to improve their efficiency. As a result, Kandilli and Koclu [33] provide a study aimed to assess optimum operation condition of a waste heat recovery system that employs plate heat exchanger for textile industry. Coşkun, et al. [14] conduct experimental studies to investigate the effect and optimization of control parameters on the system performance in a waste heat recovery application using mechanical heat pump. Among the articles that encompass optimization of equipment for waste heat recovery, one can find a research of He, et al. [34] aimed to improve the recovery of the waste heat of an internal combustion engine, along with studies of Crane and Jackson [35] and Söylemez [36] carried out to optimize cross flow heat exchangers and finned pipes, respectively. It is important to mention, that studies dedicated to the ORC optimization through evaluation of cycle performance using different working fluids occupy a special niche in the waste heat recovery investigation. Selection of a proper working fluid for an ORC has been reported in such articles as [12], [37], [16], [38], [39], [40], [41], [42], [43], [44], etc. This increased interest can be explained by the fact that the properties of the working fluid affect the cycle efficiency and capital cost.

Another group of articles is focused on investigation of the heat recovery potential/performance of equipment as well as of entire industries. Thus, Srinivasan, et al. [45] explore the waste heat recovery potential of high-efficient, low-emission dual fuel low temperature combustion engine using ORC, while Liu, et al. [46], Wang, et al. [47], Gou, et al. [48] and Butcher and Reddy [49] study the performance of low pressure economizer, looped two-phase separate heat pipe, thermoelectric generator and waste heat recovery power generation system, respectively, for waste heat recovery purposes. In addition, Pulat, et al. [50] evaluate waste heat recovery potential from dyeing process at Turkish textile industry and Bonilla, et al. [51] analyze technological recovery potential of waste heat recovery in 10 industrial sectors of Basque country.

A particular attention in a waste heat recovery research is paid to the review of issues, like recent developments, applications, technologies, etc. related to the subject. For example, Ma, et al. [52] present an overview of waste heat recovery situation, sources and utilization in China steel and iron industry, while Dupont and Sapora [53] explore the waste heat recovery potential of French industry. On the other hand, Tchanche, et al. [54], Yang [55] and Zhang and Zhuang [56] provide a review of different applications related to heat recovery, like ORC applications (including for low-grade heat recovery), applications of thermoelectric waste heat recovery devices in automotive industry and industrial applications of heat pipe technology in China for waste heat recovery and other purposes, respectively. Besides, there are different studies, like [57] and [15], dedicated to the review of technologies and strategies for a vast range of applications, including waste heat recovery.

2.2. Waste heat recovery in ceramic industry

As it can be observed from the previous section, the problem of waste heat recovery is present in different industries, like textile, steelmaking, iron, transport, food, etc. and can be employed for a range of applications, e.g. metal production, processing of phosphoric acid wastes, industrial wastewater treatment, air conditioning, district heating, road maintenance, among the others. However the main focus of this work is to study waste heat recovery within ceramic industry domain.

A search performed on *Science Direct* database aimed to indentify scientific articles or conference proceedings that are addressing the waste heat recovery issue in ceramic industry resumed to only one article written by Agrafiotis and Tsoutsos in 2001 [8]. This study provides an overview of energy saving technologies in the European ceramic sector. Nevertheless, the waste heat recovery technologies proposed by the authors in order to improve efficiency of drying and firing processes are resumed to heat exchanger systems and high-performance metal or ceramic recuperators. Besides, there is no detailed description of the systems functioning and analysis related to their applicability.

On the other hand, there are publications provided by different ceramic associations, like Portuguese Association of Ceramic Industry (APICER) or Brazilian Ceramic Association. For example, APICER has published a *Handbook of Good Practices on Rational Use of Energy and Renewable Energy* [58], where it describes measures to rationalize use of energy, including the waste heat recovery option. Brazilian Ceramic Association has a proper journal called *Cerâmica Industrial* that is published bimonthly. Among a variety of problems discussed in the articles of *Cerâmica Industrail*, one can find a waste heat recovery issue, for example, in the works of Recco [59], Fontana and Montedo [60] and Nassetti [61].

One of the most relevant publications about energy efficiency in ceramic industry was elaborated in 2007 by European Commission – *Reference Document on Best Available Techniques in the Ceramic Manufacturing Industry* [62]. This document provides a summary of the principal best available techniques and the associated consumption and emission levels in the ceramic industry. Among the described techniques there are also those that refer to the waste heat recovery.

In addition to the scientific publications, articles provided by Ceramic Associations and reports elaborated by European Commission, there are also studies performed by manufacturing organizations that explore the energy efficiency potential of the produced equipment. One of such organizations is *SACMI Group* that produces manufacturing machines for different industries, including the ceramic one. *SACMI* has an associated investigation laboratory that publishes reports that describe and assess developing innovative technologies aimed at optimal resource saving at all stages of ceramic production processes, e.g. [63].

III. CHARACTERIZATION OF CERAMIC INDUSTRY

1. Definition and classification of ceramics

Historically, the word *ceramics* is derived from the Greek's word *keramikos* that has a literal meaning of the potter's earth [64]. Ceramics are defined as inorganic, non-metallic materials (possibly with some fraction of organic compounds) that acquire the desired properties under the application of heat inside high-temperature kilns, generally, for long periods of time [8, 65].

Among the characteristic properties of ceramics European Commission [62] distinguishes high strength, wear resistance, long service life, chemical inertness, non-toxicity, resistance to heat and fire, electrical resistance and sometimes specific porosity.

There are different classifications of ceramics. One of them, proposed by Basu & Balani [64], distinguishes *traditional* and *advanced* ceramics. Traditional ceramics are mainly silica or clay based with low-cost fabrication processes. On the other hand, advanced ceramics are produced from the high-purity ceramic powders with the possibility of manipulating their properties by varying process parameters, thus resulting in more expensive production.

Figure 4 illustrates the historical evolution of the ceramics applications and industries from early ceramics passing through the traditional ceramic in direction to the advanced one.

Another categorization of ceramic sector deals with statistical classification of economic activities within the European Community [66]. Table 1 provides statistical definition of sub-sectors in ceramic industry with the respective classes.

Table 1 – Statistical definition of ceramics sub-sectors [66].

Sub-sector	Sub-sector definition	Class	Class definition
232	Manufacture of refractory products	2320	Manufacture of refractory products
233	Manufacture of clay building materials	2331	Manufacture of ceramic tiles and flags
		2332	Manufacture of bricks, tiles and construction products, in baked clay
234	Manufacture of other porcelain and ceramic products	2341	Manufacture of household and ornamental articles
		2342	Manufacture of ceramic sanitary fixtures
		2343	Manufacture of ceramic insulators and insulating fittings
		2344	Manufacture of other technical ceramic products
		2349	Manufacture of other ceramic products

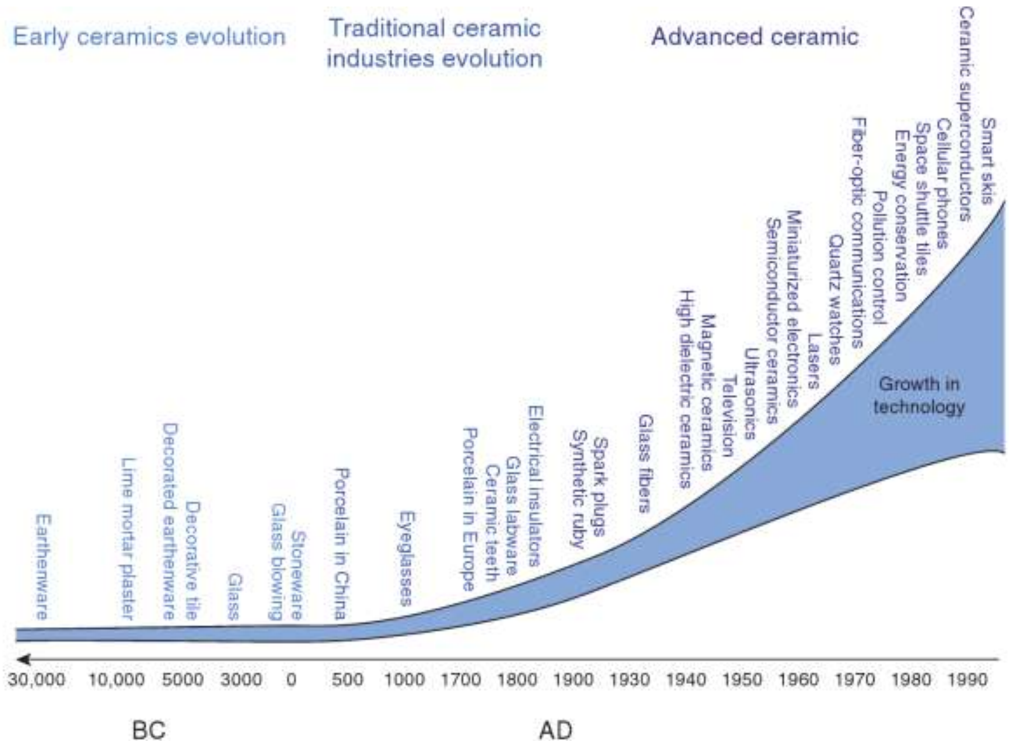


Figure 4 – Historical evolution illustrating the growth of ceramics applications and industries [64].

According to *Portuguese Association of Ceramic Industry* (APICER) [67], the ceramic sector is divided into: (*i*) building ceramic that is composed of structural and finishing sub-classes, (*ii*) household and ornamental ceramic, and (*iii*) technical ceramic.

Figure 5 illustrates the *APICER* classification enriched with the statistical definition of the ceramic sub-sectors.

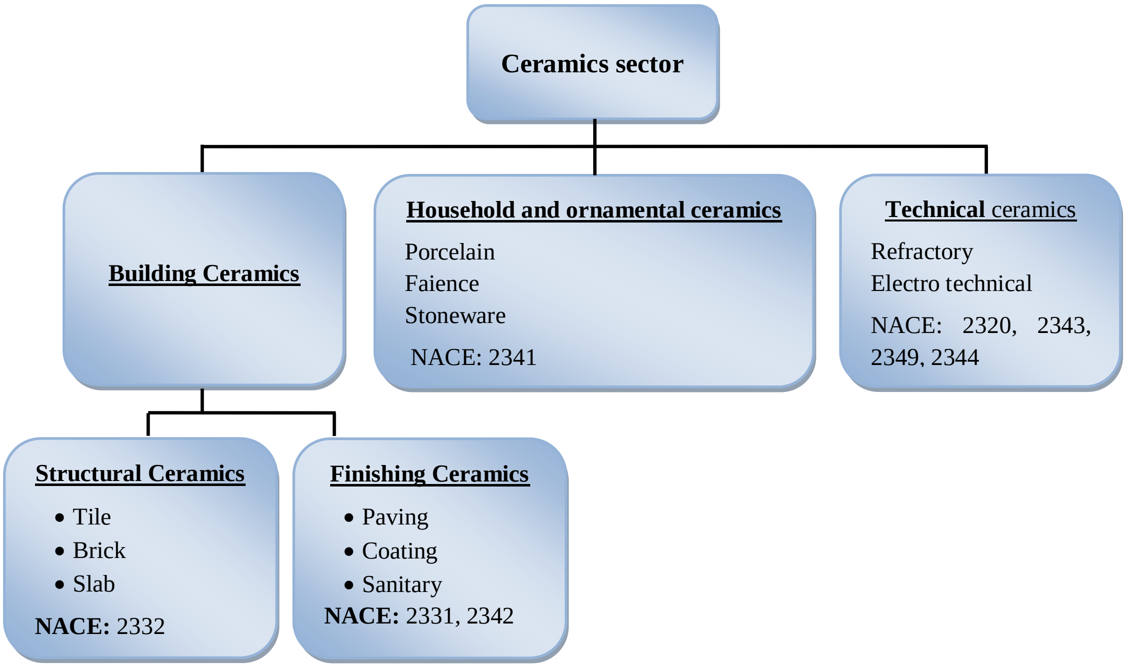


Figure 5 – Classification of ceramic sector (adapted from [58]).

2. *Economic analysis of ceramic industry in Portugal*

Center is the main ceramic producing region in Portugal, where the special emphasis is placed over Aveiro, Leiria and Coimbra districts with 59%, 19% and 5% of total business volume, respectively (Figure 6).

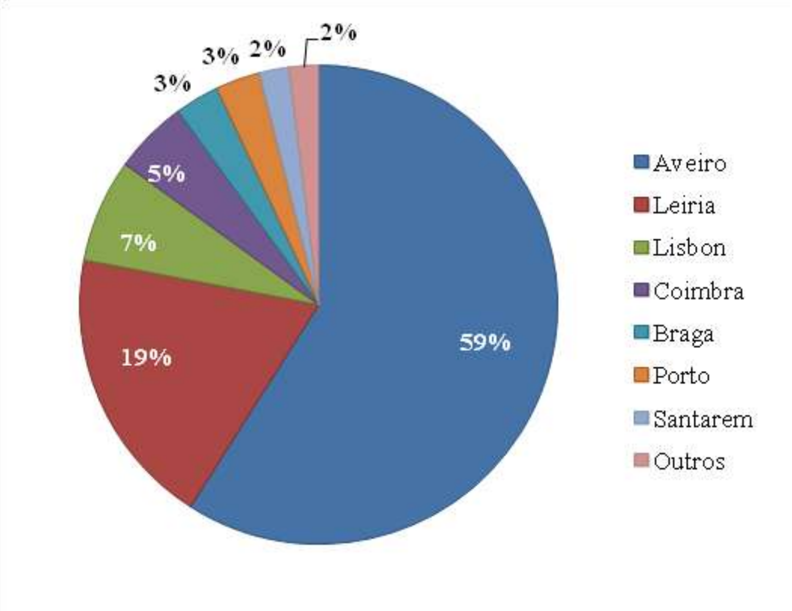


Figure 6 - Distribution of business volume in ceramic sector per region in Portugal [68].

Figure 7 illustrates evolution of the number of functional units within ceramic sector in Portugal for 2004-2010.

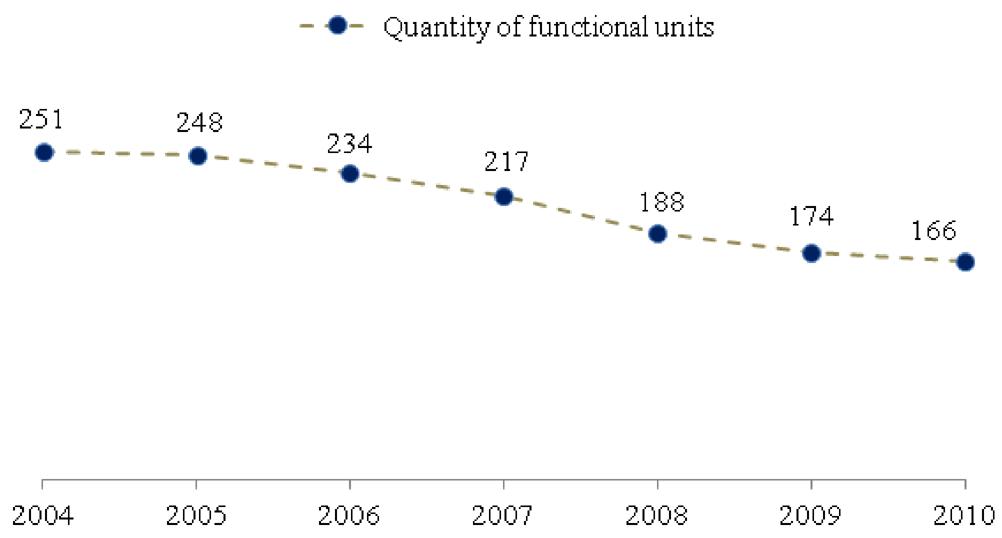


Figure 7 – Evolution of number of functional units within ceramic sector during 2004-2010 [69].

According to the data analysis, for the period from 2004 to 2010, ceramic industry has registered downward tendency in terms of the number of functional units. For this period Portuguese ceramic industry has faced a decrease of 33% in terms of number of functional units working in this sector (as in 2010 there were registered 166 functional units, compared to 251 ones in 2004). In part, this decrease can be explained by the ascendant tendency of the prices of the energy sources used in ceramic industry. Therefore, the average Portuguese industrial electricity price increased by more than 30% in 6 years from 0,0684 €/kWh in 2004 to 0,0896 €/kWh in 2010 [70], while the price of natural gas increased by 34% over the same period [71].

From Figure 8 that presents the distribution of sales in ceramic industry for 2004-2010, it can be noticed that in 2004 the existing (251) functional units were responsible for the production of approximately €975 mln worth of different ceramics products. Following the tendency of number of functional units, the sales within the ceramic sector have also diminished. In this way, in 2010 there were produced only €779 mln worth of ceramics products.

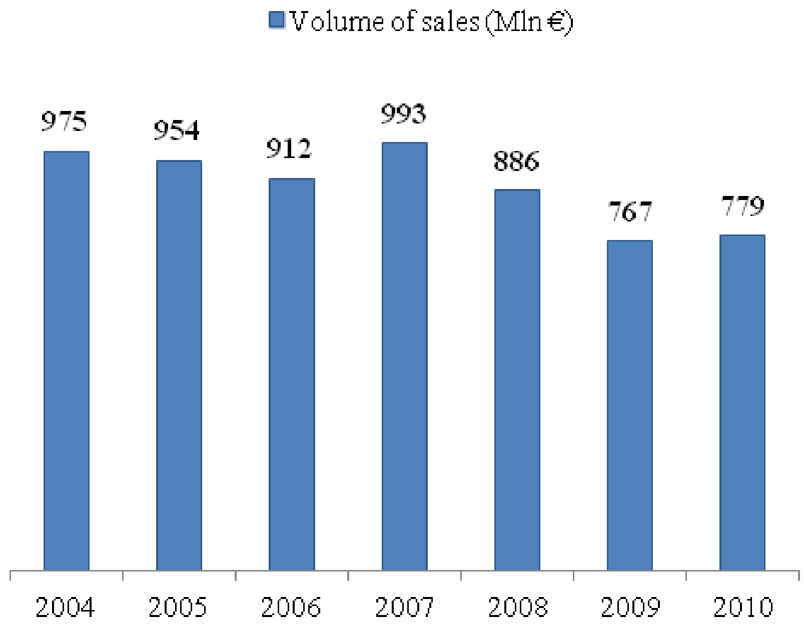


Figure 8 – Distribution of volume of sales in ceramic industry per year [69].

Figure 9 presents distribution of Portuguese ceramics products sales around the world for 2004-2010.

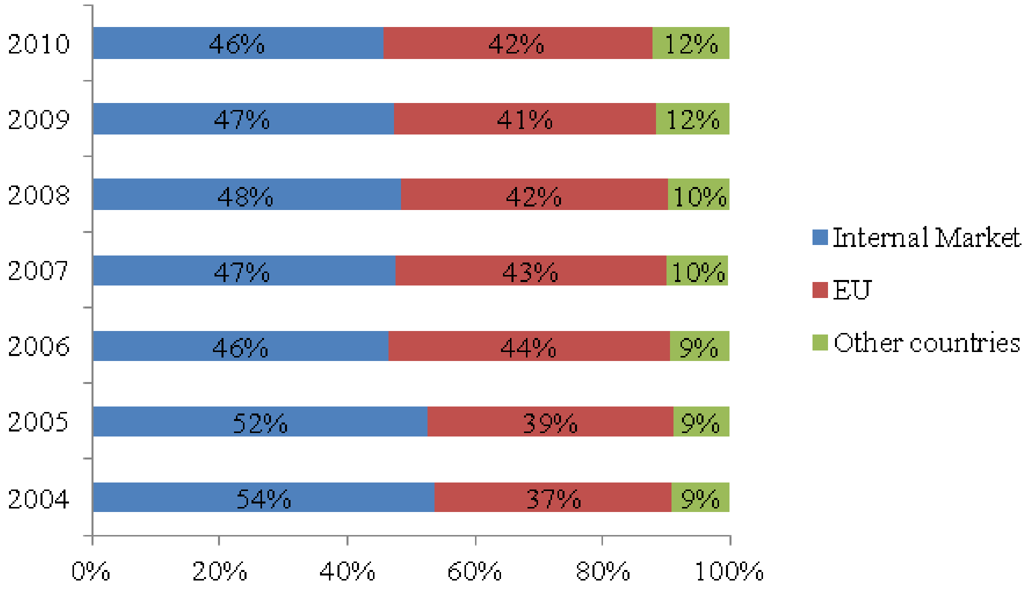


Figure 9 – Distribution of Portuguese ceramic products sales per market [69].

In spite of decrease in the sales within the internal market along 7 years, it reveals to be the primary consumer of the ceramics goods produced in Portugal. Nevertheless, the share of the EU market has been growing and in 2010 it registered 42% of all sales, compared to 46% of the respective sales within the internal market. Similar to the sales in EU countries, the sales in other countries have also increased: from 9% in 2004 – to 12% in 2010.

Figure 10 illustrates the contribution of the ceramics classes to the ceramic products sales along the period 2004-2010. As it can be observed, during the 2004-2007, *Manufacture of other technical ceramic products* class was responsible for 35%-41% of the worth created within the sector, followed by *Manufacture of refractory products*, *Manufacture of other ceramic products* and *Manufacture of ceramic tiles and flags*, respectively. Since 2008, the ceramic sector has suffered significant changes in the demand (and as a result – in the sales) of the ceramic products. Thus, approximately 50% of all the sales from the sector were managed by the *Manufacture of ceramic tiles and flags* division, while *Manufacture of household and ornamental articles*, *Manufacture of bricks, tiles and construction products, in baked clay* and *Manufacture of ceramic sanitary fixtures* contributed with approximately 22%, 15% and 12%, respectively.

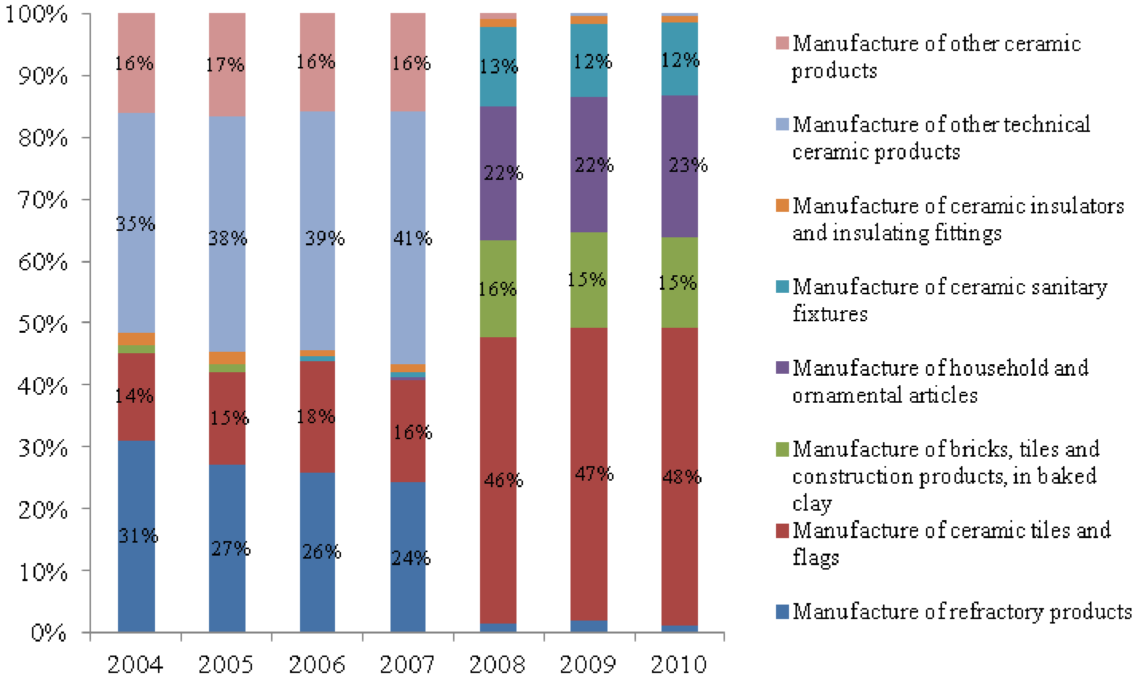


Figure 10 – Contribution of ceramics classes to sales, distributed by 2004-2010 [69].

3. Energy analysis of ceramic industry in Portugal

According to the data provided by National Statistics Institute, *Paper and paper products*, *Ceramics*, *Cement, Plastics and chemicals* and *Food and beverage* revealed to be the most energy consuming Portuguese manufacturing industries in 2009. Figure 11 illustrates the final energy consumed by these industries (in toe) with the respective percentage from the total final energy consumed by all Portuguese manufacturing industries in 2009.

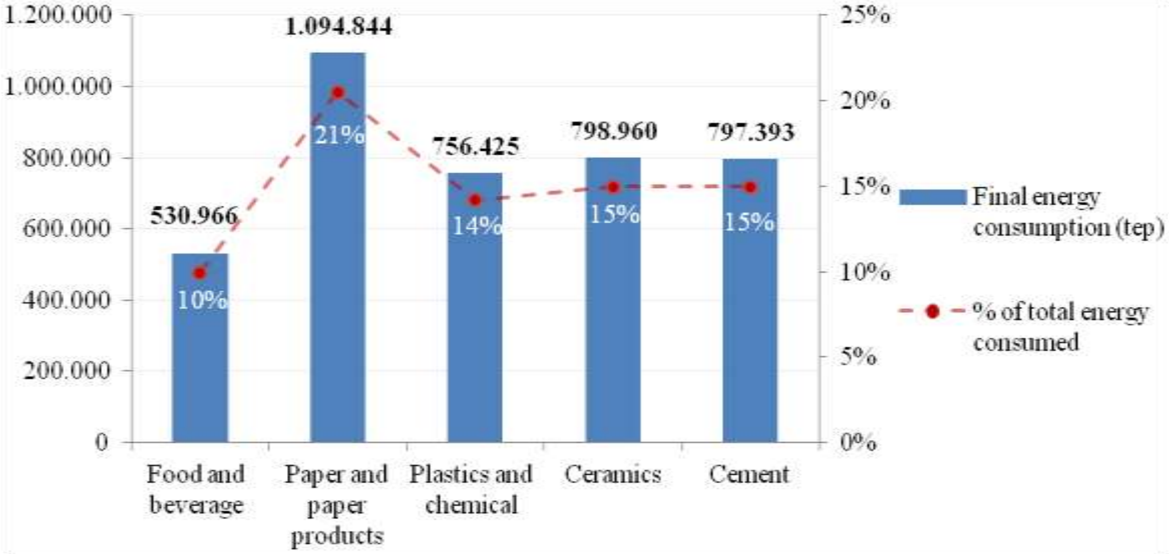


Figure 11 – Final energy consumption of the 5 most energy intensive manufacturing industries in 2009 [72].

Thus, it may be noted that *Ceramics* is the second most energy intensive industry (after the *Paper and paper products* industry) with 798.960 toe of the final energy consumed, that constitutes approximately 15% from the total final energy consumed by all manufacturing industries in 2009.

Table 2 provides detailed distribution of main types of fuels used during the ceramic manufacturing by equipments in different ceramic sectors.

Table 2 – Fuels used in ceramics manufacturing (adapted from [73]).

	Structural ceramics	*Household and ornamental ceramics*	*Paving/Coating ceramics*	*Sanitary ceramics*
Dryers	Recovered air, Fuel*, LPG, NG, Solid fuels	Recovered air, Fuel**, LPG, NG	Recovered air, LPG, NG	Recovered air, NG
Kilns	Fuel, LPG, NG, Coke, Solid fuels	LPG, NG	LPG, NG	NG
Boiler	Fuel, NG, LPG, Solid fuels	LPG, NG	-	-
Furnaces	Fuel, NG, Solid fuels	-	-	-
Atomizers	-	NG	NG	-

*central cogeneration, **practically nonexistent, LPG – Liquefied petroleum gas; NG – Natural Gas

Referring to the energy consumed by the ceramic industry, Figure 12 presents the distribution of the energy consumed by *Structural*, *Finishing* and *Household/Ornamental* ceramic sectors in 2009 (in tep), according to the energy type. From the data analysis, it can be concluded that natural gas is the principal source of the energy consumed in the *Structural*, *Finishing* and *Household/Ornamental* ceramic sectors, with 91.641 tep, 145.890 tep and 43.875 tep, respectively. However, electricity also has significant impact on the final energy consumption in the ceramic industry.

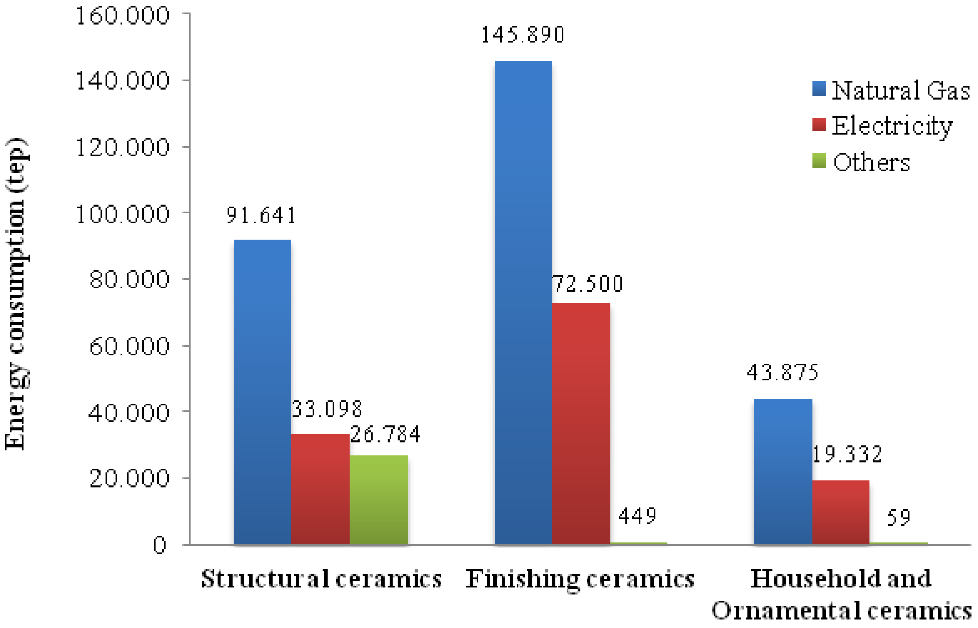


Figure 12 – Energy consumption in *Structural*, *Finishing* and *Household/Ornamental* ceramic sectors in 2009 (adapted from [74]).

4. *Manufacturing process of ceramics*

The manufacturing process of ceramics employs different types of kilns, uses a wide range of raw materials and counts with numerous shapes, sizes and colors. However, the manufacture of ceramic products is independent on the materials used and the final product, being rather uniform process.

Figure 13 schematically illustrates the generalized production scheme for the ceramic industry with general stages, supply and disposal elements. The ceramics production process consists of five main stages imbedded in the major part of the ceramic sub-sectors (preparation of raw materials, shaping, drying, firing and product finishing/sorting/firing) and two auxiliary stages that are present in the *Manufacture of clay building materials* sub-sector (spray-drying and glazing).

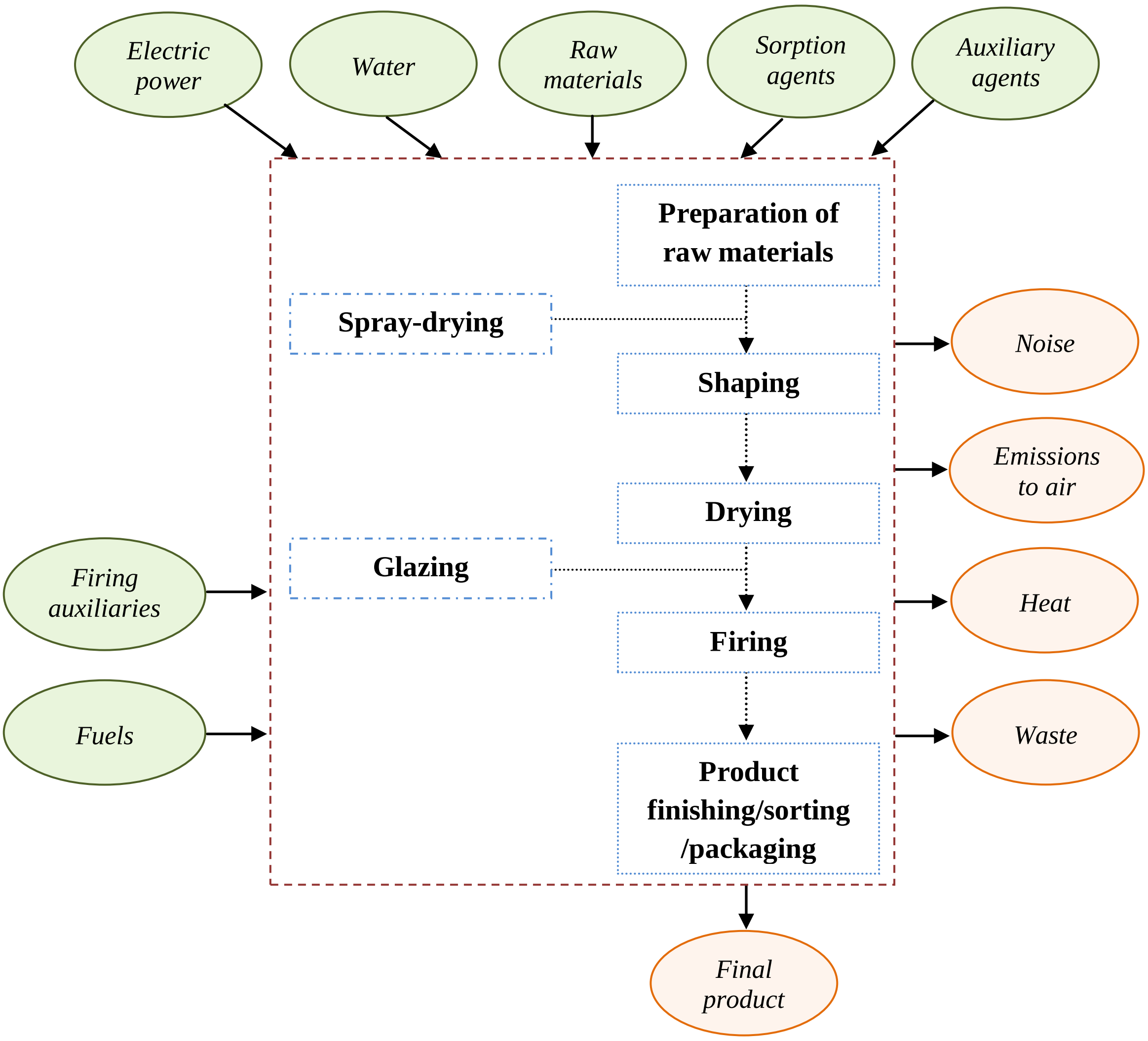


Figure 13 – General ceramics production process (adapted from [73] and [62]).

Common raw materials used to manufacture ceramics include silica, sand, quartz, flint, silicates, and aluminosilicates. Preparation of the raw materials involves their size reduction and preliminary homogenization (usually achieved by dry or wet grinding) and further preparation of the ceramic mixes with necessary additives (e.g. water, sorption and auxiliary agents) for the following stages of the process.

During the spray-drying, highly employed in the wall and floor tile industry, the aqueous suspension of raw material (with solids content range of 60 - 70 %) is sprayed under pressure to produce fine droplets as a result of contact with a stream of hot air. Droplets drying produces uniform, spherical hollow granules with a moisture content of approximately 5.5 - 7 % and elevated flowability that facilitates filling of the press dies and the subsequent pressing of large single tiles [62].

The shaping process is used to give to the material grounded in the preparation phase its required shape before firing. There is a great variety of methods exploited during the shaping that determine the shape of the final product. Among them one can find mechanical pressing that is used for the bricks production; hydraulic pressing aimed to form complex refractory shapes, isostatic pressing - employed for the manufacture of tiles and tableware; extrusion - utilized for the manufacture of clay bricks and blocks; moulding - carried out in the refractory sector to form large products, etc.

After shaping, the resulting ceramics must be dried, in order to reduce the moisture content in the body to the required levels. Drying is a slow and gentle process that has to be customized in terms of time and temperatures (varying between 60ºC and 200ºC) that depend on initial moisture content and dimensions of the ware [8]. As a result, drying requires special control to avoid distortion as well as other damages of the resulting product – dried green ceramics.

Glazing process is commonly used in the manufacture of ceramic wall and floor tiles, sanitary ware and tableware. To prepare the glazing suspension, finely ground glaze components are mixed with the water. The characteristics of the resulting suspension are determined by the application method: spraying, waterfall glazing, dry glazing or decorating. During the glazing process, the dried green ceramic ware is usually hardened by biscuit firing and then covered with a glaze layer.

Firing is a key ceramics production process that gives to the product its final properties: mechanical strength, abrasion resistance, dimensional stability, resistance to water and chemicals, and fire resistance [8, 62]. Parameters that influence firing resume to firing temperature, time, pressure, and atmosphere. Generally ceramics are fired at 50 - 75% of the absolute melting temperature of the material [75], at either continuous or intermittent kilns. The firing of ceramics products like tiles, sanitary ware and some tableware can take place in one stage. Nevertheless, other products require a series of firings that can be used to increase the strength of the ceramic substrate or to fix decoration before applying the glaze. The main types of energy used for heating purposes are fuel oil, diesel fuel, LPG, natural gas, coal and electricity.

After the firing process, some ceramic products are further processed to enhance their characteristics or to meet dimensional tolerances. The product finishing operations include grinding, drilling, sawing, polishing, carbon enrichment and tumbling. The finished products are sorted, packaged and later stored.

IV. METHODOLOGY FOR WASTE HEAT RECOVERY INCORPORATION IN THE CERAMIC INDUSTRY

Based on the literature review, the present section is aimed to establish and describe a methodology for efficient incorporation of waste heat recovery technologies in the ceramic industry. Figure 14 illustrates the main steps of methodology that resume to identification and characterization of waste heat sources in the ceramic industry, comparison of existing waste heat recovery technologies and further analysis of their applicability in order to guarantee more efficient use of thermal energy in ceramic industry.

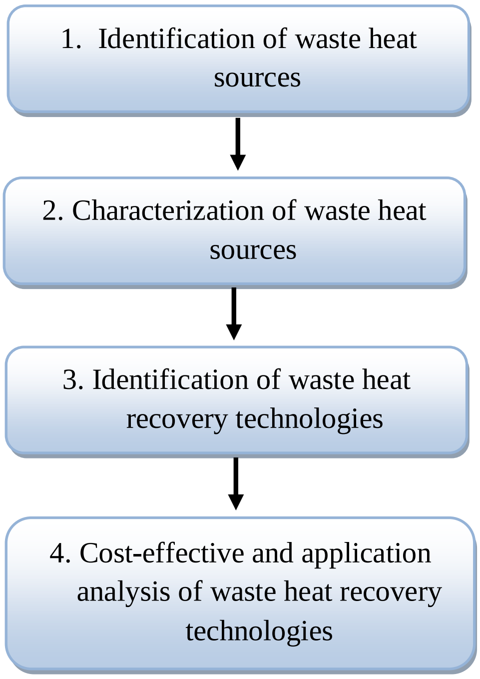


Figure 14 – Methodology for waste heat recovery in ceramic industry (adapted from [76]).

Section IV.1 identifies all significant waste heat sources existing in the ceramic industry and describes the type of losses that occur in each of them. Section IV.2 provides theoretical basis for the waste heat sources characterization in terms of their waste heat quantity, quality and temporal availability. Section IV.3 describes heat recovery technologies and devices appropriate for the waste heat capture from the identified waste heat sources. Finally, section IV.4 contains a cost-effective and application analysis of waste heat recovery technologies in ceramic industry.

1. Identification of the main sources of waste heat in ceramic industry

Due to the employment of elevated temperatures, *spray drying*, *drying* and *firing* are the most energy intensive processes during the ceramics manufacturing. As a result, equipment used in these processes is the main source of the waste heat: *kilns* – in firing, *dryers* – in drying and *spray dryers* – in spray drying. Therefore, this equipment constitutes the main focus of the present section.

1.1. Kilns

1.1.1. General considerations

Kilns are high-temperature facilities used in order to fire ceramics [77]. According to Carvalho and Nogueira [78], high-temperature equipment, such as kilns, are critical in the industrial production chain due to (*i*) the large amount of energy utilized; (*ii*) the relevance of technological processes that occur in that equipment for the final product quality; (*iii*) the significant part of the production time spent in these units; (*iv*) the important part of the plant pollution impact that is produced; (*v*) the complexity of the involved thermo-physical processes; (*vi*) the difficulty to access and measure the phenomena inside these units.

Different types of kilns are used in the ceramic industry. However, they can be grouped into two main categories that differ by the type of firing: *batch* or *continuous*. Figure 15 illustrates the evolution of modern kilns according to their type. As it can be noted, batched and continuous kilns have evolved independently in modern designs available on the contemporary markets.

The type of kiln to be chosen (batch or continuous) largely depends on the firing objectives as each of the considered types has its advantages and disadvantages. Among the advantages of continuous kilns Remmey [79] names (*i*) less fuel consumption (approximately one half of the fuel in firing the same product on the same cycle compared to the batch kiln); (*ii*) lower capital cost for large capacity kilns; (*iii*) ease of automation for loading and unloading; and (*iv*) possibility to fire faster cycles. On the other hand, batch kilns are (*i*) more flexible; (*ii*) possess lower capital cost in smaller size; (*iii*) can fire high setting heights; and (*iv*) are able to fire unusual firing cycle profiles.

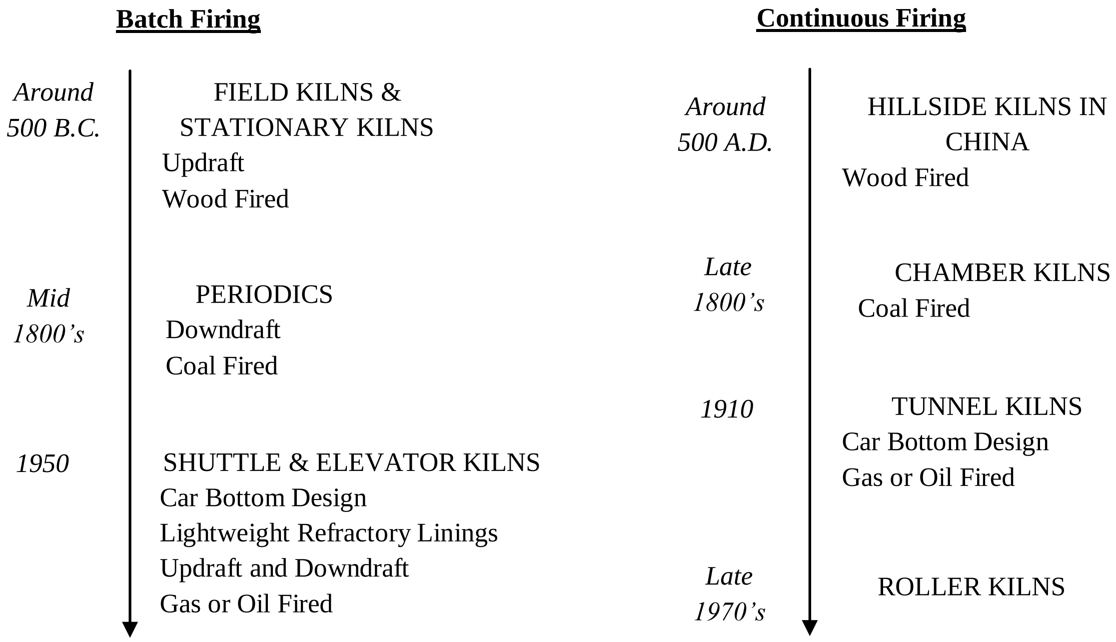


Figure 15 – Evolution of modern kilns (adapted from [79] and [8]).

1.1.2. Heat losses in kilns

Typically, energy costs of firing account for up to 30% of the costs of manufacturing ceramics products and enhancement of the energy efficiency of kilns is essential in order to reduce production costs [80]. Besides, kilns represent one of the main sources of the waste energy in the ceramic industry in a form of heat and as a result represent a vast range of possibilities for the recovery and use of the dispersed energy.

Figure 16 represents typical heat losses in a ceramic kiln. Those include: (*i*) heat storage in the kiln structure; (*ii*) losses from the kiln outside walls or structure; (*iii*) heat transported out of the kiln by the load conveyors, fixtures, trays (material handling losses); (*iv*) radiation losses from openings, hot exposed parts, etc.; (*v*) heat carried out by the waste gases (flue losses); and (*vi*) heat losses associated to product cooling process (cooling air to waste).

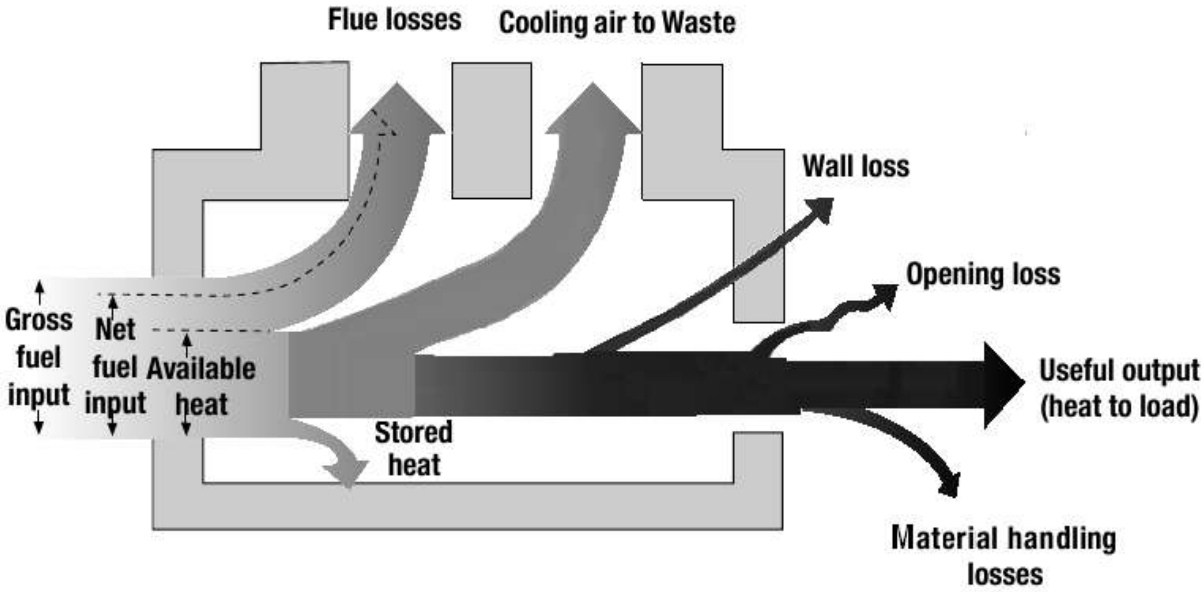


Figure 16 – Typical heat losses in a ceramic kiln (adapted from [81]).

As it can be observed from Figure 16, the most significant heat losses are associated to the waste-gas (flue) loss and heat losses associated to the fired product cooling.

During the kiln functioning its metal structure and insulation are heated so that their interior surfaces are about the same temperature as the product they contain. The stored heat is held in the structure until the kiln shuts down, then it leaks out into the surrounding area.

As long as the kiln is in production, the wall or transmission losses take place. They are caused by the conduction of heat through the walls, roof, and floor of the kiln (Figure 17). This process continues while the furnace is at an elevated temperature.

As shown on Figure 18, kilns operating at temperatures above 537ºC might have significant radiation (opening) losses. Hot surfaces radiate energy to nearby colder surfaces, and the rate of heat transfer increases with the fourth power of the surface's absolute temperature [81]. When there is an opening in the kiln enclosure, heat is lost by radiation at a rapid rate.

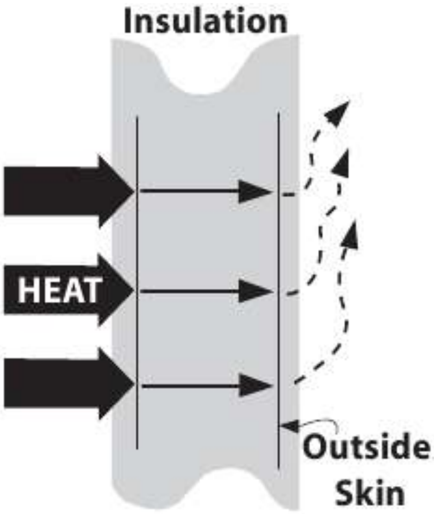


Figure 17 - Wall losses in a kiln [81].

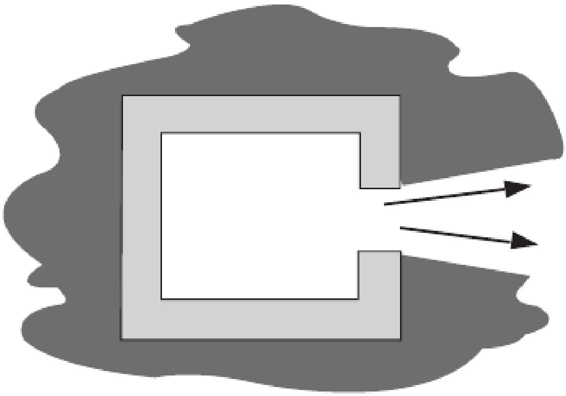


Figure 18 – Radiation losses from heated to colder surface [81].

Another type of losses – material handling losses – are associated with the fact that many furnaces use equipment to convey the work into and out of the heating chamber, leading to heat losses. Conveyor belts, product hangers or cars that enter the heating chamber cold and leave it at higher temperatures drain energy from the combustion gases.

Figure 19 presents an example of heat flow in a ceramic kiln SACMI FMS 2950/94,5. As it can be observed, the share of thermal energy associated to the final cooling at the elevated temperatures is approximately 40%. This heat, together with heat associated to flue gases, composes more than 50% of the total thermal energy used by the kiln in analysis.

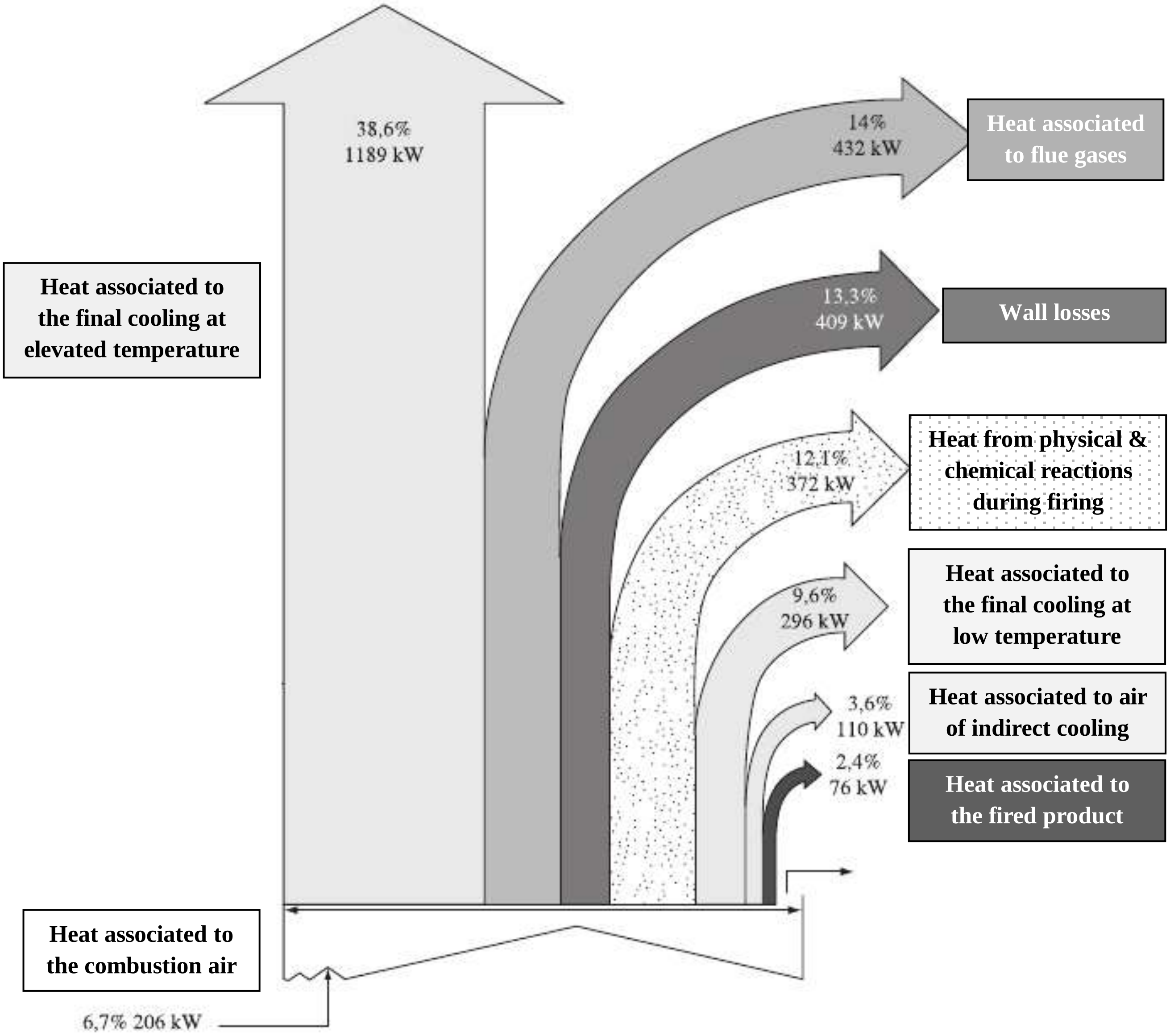


Figure 19 – Heat flow diagram of ceramic kiln SACMI FMS 2950/94,5 [61].

1.2. Dryers

1.2.1. General considerations

Industrial drying is a basic unit operation widely used in a variety of industries, among which is ceramic industry. The drying process in the ceramic industry is a second greatest energy consumer after the firing process. It is estimated that drying accounts for 15-20% of industrial energy demand in typical industrialized countries [82].

Ceramic industry counts with a great variety of dryers with different technologies and configurations that depend on the type of product to be dried. Besides, there are numerous classifications of dryers that are summarized in Table 3 (the most common of them are marked with *).

Table 3 – Classifications of dryers [83].

Criteria	Types
Mode of operation	• Batch • Continuous*
Heat input type	• Convection*, conduction, radiation, electromagnetic fields, combination of heat transfer modes • Intermittent and continuous* • Adiabatic and non-adiabatic
State of material in dryer	• Stationary • Moving, agitated, dispersed
Operating pressure	• Vacuum* • Atmospheric
Drying medium (convection)	• Air* • Superheated system • Flue gases
Drying temperature	• Below boiling temperature* • Above boiling temperature • Below freezing point
Relative motion between drying medium and drying solids	• Co-current • Counter-current • Mixed flow
Number of stage	• Single* • Multi-stage

The most frequently employed dryers in ceramics production are tunnel dryers, band dryers and batch dryers. A typical continuous type of ceramic dryer - tunnel dryer - is shown in Figure 20. A tunnel dryer consists basically of a group of truck-and-tray batch dryers that operate in a programmed series. Tunnel dryers are adaptable for mass-producing that requires long lasting drying.

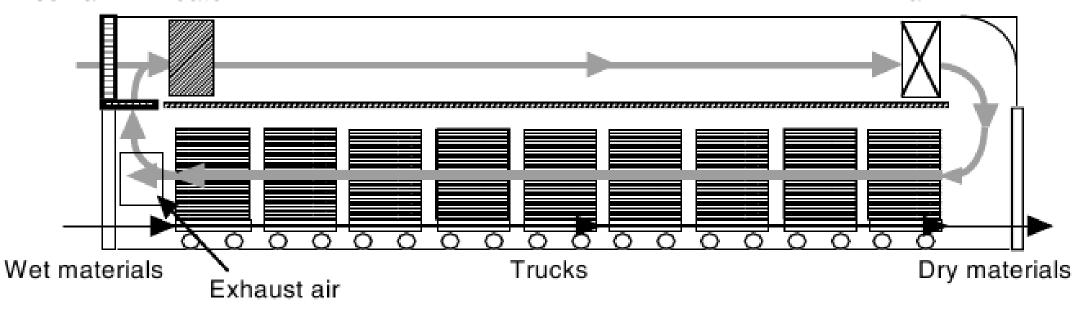


Figure 20 – Configuration of typical tunnel dryer [84].

Band dryers normally use several bands in one-above-other configuration, where the materials are conveyed as shown in Figure 21. Bands consist of a net or perforated plates, which widths vary from 0.5 m up to 2 m. Drying air temperatures ranging from 80 to 100ºC, initial moisture contents of 45–100% and drying rates of 5–18 kg/m^2·h are usual for band dryer operation.

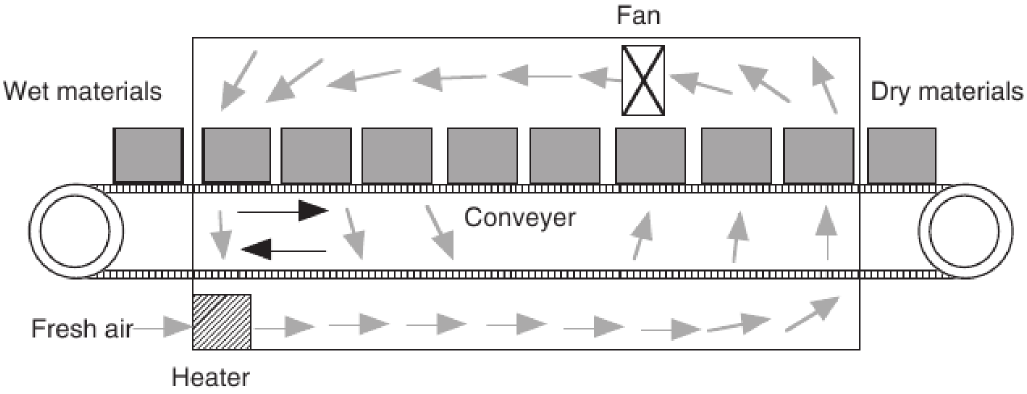


Figure 21 – Configuration of typical band dryer [84].

Figure 22 illustrates configuration of a typical batch dryer.

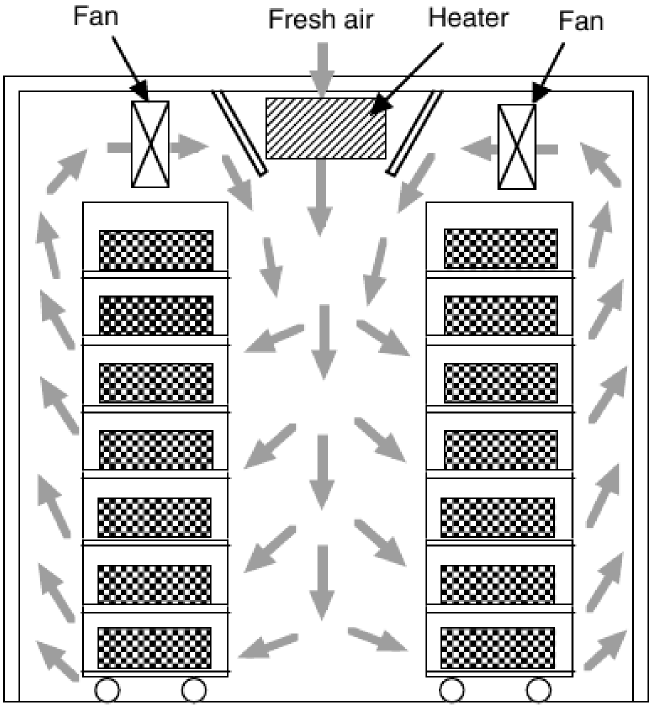


Figure 22 - Configuration of typical batch dryer [84].

Batch dryers are commonly used to dry small quantities of products or when the drying times are very long. During batch dryer operation, wet materials are placed on trays or shelves, which are set in a dryer’s room, while the hot air circulates among the shelves in the room by a blower. Batch dryers can be used to dry different types of ceramics at a variety of drying conditions, i.e. time, temperature, air rate, etc. that can be easily changer and controlled.

1.2.2. Heat losses in dryers

As it was already mentioned, drying is one of the most energy-intensive operations due to the high latent heat of vaporization and the inherent inefficiency of using hot air as the most common drying medium.

Figure 23 illustrates typical thermal energy losses in a ceramic dryer. It can be observed that they are similar to the heat losses present in ceramic kilns, except the fact that heat losses associated to the air cooling in ceramics firing are absent during drying process. For more detailed analysis of the heat losses, see section 1.1.2.

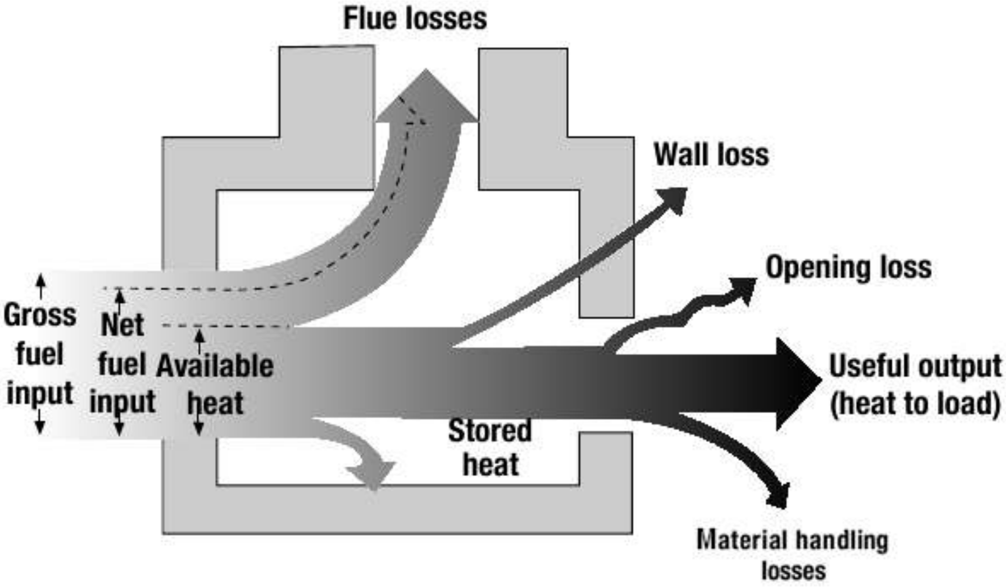


Figure 23 – Typical heat losses in a ceramic dryer (adapted from [81]).

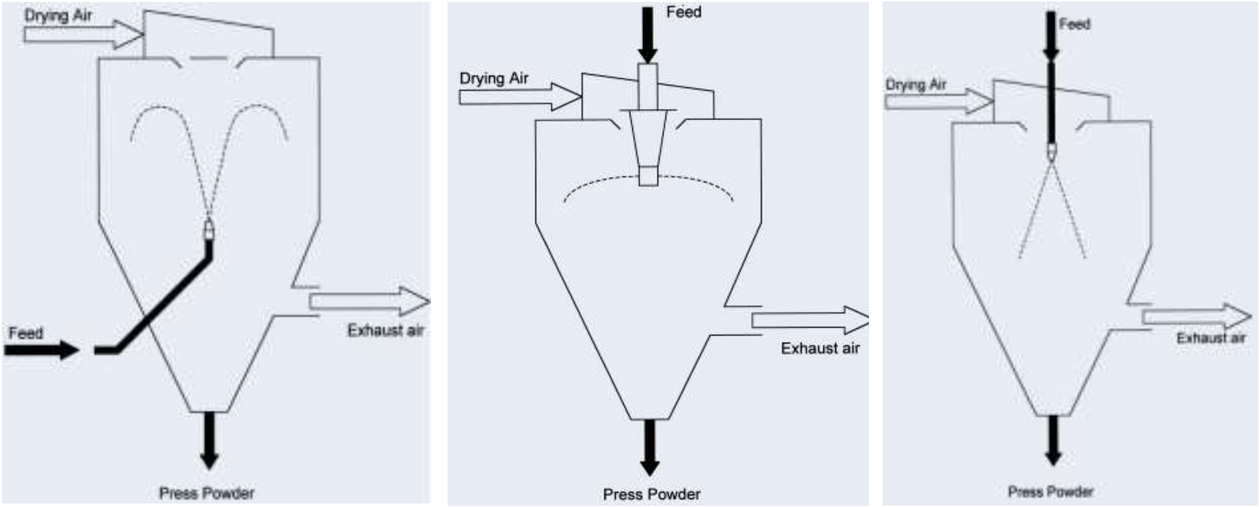
According to [80], less than 50% of the energy used in a conventional dryer is used to heat the product and evaporate water. The remained energy is used by the dryer structure, ware supports and exhausted air.

1.3. Spay dryers

1.3.1. General considerations

Spray drying has been a widely used technique since its invention in 1878 by Samuel Perey. Referring to the ceramic industry, spray drying is used for conversion of ceramic slurries into free-flowing powder [85]. Spray drying is a one-step continuous unit processing operation that, generally, consists of three main stages: (*i*) atomization; (*ii*) spray-air mixing and moisture evaporation; and (*iii*) separation of dry product from the exit air [86]. The spray drying begins from the liquid pumping from the product feed tank to the atomization device. Next, the drying air is drawn from the atmosphere through a filter by a supply fan and is passed through the air heater to the air distributor. When the droplets produced by the atomizer meet the hot air, the evaporation takes place. After the drying of the droplets in the chamber, the majority of the dried product falls to the bottom of the chamber and entrains in the air. Next, they pass through the cyclone in order to separate dried particles from the air. The dried particles are discharged from the bottom of the cyclone via a rotary valve and are collected or packed later. The air used in the process is pulled out of the top and is released to the atmosphere or sent to a baghouse separator for further cleaning.

Depending on the size of the particles desired for the spray-dried powder, the basic spray dryer configurations count with a mixed flow drying systems with a fountain nozzle (particles size of 75-150 microns), co-current drying system with a rotary atomizer (particles size of 25-100 microns) and co-current drying systems with a nozzle atomizer (used for very fine grain ceramics) [85]. The concepts behind mixed flow drying systems with a fountain nozzle, co-current drying system with a rotary atomizer and co-current drying systems with a nozzle atomizer are illustrated on Figure 24 a-c, respectively.



a. **c.**

Figure 24 – **a.** A scheme of a mixed flow drying systems with a fountain nozzle; **b.** A scheme of a co-current drying system with a rotary atomizer; **c.** A scheme of a co-current drying systems with a nozzle atomizer [85].

1.3.2. Heat losses in spray dryers

Spray drying is an energy intensive operation and comprises a significant portion of final industrial energy use worldwide [87], and is especially important in ceramics drying.

Figure 25 illustrates an example of typical heat losses in spray dryers in ceramic industry. The spray dryer has thermal efficiency (η_{TH}) of 83%, air inlet (T_{a1}) and outlet (T_{a2}) temperatures of 500ºC and 65ºC, respectively. As it may be noticed, the main heat losses during the spray driers functioning occur in air heater, in drying installation, during powder drying and with exhaust air.

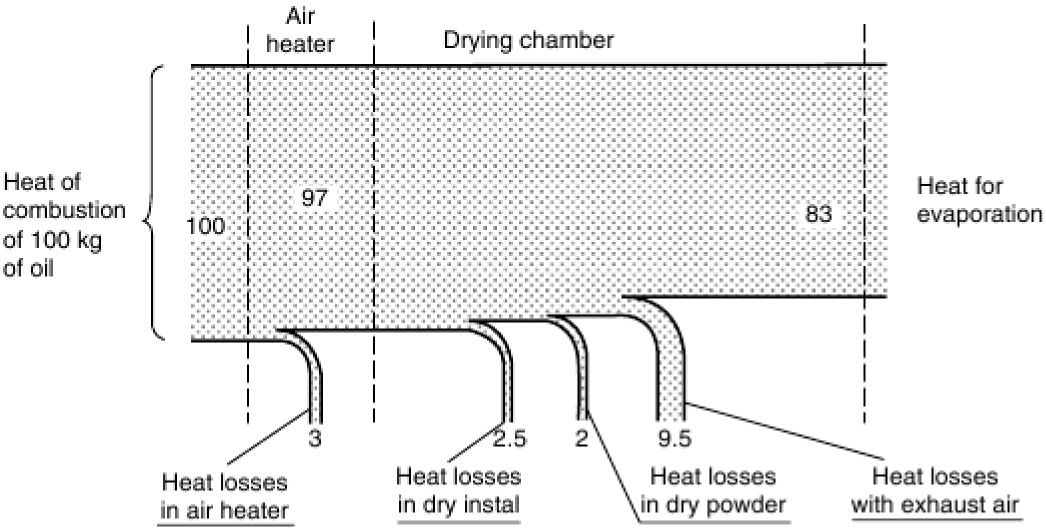


Figure 25 – Thermal efficiency of spray dryer with η_{TH} = 83%, oil, T_{a1} = 500ºC, T_{a2} = 65ºC.

2. Characterization of the waste heat sources

This section provides theoretical basis for the waste heat sources characterization. In general, there are three basic parameters that are used to evaluate the feasibility of waste heat recovery in different sources: waste heat quantity, quality and temporal availability [88]. The following sections provide deeper insight into each of these parameters.

2.1. Heat quantity

Heat quantity measures how much energy is contained in a waste heat stream [13]. In general, the heat quantity of the inlet or outlet stream (Q) is a function of a temperature and mass flow rates [88]:

$$Q = \dot{m} \cdot H \tag{2.1}$$

where $\dot{H}$ is enthalpy of corresponding heat stream (J/kg) and $\dot{m}$ – mass flow rate of heat stream (kg/s).

The enthalpy of the heat stream can be calculated using the following expression [89]:

$$H = H_G + H_W \tag{2.2}$$

where H_G is the enthalpy of the dry air (J/kg) and H_W is the enthalpy of the moisture (J/kg).

$$H_G = C_G \cdot T_a \tag{2.3}$$

where C_G is the specific heat of dry air (J/(kg·ºC)) and T_a is the air temperature (ºC).

$$H_W = \Omega \cdot (C_V \cdot T_a + \lambda) \tag{2.4}$$

where Ω is the absolute humidity (kg water/kg dry air), C_V is specific heat of vapour stream (J/(kg·ºC)), T_a is the air temperature (ºC) and λ is the latent heat of water evaporation (J/kg).

The procedure of the heat quantity determination can be based on the measurements of the waste heat stream characteristics (temperature, volume, humidity) on the output of the heat source. Another option is based on the measurements of the inlet energy (e.g. thermal energy from fuel combustion, inlet air and incoming products) and further calculation of the outlet characteristics of the waste heat stream, using the principles of mass and heat conservation. This method uses the heat and mass balances in order to illustrate the distribution of energy along the process responsible for the residual heat generation. Mass balance is fundamental to the control of processing, particularly in the control of yields of the process, while heat balance is used in the examination of the efficiency of a combustion process.

As it was afore-mentioned, the basic principles of heat and mass balances are based on the concepts of heat and mass conservation, respectively. According to these statements, in a case when there is no accumulation, what goes into a process must come out. Resuming, heat balance is used to determine where all heat energy enters and leaves the system [90]. Similarly, mass balance is focused on determination where all mass enters and leaves a system.

The following sections present theoretical fundaments for the calculation of mass and heat balances for earlier identified waste heat sources (kilns, dryers and spray-dryers).

2.1.1. Heat and mass balances in kilns

The major part of kilns used in ceramic industry operates in continuous mode. Figure 26 illustrates the data used for the calculation of mass and heat balances in ceramic kilns.

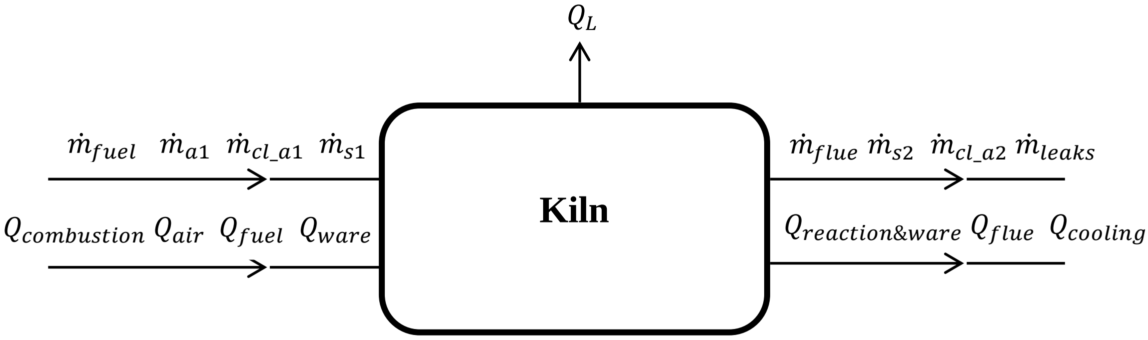


Figure 26 – Data for calculation of heat and mass balances in ceramic kiln.

The mass balance for the kilns is given by the following expression:

$$\dot{m}_{fuel} + \dot{m}_{a1} + \dot{m}_{cl\_a1} + \dot{m}_{s1} = \dot{m}_{flue} + \dot{m}_{s2} + \dot{m}_{cl\_a2} + \dot{m}_{leaks} \tag{2.5}$$

where $\dot{m}_{fuel}$ is a mass flow rate of fuel (kg/s), $\dot{m}_{a1}$ – mass flow rate of inlet air (kg/s), $\dot{m}_{cl\_a1}$ – mass flow rate of inlet cooling air (kg/s), $\dot{m}_{s1}$ – mass flow rate of inlet solid (kg/s), $\dot{m}_{flue}$ – mass flow rate of flue gases, $\dot{m}_{s2}$ – mass flow rate of outlet solid (kg/s), $\dot{m}_{cl\_a2}$ – mass flow rate of outlet cooling air (kg/s) and $\dot{m}_{leaks}$ – losses of air mass flow rate due to leaks (kg/s).

The heat balance of ceramic kiln is expressed by equation that relates the quantity of heat released during the kiln's functioning with the quantity of heat used for technological processes (useful heat) and heat losses [91]:

$$Q_{combustion} + Q_{air} + Q_{fuel} + Q_{ware} = Q_{reaction\,\&\,ware} + Q_{flue} + Q_{cooling} + Q_L \quad (2.6)$$

Where $Q_{combustion}$ is a heat released during the fuel combustion (J/s), Q_{air} – inlet air heat (J/s), Q_{fuel} – inlet fuel heat (J/s), Q_{ware} – inlet ware heat (J/s), $Q_{reaction\,\&\,wares}$ – heat used for reactions and outlet ware heat (J/s), Q_{flue} – heat of the flue gases (J/s), $Q_{cooling}$ – outlet air heat in the cooling zone (J/s) and Q_L – non-applicable heat losses (J/s).

The non-applicable heat losses, Q_L, are those that are generally not considered for the waste heat recovery applications due to a number of reasons (e.g. low quantity of heat, complex process of waste heat recovery). Q_L in the kilns are determined as follows:

$$Q_L = Q_{wall} + Q_{rad} + Q_{leaks} \quad (2.7)$$

where Q_{wall} are the heat losses through the kiln's walls (J/s), Q_{rad} are the heat losses by radiation (J/s) and Q_{leaks} are the heat losses caused by construction of kiln that originate heat leaks (J/s).

To calculate the thermal efficiency of the kiln, the following equation could be used:

$$\eta_{TH} = \frac{Q_{tech\_process}}{Q_{combustion} + Q_{air} + Q_{fuel} + Q_{ware}} \times 100\% \quad (2.8)$$

where $Q_{tech\_process}$ – heat used for technological processes (J/s).

2.1.2. Heat and mass balances in dryers

Similar to ceramic kilns, the majority of dryers employed in ceramic industry operate in continuous mode. Heat and mass balances in continuous dryers refer to a situation when wet materials with the moisture content W_{s1} (kg water/kg dry solid) and temperature T_{s1} (ºC) are dried in a dryer and the dry products with the moisture content W_{s2} (kg water/kg dry solid) and temperature T_{s2} (ºC) are obtained (Figure 27).

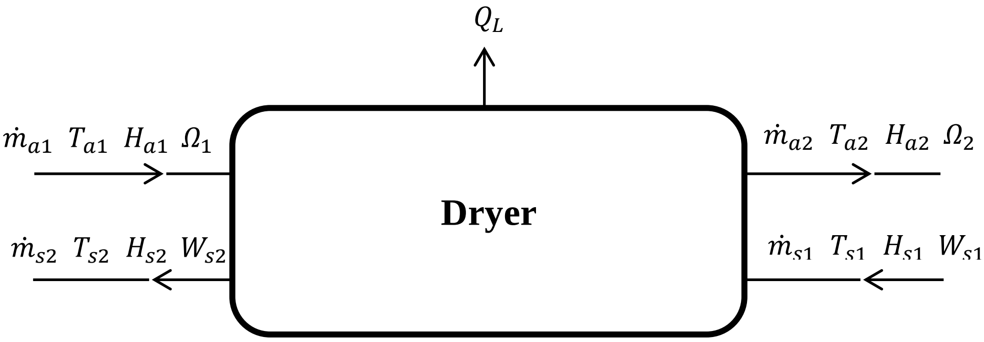


Figure 27 – Data for calculation of heat and mass balances in continuous ceramic dryer.

According to [84], the total heat balance equation is expressed by:

$$\dot{m}_{a1} \cdot H_{a1} + \dot{m}_{s1} \cdot (C_{DS} + C_W \cdot W_{s1}) \cdot T_{s1} = \dot{m}_{a2} \cdot H_{a2} + \dot{m}_{s2} \cdot (C_{DS} + C_W \cdot W_{s2}) \cdot T_{s2} + Q_L \tag{2.9}$$

where $\dot{m}_{a1}$ is the mass flow rate of inlet air (kg/s), $\dot{m}_{a2}$ is the mass flow rate of outlet air (kg/s), $\dot{m}_{s1}$ is mass flow rate of inlet solid (kg/s), $\dot{m}_{s2}$ is mass flow rate of outlet solid (kg/s), H_{a1} is the enthalpy of inlet air (J/kg), H_{a2} is the enthalpy of outlet air (J/kg), C_{DS} is the specific heat of dry solid (J/(kg·ºC)), C_W is the specific heat of water (J/(kg·ºC)), W_{s1} is moisture in feed (kg water/kg dry solid), W_{s2} is moisture in dried product (kg water/kg dry solid), T_{s1} – temperature of product dried in a dryer (ºC), T_{s2} – temperature of obtained product (ºC) and Q_L are the non-applicable heat losses (J/s).

The non-applicable heat losses in the dryer, Q_L, are determined as follows:

$$Q_L = Q_{wall} + Q_{leaks} \tag{2.10}$$

where Q_{wall} are the heat losses through the dryer's walls (J/s) and Q_{leaks} are the heat losses caused by construction of the dryer that provoke heat leaks (J/s).

The enthalpy of both inlet and outlet air in the dryer, H_{a1} and H_{a2}, respectively, is given by:

$$H_a = C_G \cdot T_a + (\lambda + \mathrm{C_V} \cdot T_a) \cdot \Omega \tag{2.11}$$

where C_G is the specific heat of the dry air (J/(kg·ºC)), T_a is the air temperature (ºC), λ is the latent heat of water evaporation (J/kg), $\mathrm{C_V}$ is the specific heat of vapour stream (J/(kg·ºC)) and Ω is the absolute humidity (kg water/kg dry air).

The mass balance on the inlet and outlet moisture is as follows:

$$\dot{m}_a \cdot \Omega_1 + \dot{m}_s \cdot W_{s1} = \dot{m}_a \cdot \Omega_2 + \dot{m}_s \cdot W_{s2} + \dot{m}_{leaks} \tag{2.12}$$

Where $\dot{m}_a$ – mass flow rate of dry air (kg/s), $\dot{m}_s$ – mass flow rate of dry solid (kg/s), $\dot{m}_{leaks}$ represent the losses of air mass flow rate due to leaks (kg/s), while Ω_1 and Ω_2 are the absolute humidity of inlet and outlet air (kg water/kg dry air), respectively.

The thermal efficiency of ceramic dryer can be estimated as follows:

$$\eta_{TH} = \frac{Heat\ used\ in\ evaporation}{Heat\ input} = \frac{T_{a1} - T_{a2}}{T_{a1} - T_{amb}} \times 100\% \tag{2.13}$$

where T_{a1} is the inlet air temperature, T_{a2} is the outlet air temperature and T_{amb} is the ambient air temperature.

2.1.3. Heat and mass balances in spray dryers

Heat and mass balances in spray dryer provide data of air-product flow and temperature, used to assess its performance. In ceramic industry spray dryers operate in continuous mode with negligible hold-up of the product in chamber. For this operation mode: (*i*) the mass input of air and feed in unit type equals the mass output of air and product, and (*ii*) heat input of air and feed equals heat output of air and product plus the heat losses from the drying chamber [92].

The data used for calculation of heat and mass balances in spray dryers are shown on Figure 28. The reference temperature necessary for the calculations of enthalpies is assumed to be a freezing point of water. Besides, the mass balances calculations are based on the unit weight of bone dry product.

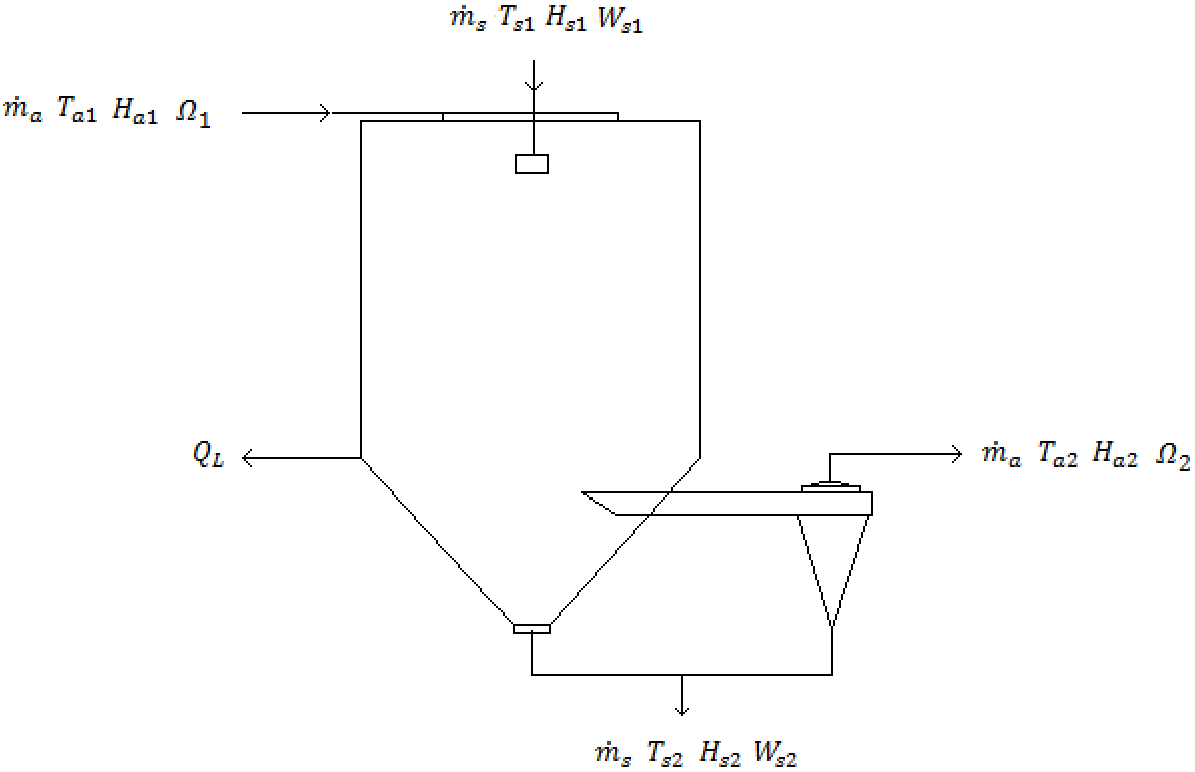


Figure 28 – Spray dryer data for calculation of heat and mass balances [92].

According to [92], for continuous operation mode:

$$Input = Output \tag{2.14}$$

Thus, similarly to the dryer mass balance:

$$\dot{m}_s \cdot W_{s1} + \dot{m}_a \cdot \Omega_1 = \dot{m}_s \cdot W_{s2} + \dot{m}_a \cdot \Omega_2 \tag{2.15}$$

At the same time,

$$\dot{m}_a \cdot H_{a1} + \dot{m}_s \cdot H_{s1} = \dot{m}_a \cdot H_{a2} + \dot{m}_s \cdot H_{s2} + Q_L \tag{2.16}$$

The non-applicable heat losses in spray-dryer, Q_L, are calculated through application of the standard heat transfer equation:

$$Q_L = U \cdot A \cdot \Delta T, \tag{2.17}$$

where U is the overall heat transfer coefficient (W/(ºC·m^2)), A is the heat transfer area (m^2) and ΔT is the difference between the inlet and outlet temperatures (ºC).

The enthalpy of the feed entering the spray drier, H_{s1}, and the enthalpy of the dried product leaving the spray dryer, H_{s2}, are calculated as:

$$H_s = C_{DS} \cdot \Delta T + W_s \cdot C_W \cdot \Delta T \tag{2.18}$$

where C_{DS} is specific heat of dry solid (J/(kg·ºC)), C_W – specific heat of moisture (J/(kg·ºC)) and ΔT is the difference in temperature between feed temperature and the reference temperature level (water freezing point).

On the other hand, the enthalpy of the drying medium either entering, H_{a1}, or leaving the dryer, H_{a2}, is expressed in the following manner:

$$H_a = C_S \cdot \Delta T + \Omega \cdot \lambda \tag{2.19}$$

where C_S is the specific heat of the drying medium (J/(kg·ºC)), ΔT is the difference in temperature between air temperature and the reference temperature level (water freezing point) and λ is the latent heat of evaporation (J/kg).

Just as in dryers, the thermal efficiency of spray-drying is related to the heat input required to produce a unit weigh of dried product and can be obtained using equation (2.13).

2.2. Heat quality

Although the quantity of available waste heat is an important parameter, the potential for economic waste heat recovery is more dependent on its quality [88]. Heat quality is aimed to measure the usefulness of the waste heat, and is determined by the temperature of the waste heat stream [13].

To guarantee efficient heat transfer and recovery, it is necessary that the waste heat source temperature is higher than the heat sink temperature. As it was already mentioned, waste heat sources are divided into three categories (low, medium and high), according to the temperature ranges:

High: > 650ºC
Medium: 230ºC - 650ºC
Low: < 230ºC

Generally, the higher the temperature the higher the quality of the waste heat and more efficient is the heat transfer per unit of surface area. On the other hand, waste heat recovery from the high temperature sources requires elevated technology investments dictated by the special engineering and materials required for this purpose.

It is a well known fact that low temperature waste heat is abundant, accounting for 50% or more of the total heat generated in industry [40]. However, the use of the low grade heat is more problematic because of a lack of efficient recovery methods. In practice low grade heat is used for the preheating purposes [93], [88].

Some examples of sources of low, medium and high temperature waste heat are listed in Table 4.

Table 4 – Temperature classification of some waste heat sources (adapted from [13] and [93]).

Temperature range	Sources	Temperature (ºC)
High > 650ºC	Nickel refining furnace	1370-1650
	Steel electric arc furnace	1370-1650
	Glass melting furnace	1300-1540
	Hydrogen plants	650-980
	Aluminium refining furnace	650-760
Medium 230ºC – 650ºC	Gas turbine exhausts	370-540
	Reciprocating engine exhausts	315-600
	Heat treating furnace	430-650
	Drying and baking ovens	230-590
	Cement kiln	450-620
Low < 230ºC	Process steam condensate	50-90
	Cooling water from: furnace doors air compressors internal combustion forming dies	 30-50 30-50 70-120 27-88
	Drying, baking and curing ovens	90-230
	Hot processed liquids-solids	30-230

Waste heat sources in ceramic industry belong to the medium and low temperature ranges due to the fact that temperatures of the waste heat resulting from the ceramics production process do not overpass the 650ºC.

2.3. Temporal availability

Finally, economical feasibility of the waste heat recovery depends on the temporal availability of the residual heat. Each waste heat recovery source has its own operating schedules that vary according to the production mode in the industrial facility. It makes temporal availability one of the parameters to consider for the waste heat recovery.

3. Identification of waste heat capture technologies and devices in ceramic industry

Thermal energy recovery in ceramic industry is a significant issue due to the high temperatures and multiple heat intensive processes involved (e.g. firing and drying). As it was already mentioned, medium and low grade thermal energy are typically available during the ceramics production.

Medium grade heat is viable for reuse in the industrial processes for example for combustion air pre-heating, feed water pre-heating, etc. While, low grade heat that can be applied for electric power generation, heating, cooling, fresh water production or hydrogen production [18].

Table 5 contains a summary of the most common technologies and devices used in ceramic industry for the waste medium and low grade heat recovery.

Table 5 – Summary of common waste heat recovery technologies/devices in ceramic industry.

	Low grade heat recovery	**Medium grade heat recovery**
Direct recirculation of waste heat installation	x	x
Convective recuperator		x
Mechanical vapour recompression system		x
Heat pump	x	x
Economizer	x	x
Heat pipe	x	x
Heat pipe heat exchanger	x	x
Metallic heat wheel	x	x
Ceramic heat wheel		x
Hydroscopic heat wheel	x	
Passive regenerator	x	x
Waste heat boiler	x	x
Organic Rankine cycle	x	x

In order to select a waste heat recovery technology/device a set of parameter should be specified [88]: (*i*) temperature of waste heat fluid; (*ii*) chemical composition of waste-heat fluid; (*iii*) minimum allowable temperature of waste heat fluid; (*iv*) amount and type of contaminants in the waste heat fluid; (*v*) allowable pressure drop for waste heat fluid; (*vi*) temperature of heated fluid; (*vii*) flow rate of heated fluid; (*viii*) chemical composition of heated fluid; (*ix*) maximum allowable temperature of heat fluid; (*x*) allowable pressure drop in the heated fluid; and (*xi*) control temperature (in a case when control is required).

The next sections provide a brief overview of the waste heat recovery technologies and devices presented in Table 5.

3.1.1. Direct recirculation of heat

Direct recirculation of heat is considered to be one of the most efficient methods of waste heat recovery since it allows for almost 100% recovery of the thermal energy. Direct recirculation is based on a fact that even in the highest temperature processes the load (e.g. fuel, combustion air, ware) that enters the process has ambient temperature. If exhaust gases or cooling air leaving the high temperature process (like drying, firing or spray drying) can be brought into contact with incoming load, the energy will be transferred to the load, preheating it and reducing the amount of purchased fuel required to sustain the process. More often, heat is transferred to combustion air of the burner system.

In ceramic industry the cooling air that leaves the high temperature process can be directly used for the preheating, while exhaust gases have to suffer preliminary decontamination from substances present in them.

The typical direct waste heat recovery installation basically consists of equipment for heat transfer, like pumps, ducts, tubes, etc. The heat available from the elevated temperature processes is expresses by the following equation [89]:

$$Q = \dot{m}_A \cdot (C_G \cdot (T_{a2} - T_{amb}) + \Omega \cdot (C_V \cdot (T_{a2} - T_{amb}) + \lambda)) \tag{3.1}$$

where Q is heat quantity of the stream (J/s), $\dot{m}_A$ – mass flow rate of air (kg/s), C_G – specific heat of the dry air (J/(kg·ºC)), C_V is the specific heat of vapour stream (J/(kg·ºC)), T_{a2} – outlet air temperature (ºC), T_{amb} – ambient air temperature (ºC), λ is the latent heat of water evaporation (J/kg) and Ω – absolute humidity (kg water/kg dry air).

3.1.2. Convective recuperator

Recuperators are gas-to-gas heat exchangers that are used in recovering waste heat to be applied for heating gases in medium to high temperature ranges. There are a lot of designs of recuperators that are generally based on tubes or plates to transfer heat from the outgoing exhaust gas to the incoming combustion air, while keeping the two streams from mixing [76].

Figure 29 depicts a convective recuperator with flue gases flowing normal to a tube bundle with air to be pre-heated flowing in the tubes. The tubes can be baffled to allow gas to pass over them again. Baffling increases the effectiveness of heat exchanges, however, it increases the cost of manufacturing and the pressure drop in the air pass.

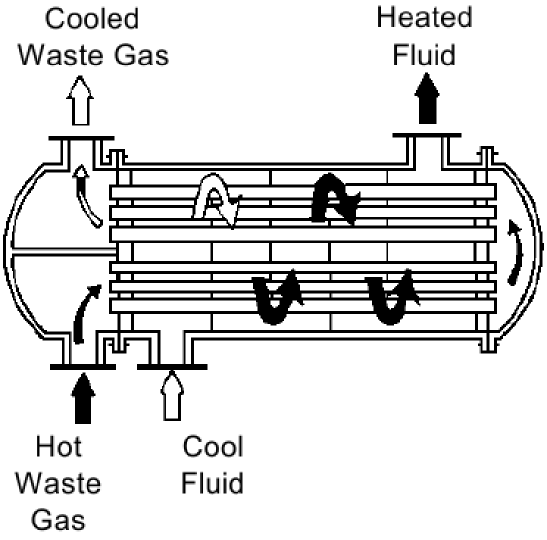


Figure 29 – Convective recuperator [94].

Convective type recuperators must be protected against overheating. Large temperature fluctuations can cause expansion and contraction of recuperator components, possibly leading to cracks or separations. This causes efficiency losses that may increase fuel costs by 10% to 15%, and rebuild costs may be as high as 90% of initial costs. Besides, convective recuperators may not be suitable for some corrosive or dirty exhaust gases.

Figure 30 presents alternative arrangement for the convective recuperator. In this device the cold combustion air is heated in a bank of parallel vertical tubes which extend into the flue gas stream. The main advantages of this arrangement are compactness, relatively low cost and ease of replacing of individual units that can be done during the recuperator’s full-load operation. On the other hand, effectiveness of vertical tube-within-tube recuperator is not high.

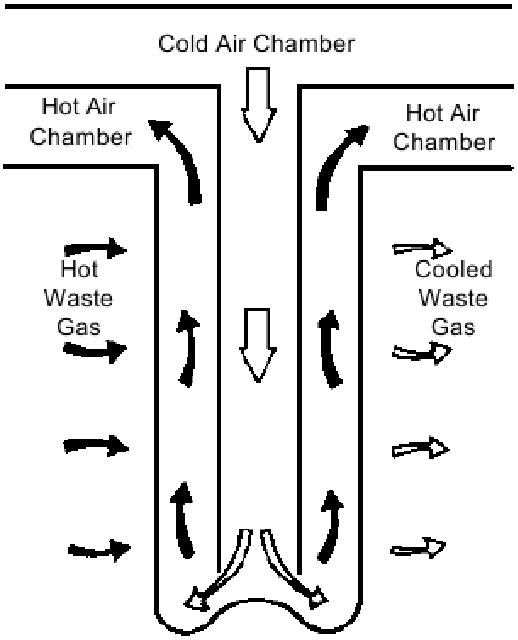


Figure 30 – Vertical tube-within-tube recuperator [94].

As it was already mentioned, convective recuperators are rather inexpensive and lead to fuel consumption reduction. However, installation of these devices requires significant capital investments as higher combustion air temperatures may require [88]: burner replacement, larger-diameter air lines with flexible expansion fitting, cold-air piping for cooling higher temperature burners, modified combustion controls, stack dampers, cold air bleeds, recuperator protection system, etc.

3.1.3. Mechanical vapour recompression system

Vapor recompression is a form of heat pumping in which low temperature waste stream vapor from a process is recompressed to raise its temperature and pressure. In the mechanical vapor recompression compressor is driven by the electricity or the output from a plant turbine, adding the energy to the vapor.

Among the principal reasons for the mechanical vapor recompression use [95] highlight: (*i*) low specific energy consumption; (*ii*) gentle evaporation of the product due to low temperature differences; (*iii*) short residence times of the product; (*iv*) high availability of the plants due to the simplicity of the process; (*v*) excellent partial load behavior and (*vi*) low specific operating costs. Generally, the mechanical vapor recompression is employed in the cases where waste heat temperature is in excess of 70ºC, temperature of upgrades does not exceed 10ºC and waste heat availability and use are simultaneous and quantities are well matched [96].

The most typical application of the mechanical vapor recompression system is for the evaporation purposes. Figure 31 illustrates heat flow of an evaporator heated by mechanical vapor recompression.

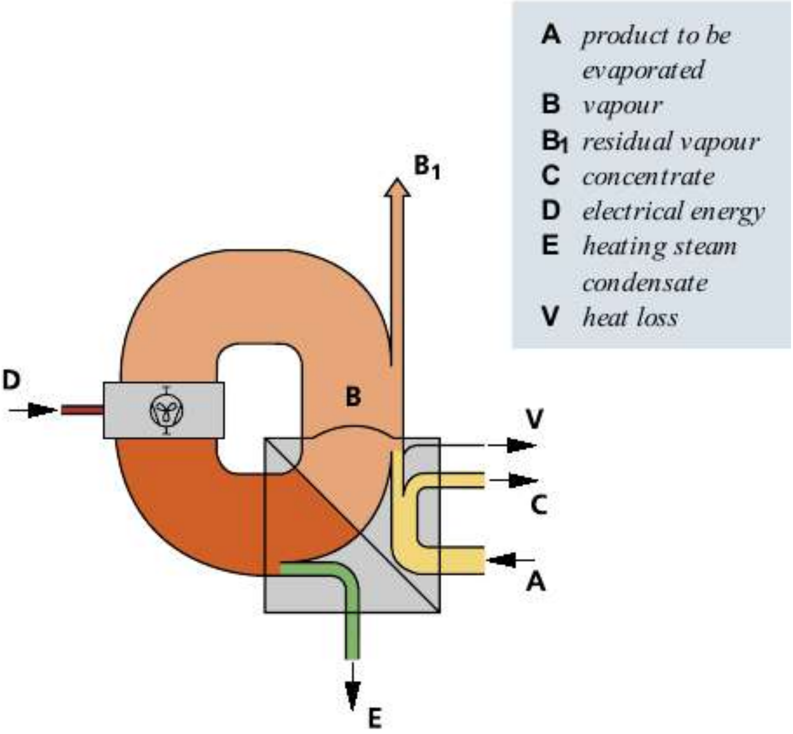


Figure 31 - Heat flow diagram of an evaporator heated by mechanical vapor recompression [95].

3.1.4. Heat pump

A heat pump is a device that operates cyclically, using external energy inputs to drive a cycle that absorbs energy from a low temperature source and rejects it at a higher temperature. Depending on the design, heat pumps are capable of either upgrading waste heat from a low temperature residual industrial heat source to a higher temperature, or using waste heat as an energy input for driving absorption cooling system [13, 18].

A simple heat pump consists of three elements (Figure 32): (*i*) a heat source that provides a heat input (Q_{in}) to a heat pump; (*ii*) a heat sink that receives the discharged heat (Q_{out}) from the heat pump; and (*iii*) external source that delivers work (W).

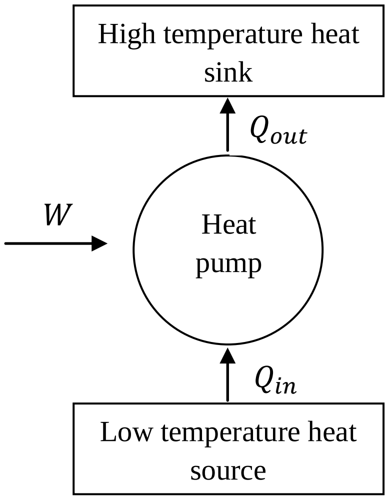


Figure 32 – A simple heat pump (adapted from [97]).

Among a variety of technologies available for heat pumps, sorption cycles and vapour compression cycles are the most popular principles used in heat pump. Vapour compression heat pumps are by far more commonly used in the industry due to their high efficiency and relatively simple construction. On the other hand, vapour compression heat pumps require electricity to drive a compressor. Owing to this fact, sorption cycle heat pumps are believed to be more environmentally friendly as they can use waste heat as the only energy source.

A schematic diagram of vapour compression heat pump is shown on Figure 33. The heating is provided to evaporator. In the evaporator the heat is extracted from the heat source to boil the working fluid. Next, this fluid is compressed by the compressor, raising its pressure and temperature. Further, the heat is delivered to the condenser. Finally, the pressure of the working fluid is reduced back to the evaporator condition in the throttling valve, where the cycle repeats.

The energy balance of heat pump is given by:

$$Q_{in} + W = Q_{out} \tag{3.2}$$

The efficiency of the heat pump is measured by the coefficient of performance (COP). COP provides information on how efficient the heat pump is extracting or discharging the heat to how much work is added. In this way COP is defined on a cooling or a heating basis as:

$$COP_{Cooling} = \frac{Q_{in}}{W} \tag{3.3}$$

or

$$COP_{Heating} = \frac{Q_{out}}{W} \tag{3.4}$$

It is important to mention that since the only energy used is the mechanical work in the compressor, COP of this system is higher than 100%. Nevertheless, the cost of energy required by the heat pump drive (electricity) may be higher than the value of the recovered heat. Thus, the economic attractiveness of the device largely depends on the energy price.

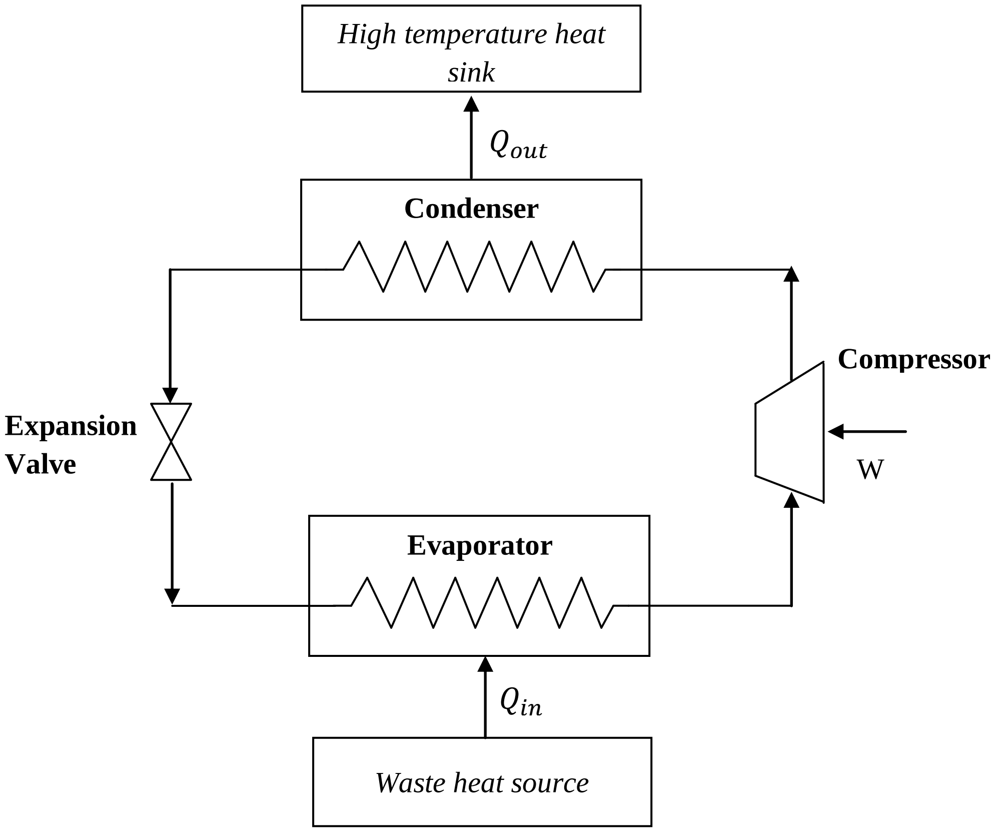


Figure 33 – A vapour compression heat pump (adapted from [97]).

3.1.5. Economizer

Economizer, or finned tube heat exchanger, is a heat exchanger that uses hot flue gas to heat the water. Figure 34 illustrates the ordinary construction of economizer that is made of a series of horizontal tubular elements (finned tubes). The finned tube consists of a round tube with attached fins that maximize surface area and heat transfer rates. The cold liquid flows through the tubes and receives heat from hot gases flowing across the tubes. To avoid the tubes overheat and damage, it is important to ensure that the water flow is always high enough to circumvent boiling of the water inside the tubes.

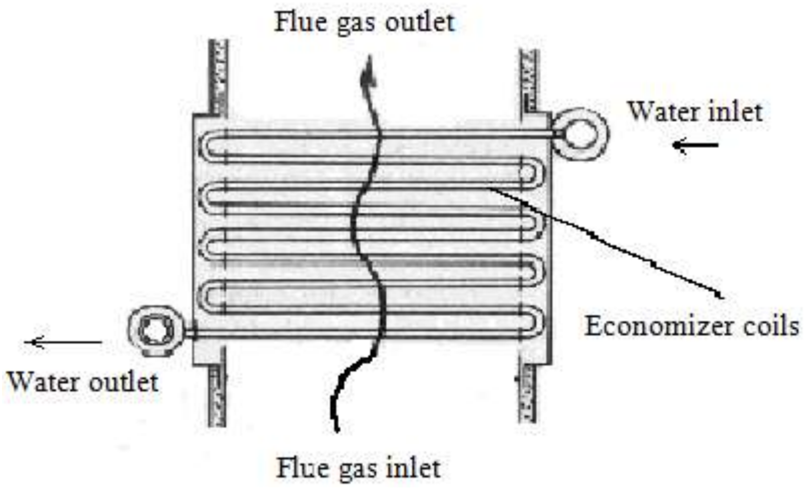


Figure 34 – Economizer [93].

The applications of economizer for the waste heat recovery purposes include boiler feedwater preheating, hot process liquids, hot water for space heating, etc. Figure 35 depicts one of the most common applications of economizer, also known as boiler economizer, where boiler exhaust gases are used for feedwater preheating. According to [15], for every 22 ºC reduction in flue gas temperature by passing through economizer, there is a 1% of the efficiency gain. As a result, adoption of feed water heating from flue gases using economizer gives the highest fuel economy, as one can pre-heat feed water almost up to the saturation temperature of steam.

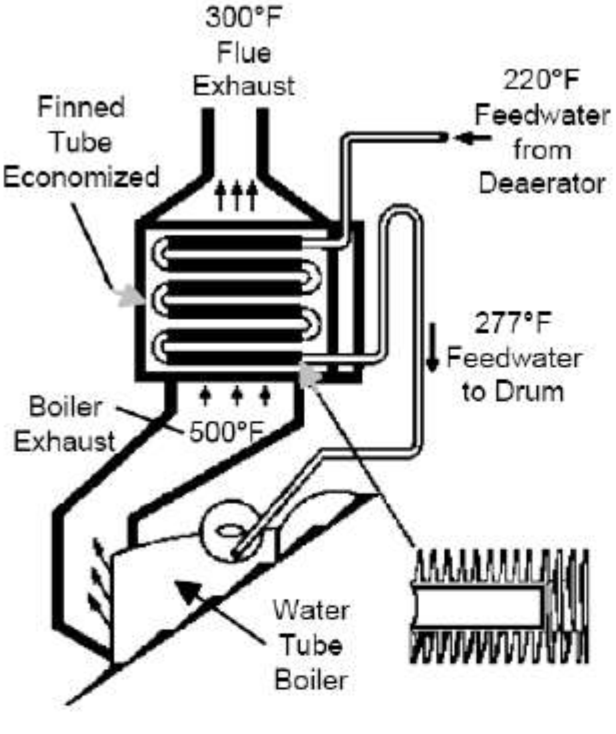


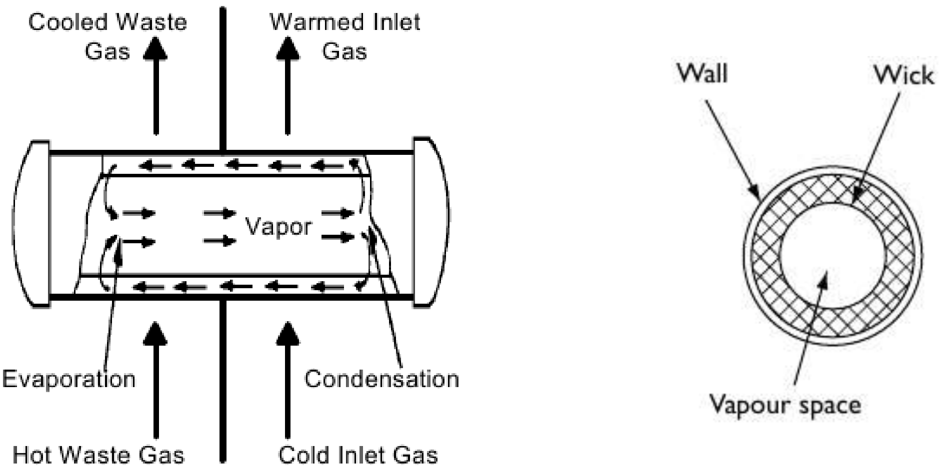
Figure 35 – Boiler economizer [13].

The extent of heat recovery in the economizer may be limited by the lowest allowable flue gas temperature. Thus, cooling below these limits can result in condensation and possible corrosion of the structural material.

One of the disadvantages of the economizers applications resides in a fact that these devices may not be usable for dirty stack gases (unless a means of cleaning the fins is provided) [11]. Besides, if the fluid contains sulphur, the sulphur-dioxide will be absorbed by the condensed water to form sulphuric acid. Due to its high corrosiveness it will attack the breeching downstream of the economizer and the stack lines [88].

3.1.6. Heat pipe

Heat pipe is a thermal energy absorbing and transferring system. Heat pipe is composed of three basic components: (*i*) the working fluid, (*ii*) the wick (or capillary structure) and (*iii*) sealed container. Figure 36 a. and b. show longitudinal and cross sections of the heat pipe with the respective main regions in each of them. The heat transferred from the hot gases evaporates the fluid in the wick. This provokes vapour expansion into the centre core of the heat pipe. The latent heat of evaporation is carried in the vapour to the cold end of the heat pipe where the vapour condenses. The formed condensate is then carried back in the wick to the hot end of the tube.



a. **b.**

Figure 36 – **a.** Longitudinal section of the heat pipe [13]; **b.** Cross section of the heat pipe [98].

The main characteristics of heat pipes resume to: (*i*) very high effective thermal conductance (can transfer up to 100 times more thermal energy than copper [93]); (*ii*) an isothermal surface of low impedance and (*iii*) the ability to act as a thermal flux transformer.

Referring to the waste thermal energy applications of heat pipes it is important to mention the heat pipe heat exchangers. Heat pipe heat exchangers are gas-to-gas heat exchangers that consist of a bundle of externally finned tubes that are made up as individual heat pipes (Figure 37). Each pipe contains a capillary wick structure that facilitates movement of the working fluid between the hot and cold ends of the pipe.

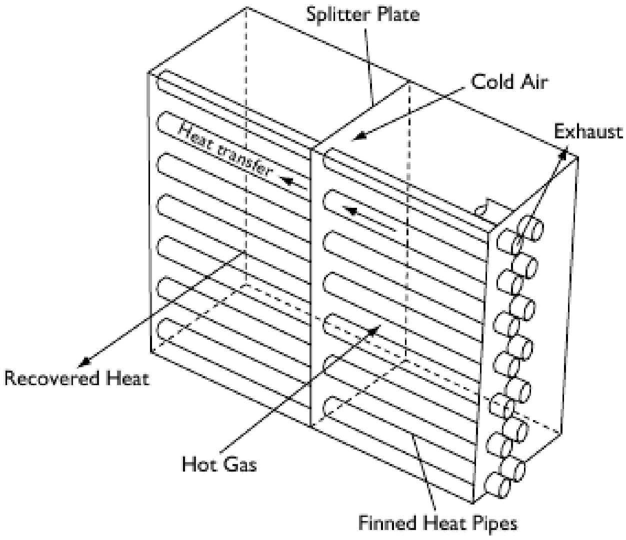


Figure 37 - Layout of a heat pipe heat exchanger showing means of heat transfer [98].

Heat pipe heat exchangers can be successfully employed for the heat recovery in air-conditioning systems, recovery of heat from a process exhaust stream for space heating or reuse in the process, etc. The attractiveness of the heat pipe heat exchanges utilization for the waste heat recovery is explained by a number of features [11, 88, 98]: (*i*) compact size ensured by good configuration for convective heat transfer; (*ii*) elevated system efficiency; (*iii*) absence of moving parts and external power requirements, implying high reliability; (*iv*) elimination of cross-contamination because of a solid wall between the hot and cold gas streams; (*v*) availability of a great variety of unit sizes suitable for low and medium temperature applications; (*vi*) reversibility of the system as the heat can be transferred in both directions; and (*vii*) simple maintenance.

3.1.7. Heat wheel

Heat wheel, also known as rotary generator or air pre-heater, is a rotary air-to-air heat exchanger composed of a large porous wheel (fabricated from material with high heat capacity) that rotates between two adjacent ducts. One of the ducts contains a hot gas, while another – a cooler gas. The axis of the disk is parallel to the stream flows at the partition between the ducts. As the disk rotates the heat is transferred from the hot gas duct to the cold one. Figure 38 illustrates the application of the heat wheel.

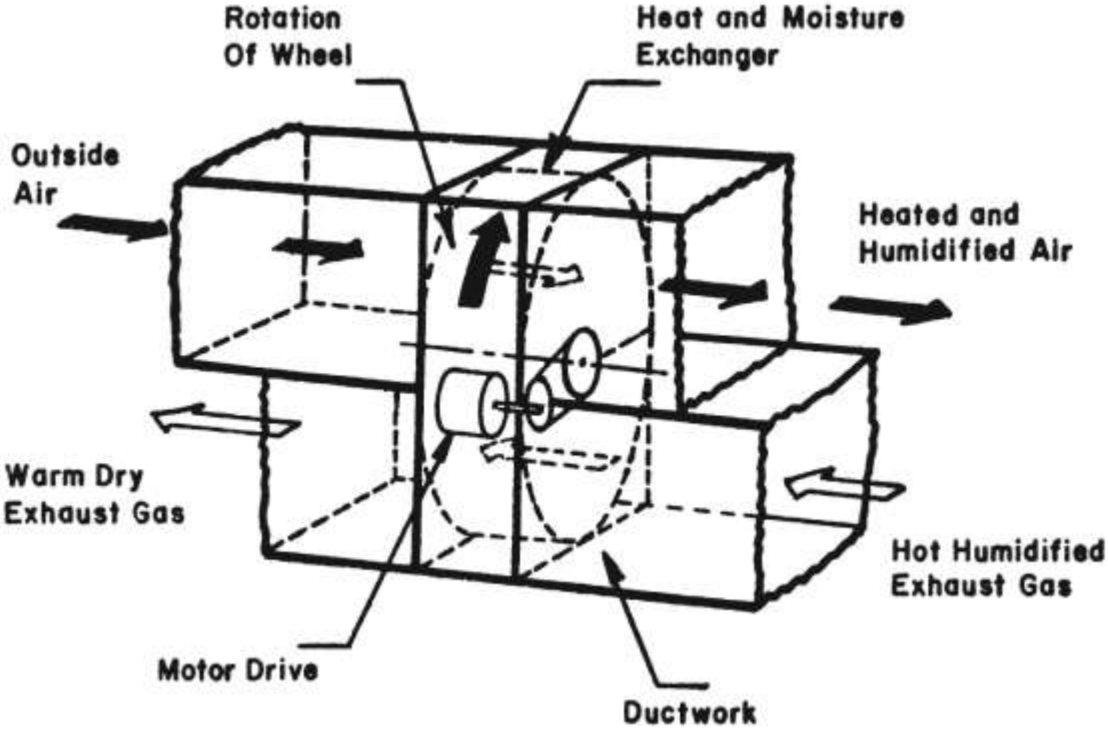


Figure 38 – Heat wheel [94].

There are four types of heat wheels. The first, called a packed wheel, has a metal frame packed with a core of knitted mesh stainless steel or aluminium wire. The second type is called laminar wheel composed of corrugated metal with many parallel flow passages. The third heat wheel type is also of laminar type. It is constructed from a ceramic honeycomb matrix and is generally used for higher temperature applications. The fourth heat wheel type, like the previous two, is a laminar wheel in which the flow passages are coated with a hygroscopic material, allowing in this way moisture recovery.

One of the most common problems inherent to heat wheels is a cross contamination between stream flows. However this problem can be mitigated by addition of the purging section that allows to reduce cross contamination between two gas streams to less that 1%.

Waste heat recovery applications of heat wheels are generally restricted to low and medium grade heat recovery with thermal efficiency of up to 85%.

3.1.8. Passive regenerator

Passive regenerators are basically gas-to-gas hear recovery devices used for low and medium temperature applications, where cross-contamination between gas streams should be prevented. Figure 39 illustrates a typical passive regenerator – plate type gas-to-gas regenerator. The plate type regenerator is composed of two sets of alternating channels separated by thin metal walls, through which pass hot and cool gases. The heat is transferred across the separating boundaries.

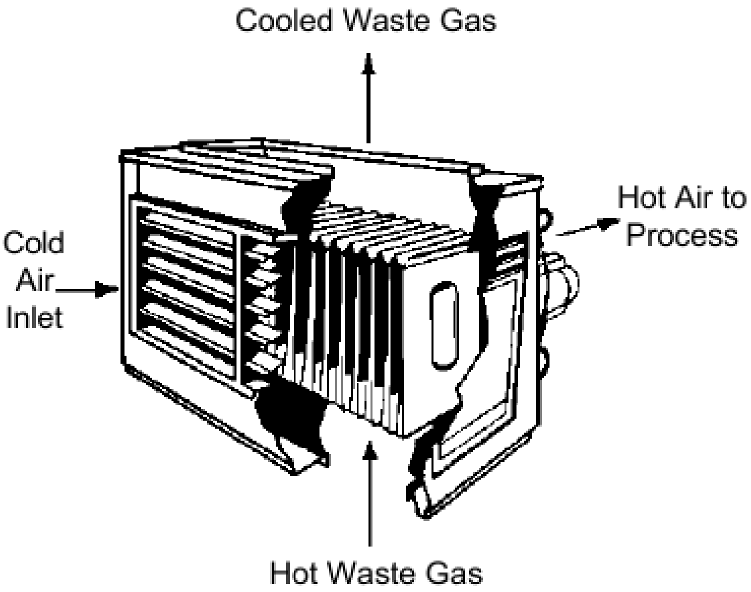


Figure 39 – Passive gas-to-gas regenerator [13].

The practical applications of passive regenerators include drying, curing and baking ovens; air preheaters in steam boilers; air dryers, water heat recovery from exhaust steam or conditioned air; secondary recovery from refractory kilns and reverbatory furnaces, etc.

In spite of the fact that passive regenerators are less vulnerable to contamination than other devices, they have a number of disadvantages. Among these are: the large size, elevated cost, susceptibility to fouling problems and difficulty in temperature control of the heated gas.

3.1.9. Waste heat boiler

Figure 40 shows a waste heat boiler for steam generation. Waste heat boilers are ordinarily water tube boilers that use medium to high temperature exhaust gases from gas turbines, incinerators, diesel engines, etc. to generate the steam. The produced steam can be used either for process heating or for power generation. The capacities of waste heat boilers vary from 25 m^3/min to 30.000 m^3/min of exhaust gas.

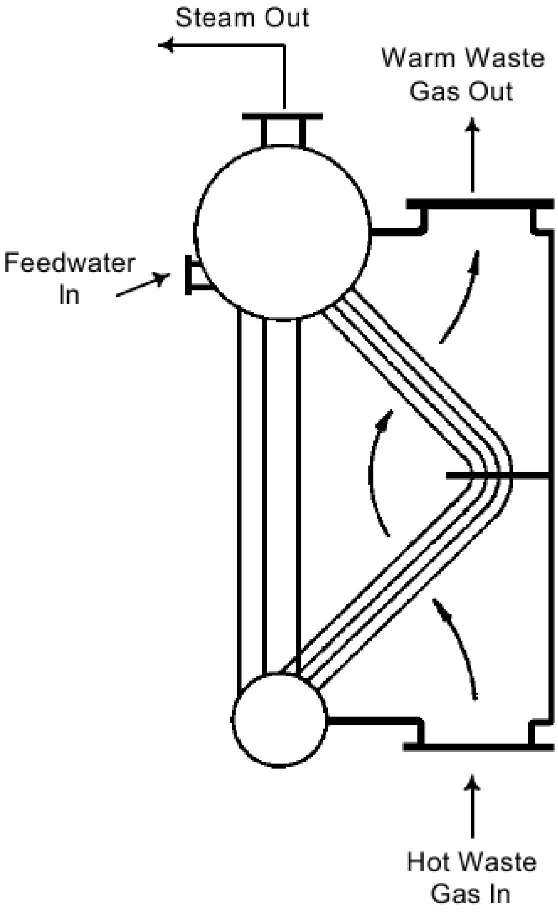


Figure 40 – Waste heat recovery boiler [11].

Typical applications of waste heat boilers are used to recover energy from the exhausts of gas turbines, reciprocating engines, incinerators, and furnaces. However, not all processes are suitable for waste heat recovery using waste heat boilers. According to [81], exhaust volumes and temperatures (below 538ºC) may be too low to provide financial justification of technology application. To solve this problem sometimes it is possible to add auxiliary burners which burn fuel in the waste-heat boiler or to add an afterburner.

As waste heat boilers do not use the burners, opposite to combustion boilers, they have the advantage of being less expensive. On the other hand, these boilers can only generate the steam while the furnace process is in operation. Besides, they have another disadvantage related to their large size, provoking difficulties for the limited space applications.

3.1.10. Organic Rankine Cycle

When utilizing low grade waste heat, the traditional steam Rankine cycle does not present satisfying performance due to its low thermal efficiency and large volume flows [99]. In order to mitigate these problems and convert low-grade waste heat into useful work, the organic Rankine cycle (ORC) has been used. Among the advantages of ORCs Wei, et al. [24] mention its capacity to use waste heat from low quality exhausts or stream, facility in operation, high reliability and flexibility. All this makes ORCs very attractive for a large range of applications.

Basic (non-recuperated) ORC system consists of at least four principal components (Figure 41): evaporator, turbine, condenser and pump.

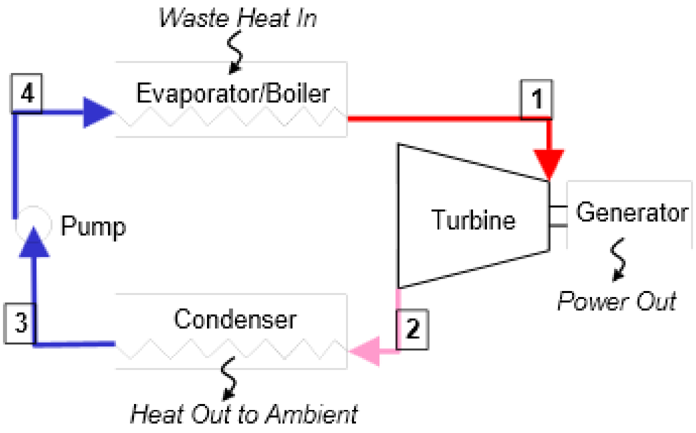


Figure 41 – Simple non-recuperated ORC system layout.

The working fluid is pumped to the evaporator where it is heated and vaporized by the exhaust heat. The generated high pressure vapour enters the turbine and produces power there. Next, the low pressure vapour is led to the condenser and condensed by air. The condensed working fluid flows into the receiver and is pumped back to the evaporator. Thus, a new cycle begins. For the cases when the waste heat streams possess higher temperature, the thermal efficiency of ORC can be improved by adding a recuperative pre-heater to the system.

In contrast to the traditional steam Rankine cycles that use water, ORCs utilize organic substances as working fluids. Among these substances are: hydrocarbons, hydrofluorocarbons, hydrochlorofluorocarbons, chlorofluorocarbons, perfluorocarbons, siloxanes, alcohols, aldehydes, ethers, hydrofluoroethers, etc. According to the slope of saturation vapour curves T-S, working fluids for ORCs can be divided into three categories: dry (positive slope), isentropic (nearly infinite slope) and wet (negative slope). The first two fluid types (dry and isentropic) are considered to be more appropriate for ORC systems as they are superheated after isentropic expansion, thus eliminating the impingement of liquid droplets on the turbine blades [100].

Figure 42 depicts a T-S diagram of a simple ideal ORC, where T_H is evaporation temperature, T_L is condensing temperature and S is entropy. As it can be observed, there are four main processes:

lifting of pressure by pump (1→ 2), heating by evaporator (2 → 22: sub-cooled; 22 → 3: vaporizing T_H), providing work output via expander (3 → 4) and, finally, cooling by condenser (4 → 44: superheat; 44 → 1: condensing T_L).

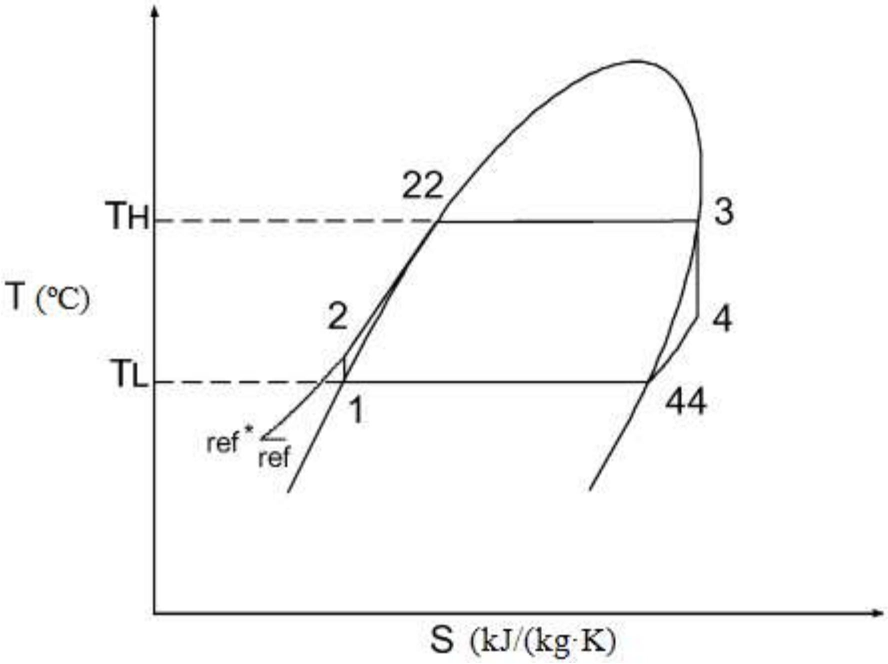


Figure 42 – A schematic T-S diagram of simple ORC [100].

The thermodynamic equations of the process in the typical ORC can be described as follows:

Process 1 → 2: Considering this process as isentropic, the work done by the pump (W_p) is:

$$W_p = \dot{m}_f \cdot (h_2 - h_1) \cdot \eta_p \tag{3.5}$$

with $\dot{m}_f$ – mass flow rate of working fluid; h_1 and h_2 – specific enthalpy at points 1 and 2, respectively; and η_p – efficiency of pump.

Process *2 → 22*: The heat transferred from the exhaust to the working fluid is given by:

$$Q = \dot{m}_f \cdot (h_{22} - h_2) \tag{3.6}$$

where h_{22} is specific enthalpy at point 22.

Process *3 → 4*: Assuming this process as isentropic, the power generated by the turbine (W_t) is:

$$W_t = \dot{m}_f \cdot (h_3 - h_4) \cdot \eta_m \tag{3.7}$$

Where h_3 and h_4 are specific enthalpy at point 3 and 4, respectively, and η_m – mechanical efficiency.

Process *4 → 44:* The power needed for the condensation process (W_c) is:

$$W_c = \dot{m}_f \cdot (h_4 - h_{44}) \cdot \eta_c \tag{3.8}$$

where h_{44} is specific enthalpy at point 44 and η_c – condenser efficiency.

The thermal efficiency of ORC (η_{TH}) is given by:

$$\eta_{TH} = 1 - \frac{\mathrm{h_4 - h_1}}{\mathrm{h_3 - h_2}} \tag{3.9}$$

The selection of working fluids and operation conditions is a key issue because thermodynamic properties of working fluids will affect the overall system efficiency, operation and environmental impact as well as the capital cost [44, 54, 100]. It explains the existence of abundant literature dedicated to study the effect of working fluids on ORCs performance (e.g. [41], [43], [44], [100], [12]). From these studies it can be concluded that the ideal organic provides maximum waste heat recovery efficiency for the particular ORC application. Table 6 provides comparative data of some operation ORC fluids.

Table 6 – Comparative data of some ORC operating fluids [101].

Operating fluid	**Global warming potential**	**Safety class**	**Cost/kg relative to NH_3 (Sept-2011)**
NH_3	0	B2	1
R234a	1300	A1	8,4
R236fa	9400	A1	42,9
R245fa	950	B1	25,2
R407c	1650	A1	5,3
R410a	1980	A1	5,9

Tchanche, et al. [54] distinguish the following characteristics of good working fluids for ORCs: (*i*) vapour saturation curve with zero or positive slope (isentropic or dry fluids); (*ii*) high latent heat of vaporization; (*iii*) high density (liquid/vapour phase); (*iv*) high specific heat; (*v*) moderate critical parameters (temperature, pressure); (*vi*) acceptable condensing and evaporating pressures (> 1 bar and < 25 bar, respectively); (*vii*) good heat transfer properties (low viscosity, high thermal conductivity); (*viii*) good thermal and chemical stability (stable at high temperature); (*ix*) good compatibility with materials (non-corrosive); (*x*) high thermodynamic performance (high energetic/exergetic efficiency); (*xi*) good safety characteristics (non-toxic and non-flammable); (*xii*) low environmental impacts and (*xiii*) low cost and good availability.

4. Cost-effective and application analysis of waste heat recovery technologies and devices

Table 7 contains a summary of operation, application and economic characteristics of waste heat recovery technologies and devices in ceramic industry. In order to perform this analysis the technologies/devices described in the previous section were characterized according to a set of features, some of which were adapted from [13], [88], [96].

The data present in Table 7 can be used a general guide for technology or device selection for residual thermal energy recovery in ceramic industry. However, it should be mentioned that each situation has to be analysed in detail as there is no general solution for everyone. Very often a support of technical advisers is required.

Table 7 – Operation, application and economic characteristics of waste heat recovery technologies in ceramic industry (adapted from [13], [88] and [96]).

	Efficiency (%)	**Economic feasibility**	**Low grade heat recovery**	**Medium grade heat recovery**	**Gas-to-gas heat exchange**	**Gas-to-liquid heat exchange**	**Compact size**	**No cross-contamination**	**Corrosive gases permited with special construction**	**Sources of waste heat in ceramic industry**			
										Kiln		**Dryer**	**Spray-dryer**
										Cooling air	**Exhaust gases**	**Exhaust gases**	**Exhaust gases**
Direct recirculation of waste heat installation	90-97[102]	+	●	●	●					●		●	
Convective recuperator	50-60[103]	o		●	●			●	●	●	●		
Mechanical vapour recompression system	300-550[96],[88]	o		●	●							●	●
Heat pump	250-350[62], [88]	o	●	●	●		●	●	●	●	●	●	●
Economizer	40-50[104]	o	●	●		●	●	●		●	●	●	●
Heat pipe	≤ 65[105]	+	●	●	●		●	●	●	●	●	●	●
Heat pipe heat exchanger	60-80[93]	+	●	●	●		●	●	●	●	●	●	●
Metallic heat wheel	≤ 90[88]	o	●	●	●		●		●	●	●	●	●
Ceramic heat wheel	≤ 90[88]	o		●	●		●		●	●	●		
Hydroscopic heat wheel	≤ 50[88]	o	●		●		●					●	●
Passive regenerator	35-55[104]	o	●	●	●			●	●	●	●	●	●
Waste heat boiler	30-40[104]	o	●	●		●		●		●		●	●
Organic Rankine cycle	10-20[13]	-	●	●		●		●		●		●	●

Key	**Economic feasibility:** + cost effective; o application specific; - cost prohibitive

V. CASE STUDY: WASTE HEAT RECOVERY IN *TOPCER* CERAMIC FACTORY

1. *Scope of the study*

The development of the present work took place in the scope of the *Galp202020@UA* Internship Program. The internship was held in 2012 for 6 months on a *TopCer* ceramic factory located in Aveiro district. Due to the fact that energy consumption of *TopCer* is above 1000 toe/year and in accordance with the Rules Management System of Intensive Energy Consumption, every six years the factory has to prepare a Plan of Energy Consumption Rationalization (PREn) and present an improvement of at least 6% of specific energy consumption and energy intensity, maintaining the carbonic intensity. The first energy audit in *TopCer* was held in 2009, giving the start to the first PREn.

This scenario enabled an opportunity to carry out a study of application of the methodology for waste heat recovery technologies incorporation in the ceramic sector in order to improve energy performance of the ceramics production processes.

2. *Characterization of TopCer*

2.1 *Institutional characterization*

The industrial unit of *TopCer* is located in the Industrial Zone of Oiã (Figure 43) and consists of a manufacturing unit of floor and wall tiles. The company has 78 employees divided by production, maintenance and administrative services.

Figure 43 – *TopCer* facilities.

TopCer was founded in March of 1992, and is currently a world leader in the manufacturing of tiles of various textures, shapes, colors and finishing (Figure 44). The economic activity of the company is classified with CAE 23312 – Manufacture of ceramic tiles and flags.

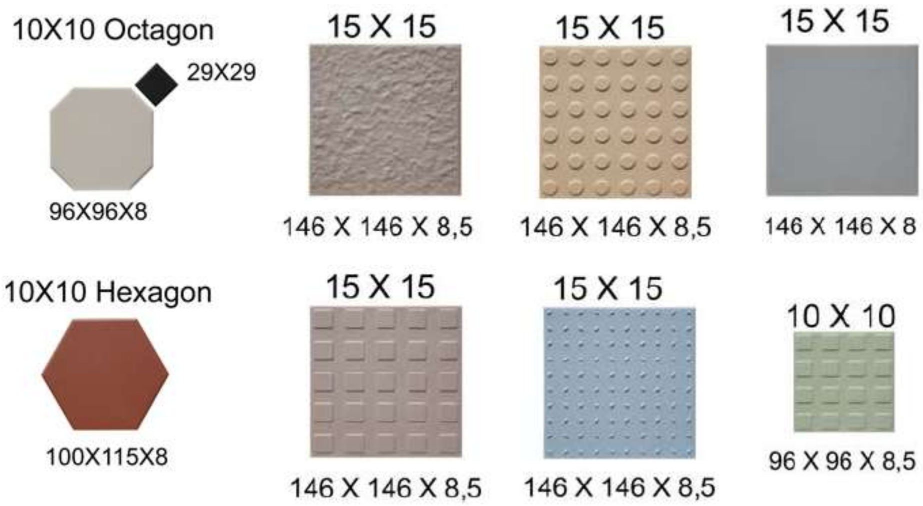


Figure 44 – Examples of produced goods.

2.2 Operational characterization

The average nominal production capacity of *TopCer* is nearly 17 ton/day, operating 24 hours for 12 months a year (with half of the production capacity in August). The degree of factory's occupation is about 67%. Thus, in 2011 there were produced approximately 6092 tons of goods (363.731 m^2 of tiles). Figure 45 presents the factory's production distribution per month in 2011.

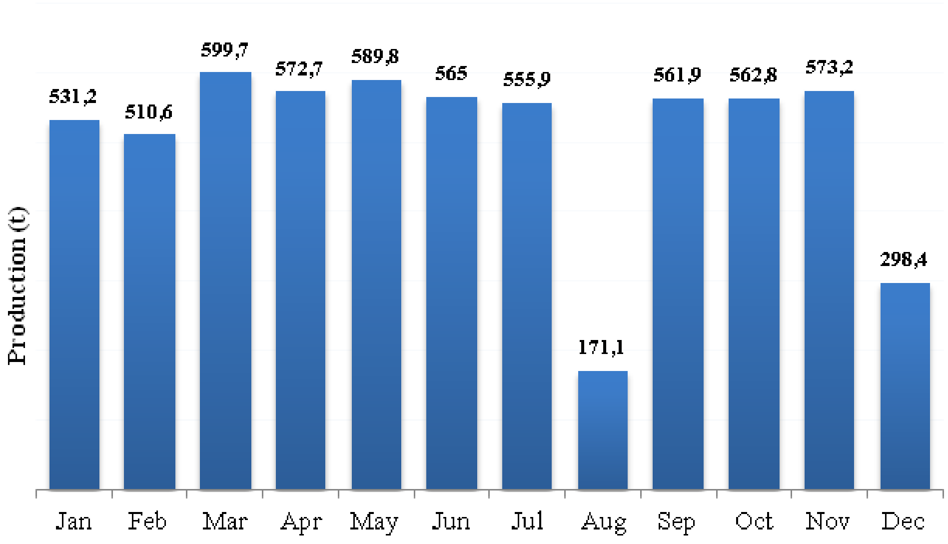


Figure 45 - Production distribution (in tons) of *TopCer* in 2011.

Figure 1A in Attachment depicts the ceramics production process in *TopCer*. It is divided into 5 main stages: (*i*) preparation of slurry, (*ii*) atomization, (*iii*) shaping/drying, (*iv*) firing, and (*v*) sorting, packaging and storing.

During the preparation stage the raw materials, initially deposited in bins, are placed in two separate dosage forms and next are distributed by storage silos with the help of embedded weighing system. Later the mixture is introduced into "Alsing" mills where the wet grinding takes place. Further the clays are distributed by extenders.

After the slurry milling and dilution of the clay, the mixture is made. The obtained slurry is discharged into tanks, suffering the first sieving and filtering, after which it is disposed to the action of agitators in order to be kept in suspension. The slurry is then transferred to the feed tank of spray-dryer, and sieved again, this time in a finer mesh.

The atomization takes place in the spray-dryer fed by high pressure hydraulic pumps. The generator of hot gases used for drying is fueled by natural gas. The produced atomized powder, with the moisture content of approximately 4% to 6%, is stored in silos that feed production lines.

In the shaping/drying stage the semi-manufactured goods are pressed and then loaded into the dryers.

The firing process proceeds in the “Forniker” roller kilns of about 40 m long. The highest firing temperature reached during the process is around 1200 °C.

Finally, in the last production stage the manual sorting, packing and storage of the manufactured goods takes place.

2.3 Energy consumption characterization

In 2011 the total annual consumption of energy in *TopCer* was about 1455 toe, while the average specific consumption rate was of 235,36 kgoe/t. Figure 46 shows the distribution of the specific energy consumption per month in 2011.

The impact of energy costs in total costs is 13,2%. Figure 47 and Figure 48 illustrate the disaggregation of energy consumption and the overall costs by energy type in 2011, respectively. The data analysis indicates that the major part of energy consumed by *TopCer* throughout 2011 is obtained with the natural gas, which is transformed into the thermal energy during the ceramics production.

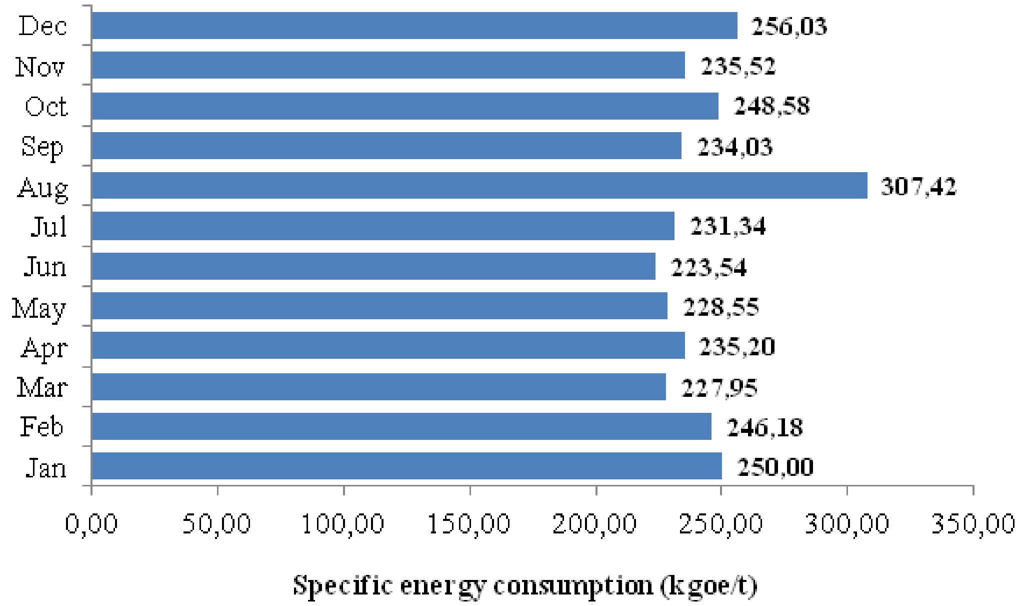


Figure 46 – Distribution of specific energy consumption in *TopCer*, 2011.

The natural gas is provided by *LusitaniaGás* with maximal concurrent flow rate of 547 Nm^3/h. Natural gas consumption presents slightly more than 68% of total energy consumption (with annual costs close to 420.195 €). According to the data registered by counter installed on the entrance of the *TopCer* gas network, the spray-drier and the kilns are responsible for the major part of this consumption (Figure 49).

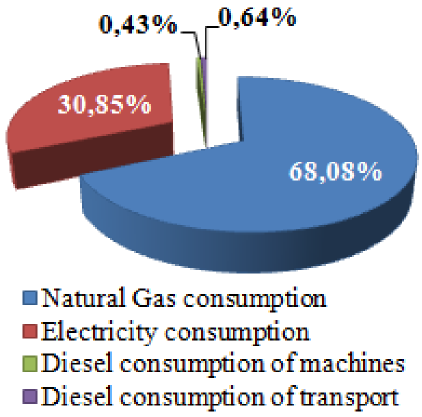


Figure 47 - Distribution of energy consumption by energy type, 2011.

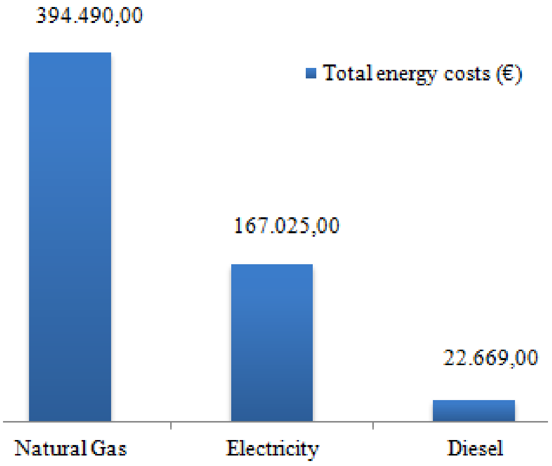


Figure 48 - Distribution of total costs per energy type, 2011.

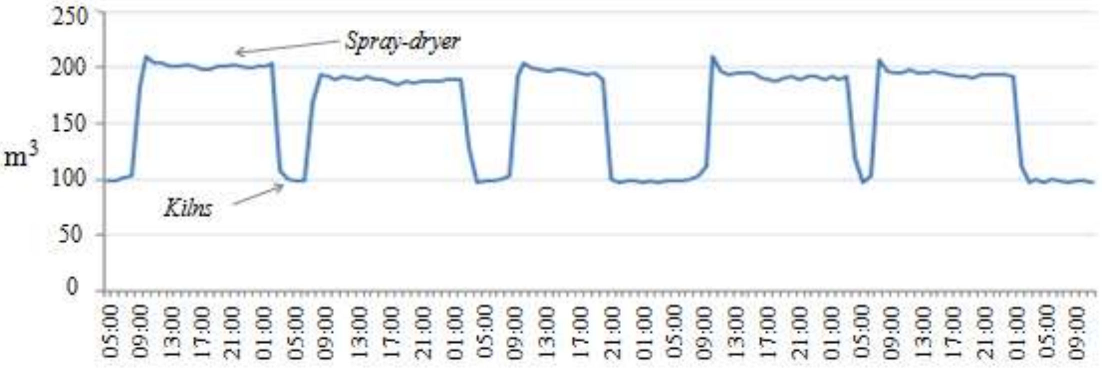


Figure 49 - Natural gas consumption (nm^3) for the period of 10/02/2012-21/02/2012.

Taking into account the energy consumption of *TopCer* (more than 500 toe in 2011) and Decree-Law nr. 71/2008 of 15 April, the factory is classified as an intensive energy consumer.

3. Objective and limitations of the study

The present study is aimed to apply the methodology for waste heat recovery incorporation described in chapter IV with the objective to explore the potential of waste heat recovery technologies in *TopCer* ceramic factory.

Referring to the limitations of the study, it should be mentioned that only one waste heat source – kiln – was considered for the waste heat recovery possibility, in spite of the presence of other waste heat sources on the factory (dryers and spray-drier). Besides, only two of three kilns installed on the factory were analysed (kiln 1 and kiln 3). The second kiln (kiln 2) was excluded from the study as it was not functioning during the period of internship. Another limitation of the study resides in reduced lack of analysed waste heat recovery technologies. Only two options were considered for the effect: direct recirculation of waste heat installation and Organic Rankine cycle. The above referred limitations are imposed by necessities and priorities established during the internship by the *TopCer* administration.

4. Study of waste heat recovery potential of TopCer

4.1 Identification of waste heat sources

According to the methodology, the first step that should be performed in order to analyse the potential of waste heat recovery consists in identification of the existing waste heat sources.

The methodology identifies three main sources of residual heat in ceramic industry: kiln, dryer and spray-dryer. All of them are present on a TopCer factory (one spray-dryer, two kilns and two dryers).

4.1.1 Spray-dryer

Figure 50 and Figure 51 illustrate the spray-dryer installed in *TopCer* and its principle of functioning, respectively. The operating mode of spray-dryer is similar to the major part of spray dryers and resume to: (*i*) atomization; (*ii*) spray air mixing and moisture evaporation; and (*iii*) separation of dry product from the outlet air.

Figure 50 - Spray-dryer on the factory.

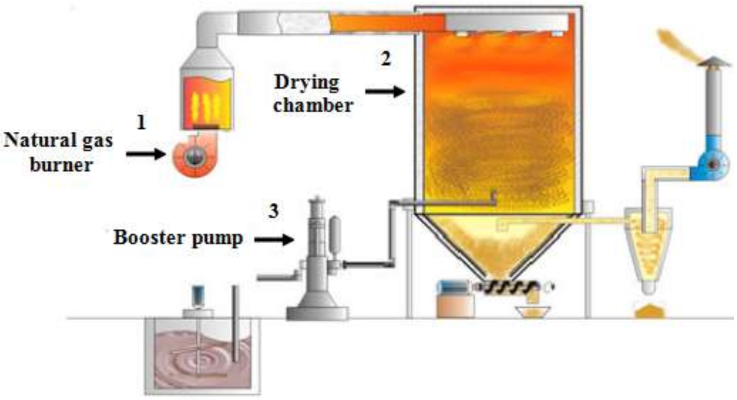


Figure 51 – Scheme of spray-dryer functioning.

The average specific annual consumption of natural gas by spray-dryer is 49,5 nm^3 per ton of produced powder. Figure 52 shows the natural gas consumption profile of spray-dryer, registered in 2011, compared to the average specific consumption in EU (consulted in [62]). As it can be observed from the figure, the average specific consumption of spray-dryer in *TopCer* exceeds the European average value by approximately 6%.

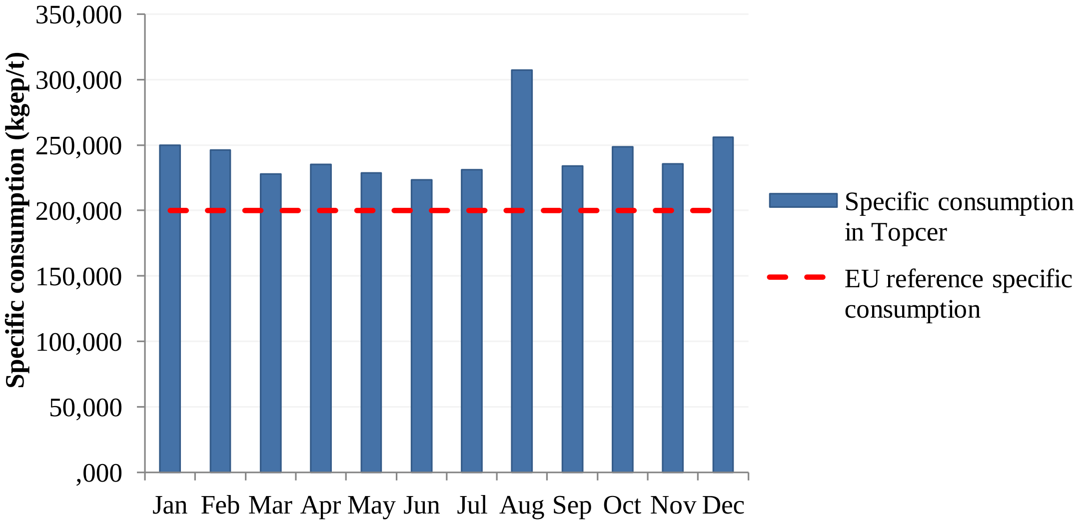


Figure 52 – Distribution of specific consumption of natural gas of spray-dryer in 2011.

4.1.2 Kilns

TopCer has three continuous roller kilns installed on the factory (Figure 53). However, only two of them were functioning during the period of analysis (kiln 1 and kiln 3). In this way, the second kiln was not included in this study.

Figure 53 – Kiln 1 on the factory.

In 2011 the average specific consumption of natural gas by kilns (1 and 3) constituted 122,24 nm^3 per ton of finished goods. As it can be observed from Figure 54, the average specific consumption of the kilns on the factory vary in accordance with the ambient temperature: the higher the temperature the lower is the specific energy consumption (except for the August when the maintenance operations take place).

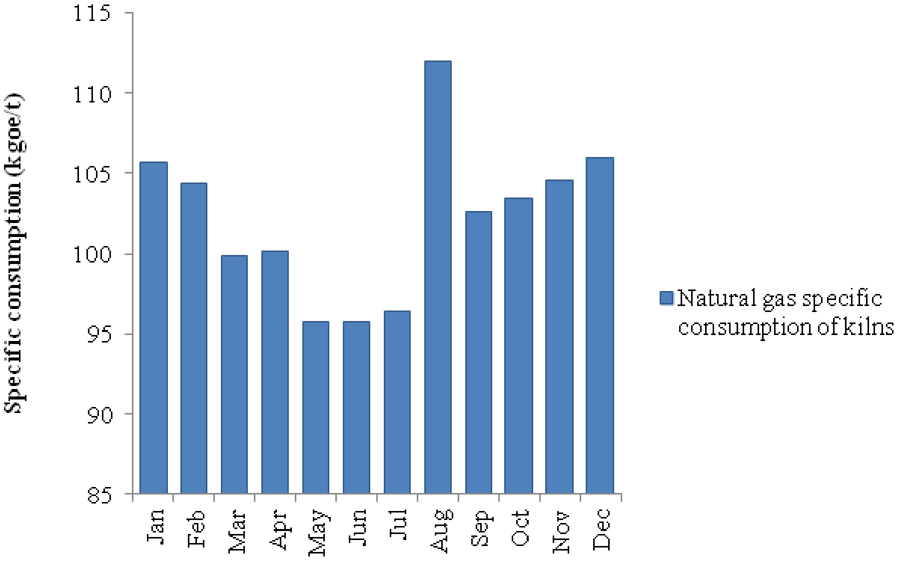


Figure 54 – Distribution of specific consumption of natural gas of kilns 1 and 3 in 2011.

4.1.3 Dryers

Figure 55 shows single stage tunnel dryers installed on the factory. The dryers operate in a continuous mode using air as a drying medium. The air enters the dryer in a convection mode, while moving in a mixed flow relatively to the drying solids that pass through the dryer.

Figure 55 - Dryer on the factory.

The drying process on the factory is alimented by the heat from the cooling zone of the kilns. According to the data provided by *TopCer*, dryers consume approximately 45% of the heat from the cooling zone, meanwhile the other 55% are sent to the environment.

4.2 Characterization of waste heat sources

As it was already mentioned, there are three basic parameters that are used to evaluate the feasibility of waste heat recovery in different sources: waste heat quantity, quality and temporal availability. These parameters were considered for characterization of the afore-described waste heat sources in *TopCer*.

The quantity of waste heat available from spray-dryer, kilns and dryers was determined on the basis of the measurements of the waste heat stream characteristics on the output of the heat source. Temperature, volume and humidity were measured with the help of exhaust gas analyzer and thermal imaging camera. To illustrate the distribution of the energy along the drying, firing and spray-drying processes responsible for the residual heat generation there were applied the mass and heat balances. The heat and mass balances were developed taking into account the results of the inlet and outlet heat stream and material measurements, respectively. Due to the lack of facilities to measure the characteristics necessary for calculation of non-applicable heat losses (e.g. the thickness of kilns walls), they were determined as follows:

$$Q_L = Q_{in} - Q_{out} \tag{4.1}$$

To determine the humidity of the inlet and outlet products in spray dryer and dryer, the thermo-gravimetric method was employed.

The quality of the waste heat was estimated on the basis of the temperature of the outlet waste heat stream measured using exhaust gas analyzer.

Finally, the temporal availability of the residual heat was determined from the operating schedules of equipment, according to the production mode of the factory.

4.2.1 Spray-dryer

Figure 56 illustrates the resulting heat and mass balances of spray-dryer. According to the provided data, the thermal efficiency of spray-drying is 82%, while the total thermal efficiency of the natural gas burner and spray-dryer is 70%.

Figure 57 depicts the temperature of the burner’s surface in the spray-dryer zone of the factory. There can be observed significant heat losses through the walls of the burner, which contribute to the decrease of the overall thermal efficiency of the spray-drying process.

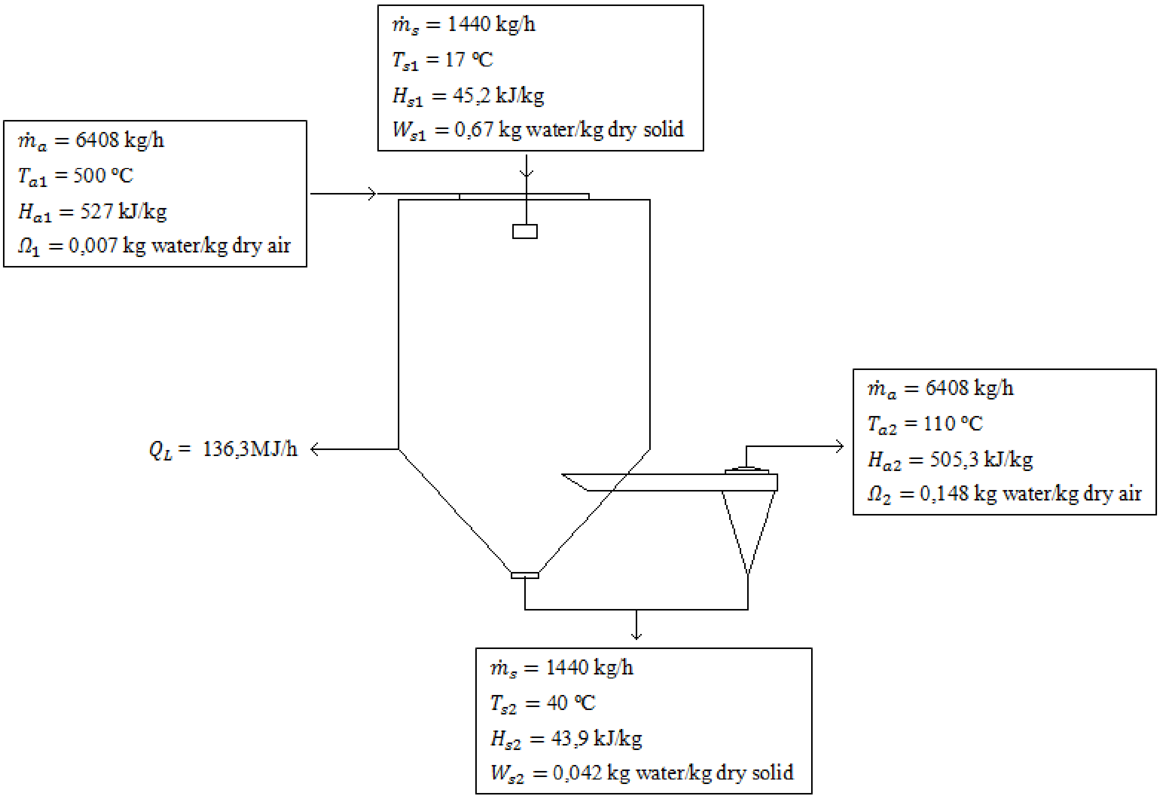


Figure 56 – Heat and mass balances of spray-dryer.

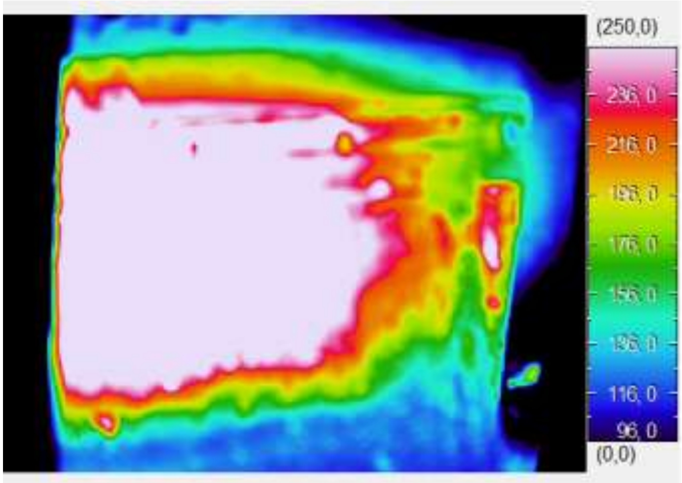


Figure 57 – Measurements with the thermal imaging camera in the spray-dryer zone.

In conformity with the outlet temperature of the waste heat stream (T_{a2} = 110 ºC), spray-dryer is classified as a low temperature waste heat source (T_{a2} < 230 ºC).

On the basis of the operating schedules of spray-dryer in *TopCer*, it can be estimated that residual heat from this source is available for approximately 70%.

4.2.2 Kilns

Figure 58 and Figure 59 present the heat and mass balances of the kiln 1 and kiln 3. The data was obtained through measurements of the inlet and outlet characteristics of the waste heat stream and material.

According to the obtained results, the thermal efficiency of the kiln 1 is 26,8%, while thermal efficiency of the kiln 3 is 24,8% .

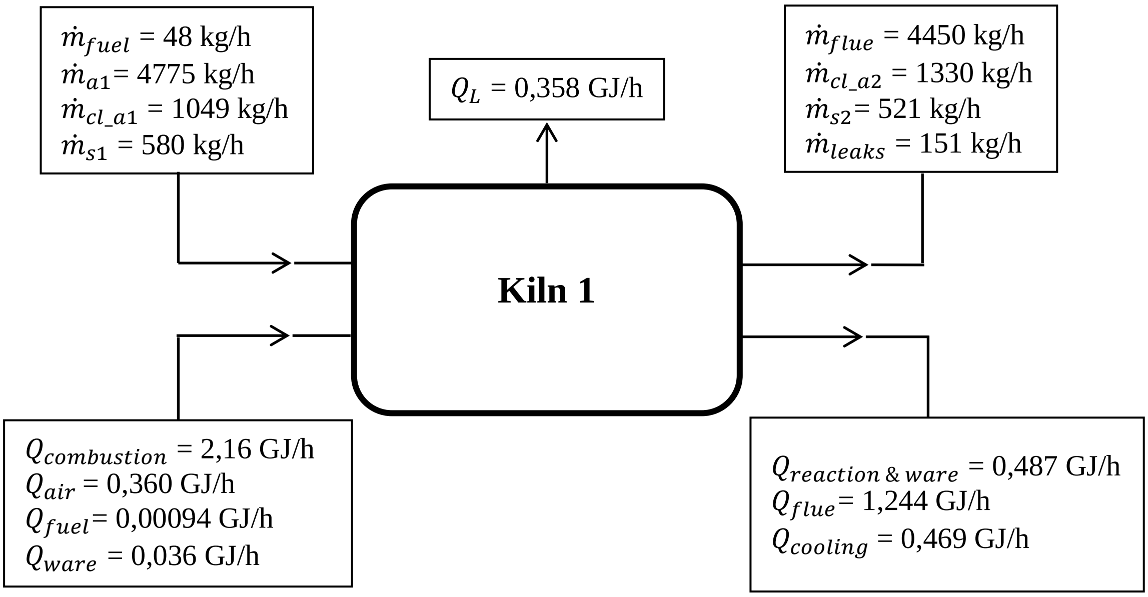


Figure 58 - Heat and mass balances of kiln 1 in *TopCer*.

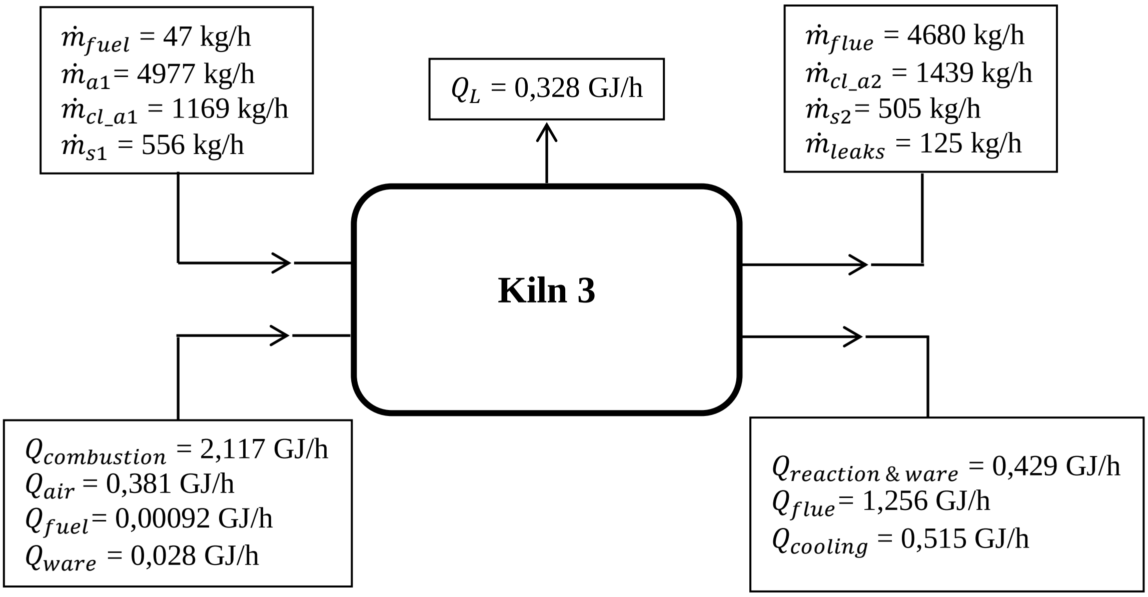


Figure 59 - Heat and mass balances of kiln 3 in *TopCer*.

Figure 60 illustrates one of the temperature distribution measurements performed on the surface of the kiln 1 with the thermal imaging camera. There can be noticed the heat losses through the walls of the kiln that account for the Q_L value.

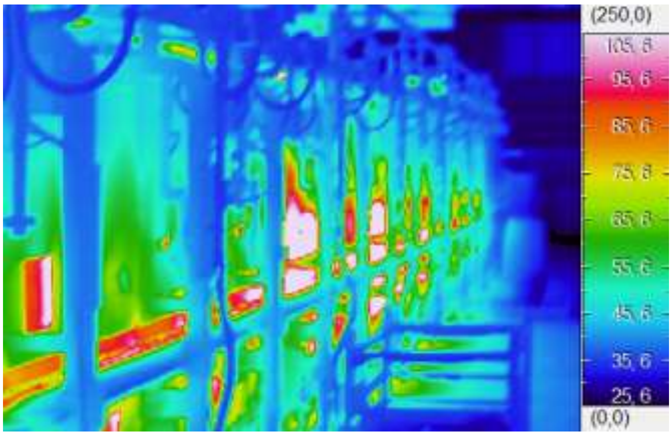


Figure 60 - Measurements with the thermal imaging camera in the kilns' zone.

According to the temperature of the waste heat stream from the cooling zone, kilns 1 and 3 are classified as medium temperature waste heat sources with 320 ºC and 328 ºC, respectively. At the same time, considering temperature of the waste heat stream of the flue gases, kilns 1 and 3 are categorized as low temperature waste heat sources because the temperatures registered in this zone are 208 ºC and 225 ºC, respectively.

Referring to the temporal availability of the waste heat from kilns 1 and 3, it is important to highlight that they are working in a continuous mode without any breaks, except in August when the maintenance occurs. Thus, residual heat from both kilns is available for approximately 91% during the year.

4.2.3 Dryers

The heat and mass balances of drier 1 and dryer 2 are depicted on Figure 61 and Figure 62, respectively. Dryer 1 is alimented by the heat from the cooling zone of kiln 1, while dryer 2 consumes the heat from the cooling zone of kiln 3.

The temperature measurements of the outlet waste heat stream of the dryer 1 and dryer 2 indicate that both heat sources are classified as low temperature ones, with 89ºC and 91ºC, respectively.

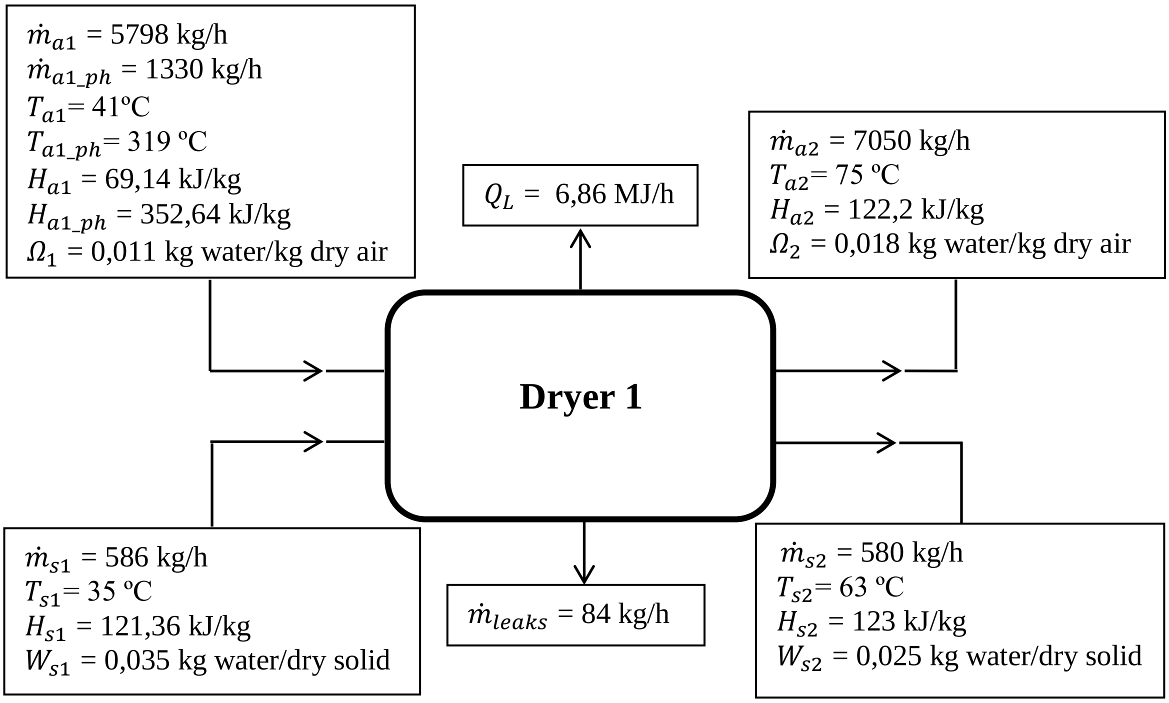


Figure 61 - Heat and mass balances of dryer 1 in *TopCer*.

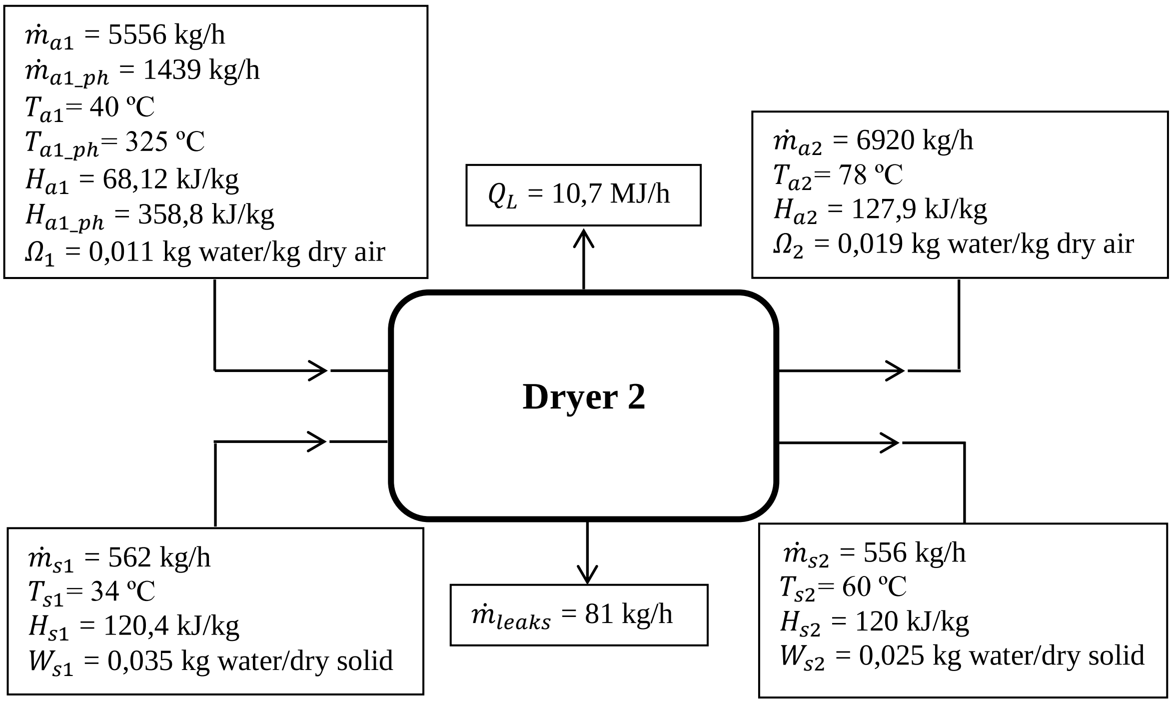


Figure 62 - Heat and mass balances of dryer 2 in *TopCer*.

Taking into account the specificity of the driers' alimentation, the temporal availability of the waste heat from dryers 1 and 2 matches with the temporal availability of the waste heat from the kilns 1 and 3. Consequently, the residual heat from both dryers is available for nearly 91% during the year.

4.3 Identification of waste heat recovery technologies

The selection of waste heat recovery technologies used for the further analysis was affected by the necessities and priorities established during the internship by the *TopCer* administration. In this way, only two technologies were considered for the effect: direct recirculation of heat and Organic Rankine Cycle. These technologies were investigated for the application on the kilns 1 and 3.

A portion of hot air from the cooling zone of the kilns 1 and 3 is used in dryers (45%), while the remaining 55% of the hot air from the cooling zone and 100% of the waste heat from the kilns' flue gases are not used and are sent to the outside. As a result, the study of the direct heat recirculation and Organic Rankine Cycle was aimed to explore the possibility to extend the universe of the waste heat applications from the kilns 1 and 3, maximizing their utility. The choice of technologies and waste heat source was dictated, on the one hand, by the needs of the factory to reduce the amount of energy consumed by spray-dryer and kilns, using the waste heat from the kilns 1 and 3. On the other hand, there was a necessity to decrease the costs of consumed electric energy by producing extra electricity through thermal energy transformation into the electric one. Accordingly, direct heat recirculation revealed to be the most attractive technology to explore in order to satisfy the first need. Meanwhile, the Organic Rankine Cycle was the selected technology to study the viability of the electric energy production by dint of conversation of thermal energy available from the kilns' flue gases.

In total there were considered four scenarios for the waste heat recovery from the kilns 1 and 3:

1. Recovery of unexploited residual heat (55%) from the cooling zone of the kilns 1 and 3 for the purposes of the spray-dryer alimentation;
2. Recovery of unexploited residual heat (55%) from the cooling zone of the kilns 1 and 3 to insufflate the burners of the kilns;
3. Recovery of waste heat from the previously filtered flue gases of the kilns 1 and 3 for the spray-dryer alimentation;
4. Recovery of waste heat from the previously filtered flue gases of the kilns 1 and 3 for the electric energy generation by means of ORC application.

Some of the above mentioned scenarios are mutually exclusive, namely (1) and (2); (3) and (4). Figure 2A in Attachment shows the scheme of the ducts installation in *TopCer*, enabling the performance of scenarios 1-4, as well as temperature distribution during the firing process in the kilns 1 and 3. The scheme was developed using the trial version of *AutoCAD® Mechanical 2012* [106].

The following section provides details of the scenarios implementation. In order to simulate the distribution of temperature along the ducts (from the waste heat sources to the respective heat sinks) in scenarios 1 and 3, *Ansys CFD* software was used [107].

4.3.1 Scenario 1

The performance of scenario 1 involves the installation of duct (Figure 63) and insufflator device.

Figure 63 – Duct (scenario 1).

Figure 64 illustrates the temperature distribution within the duct. According to the calculations performed with *Ansys CFD*, the average temperature of the gases entering the spray-dryer decreases by 2,4%. The energy losses associated with conduct are not significant and constitute 3,5%.

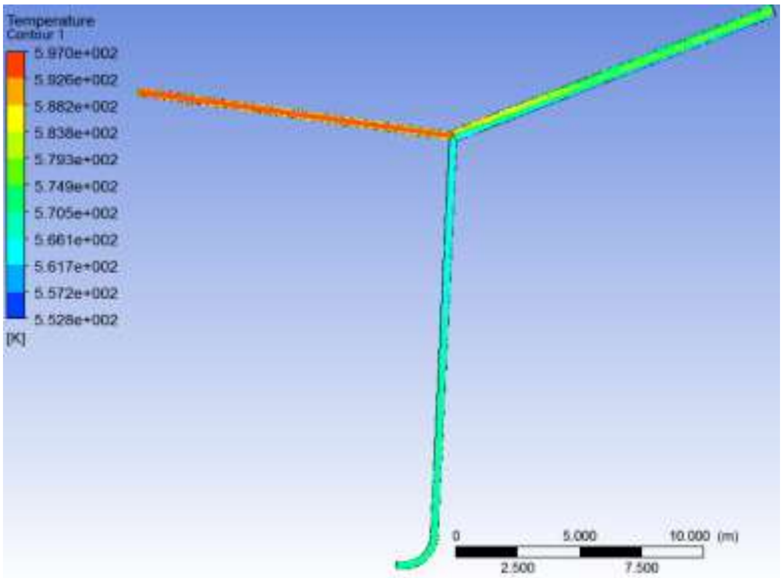


Figure 64 - Temperature distribution within the duct (scenario 1).

The diagram from Figure 65 shows the way the duct that conducts waste heat from the cooling zone of the kilns 1 and 3 will be installed on the spray-dryer system.

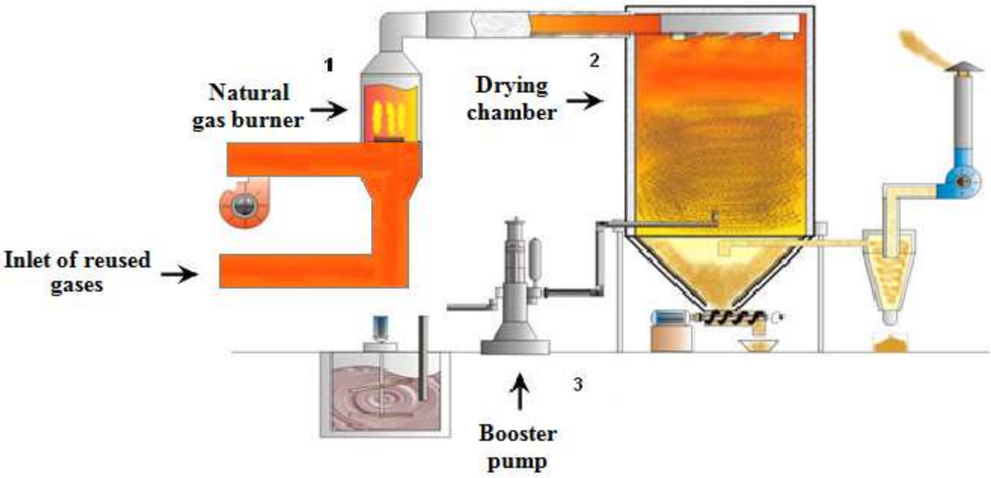


Figure 65 - Spray-drying system with waste heat recovery.

4.3.2 Scenario 2

The implementation of scenario 2 involves installation of two ducts present on Figure 66.

Figure 66 – Ducts (scenario 2).

4.3.3 Scenario 3

Realization of this scenario implies application of duct from Figure 67. Figure 65 illustrates the way the duct has to be installed in the spray-dryer system in order to facilitate the recovery of waste heat from the cooling zone of kilns 1 and 3.

Figure 67 - Duct (scenario 3).

According to the data obtained from *Ansys CFD* and illustrated on Figure 68, there is a drop in temperature and thermal energy along the duct by 2,3% and 2,8%, respectively.

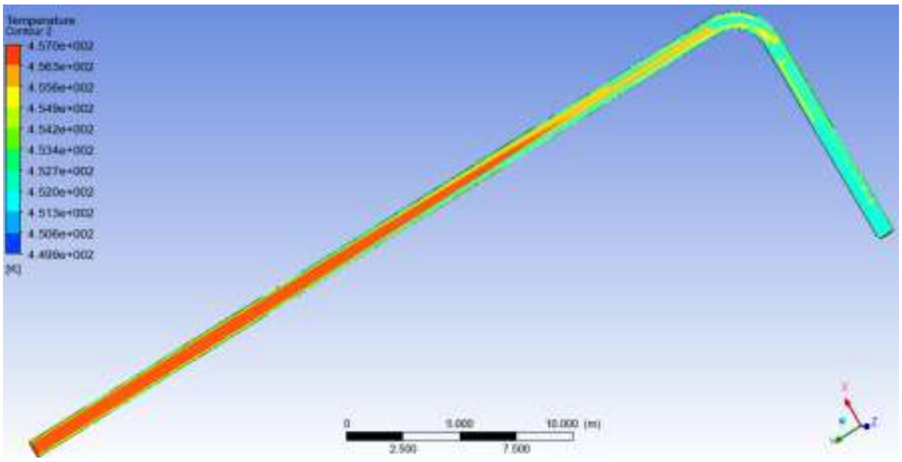


Figure 68 - Temperature distribution within the duct (scenario 3).

4.3.4 *Scenario 4*

In accordance with the temperature and flow rate measurements of the flue gases from kilns after their filtering, there is a possibility to use the available thermal energy for the electricity production through application of the ORC.

A search of turbine suitable for the amount of waste heat available from the kilns 1 and 3 resulted in selection of IT 10 turbine [108], illustrated on Figure 69. This turbine uses R245fa or R134a as a working fluid, with the temperature of the heat entering the system situated between 70°C and 120°C. The turbine has electrical efficiency of 11,8% and total efficiency (thermal and electrical) of about 85% [109].

Figure 69 – ORC (scenario 4).

4.4 Cost-effective analysis of waste heat recovery technologies and devices

This section contains a summary of cost-effective analysis of direct recirculation and ORC technologies application for the waste heat recuperation from the kilns 1 and 3.

Tables 8–11 summarize the results of the energetic and economic evaluation performed for the scenarios 1 – 4 analysis. For the first three scenarios (1 – 3) each table is divided into four main parts that present: (*i*) the energy consumption, energy costs and emissions associated to the potential waste heat sink before the scenario implementation; (*ii*) the investment necessary for the technology incorporation; (*iii*) economic, energetic and ambient impact (in terms of the quantity of emissions) of the heat sink after the respective waste heat recovery scenario realization and, finally, (*iv*) the payback period of the investment. Table 11 contains the results of the scenario 4 evaluation and presents the amount of investment, energy and ambient revenue as well as the payback period of the ORC incorporation.

For the economic and energetic evaluation of the proposals:

- The data on natural gas consumption per hour for the year 2012 were provided by *Galp Energia* enterprise;
- The prices of natural gas and electricity were consulted on the bills of *TopCer*;
- The energy conversion factors were retrieved from [110];
- The properties of air, natural gas, water and materials were found in [89].

Table 8 – Economic and energetic evaluation of scenario 1.

		Spray-dryer		
		Electricity	*Natural Gas*	*Total*
Before	Annual energy consumption (toe)	11,3	349,5	360,8
	Annual energy costs (€)	3501	161.614	165.115
	GHG emissions [tCO_2e/year]	20,4	744,2	764,6
Investment	€	25.000		
After	Annual energy savings (toe)	-5,1	36,2	31,1
	Annual saving (€)	-1.576	16.727	15.151
	GHG emissions [tCO_2e/year]	29,6	708	688,9
Payback	Years	1,65		

Table 9 – Economic and energetic evaluation of scenario 2.

		Kilns 1 and 3
		Natural Gas
Before	Annual energy consumption (toe)	662,2
	Annual energy costs (€)	306.185
	GHG emissions [tCO_2e/year]	1.410
Investment	€	5.000
After	Annual energy savings (toe)	91,8
	Annual saving (€)	42.411
	GHG emissions [tCO_2e/year]	1214,7
Payback	Years	0,1

Table 10 – Economic and energetic evaluation of scenario 3.

		Spray-dryer		
		Electricity	*Natural Gas*	*Total*
Before	Annual energy consumption (toe)	11,3	349,5	360,8
	Annual energy costs (€)	3501	161.614	165.115
	GHG emissions [tCO_2e/year]	20,4	744,2	764,6
Investment	€	25.000		
After	Annual energy savings (toe)	-7,9	72	64,1
	Annual saving (€)	-2.450	33.287	30.837
	GHG emissions [tCO_2e/year]	34,7	590,7	625,4
Payback	Years	0,8		

Table 11 – Economic and energetic evaluation of scenario 4.

		ORC
		Electricity
Investment	€	35.000
Revenue	Energy generation and supply to the network (toe/year)	20
	Decrease of GHG emissions [tCO_2e/year]	37
Payback	Years	5,4

5. Results analysis and discussion

The study described in this chapter was carried out at a Portuguese ceramic manufacturing organization with the objective of applying a methodology, developed on the basis of the literature review, in order to explore the potential of waste heat recovery technologies incorporation. The study was focused on the heat recovery from the kilns installed on the factory, analysing direct recirculation of waste heat and Organic Rankine cycle technologies.

In total, four possible scenarios were analysed: two of them were aimed to apply the waste heat from the kilns for the spray-dryer alimentation, while another two explored the possibility of the heat reuse for insufflation of the kilns' burners and electric energy generation.

The results of the economic and energetic evaluation of the proposals show that scenario 2 is the most attractive in terms of the return of investment (0,1 years) and energy savings parameters (91,8 toe/year). At the same time scenario 4 is the most expensive with the total investment of 35.000 € and payback of 5,4 years, resulting in 20 toe/year of energy generated and supplied to the network.

The results of scenarios 1 and 3, designed to investigate the opportunity of waste heat reuse from the kilns 1 and 3 for the spray-dryer alimentation, have shown that scenario 3 is more profitable with 0,8 years of the payback and 64,1 toe/year of energy savings (against 1,65 years of payback and 31,1 toe/year of energy savings in scenario 1).

Analyzing the results of four scenarios, it was concluded that combination of scenario 2 and 3 is able to bring significant profit for *TopCer*, reducing annual energy costs by 73.248 € and energy savings by 155,9 toe/year. Besides, the quantities of GHG emissions will also decrease (by 334,5 tCO_2e/year) due to the waste heat reutilization by kilns (scenario 2) and spray-dryer (scenario 3).

In conclusion, it should be emphasized that according to the waste heat quantity, quality and temporal availability parameters used for the waste heat source evaluation, spray-dryer and dryers are attractive option for the further study of waste heat recovery incorporation.

VI. GENERAL CONCLUSIONS AND FUTURE RESEARCH

1. Conclusions

During the economic crisis accompanied by growing energy costs, introduction of waste heat recovery technologies is able to provide significant energy efficiency improvements for the energy intensive sectors.

This dissertation intended to contribute to the incorporation of the waste heat recovery technologies in the Portuguese as well as European ceramic industry through compilation of the literature related to the waste heat recovery in this sector and elaboration of the methodology for the efficient integration of the waste heat recovery technologies in the ceramics manufacturing industries, with the subsequent application at a Portuguese ceramic manufacturing unit.

The focus on the ceramic industry is explained by the fact that employment of the waste heat recovery technologies in this sector is crucial due to the presence of long-lasting high-temperature production processes with elevated energy consumption and associated pollution emissions.

The literature review on the waste heat recovery has demonstrated that this area has suffered a significant increase in terms of number of publications in 2012, illustrating the growing interest of scientific communities and practitioners in the heat recovery problems.

Based on the literature review, there was developed a methodology that can be followed in order to facilitate the integration of waste heat recovery within ceramics manufacturing organizations. The methodology provides basis for identification and characterization of the waste heat sources present in ceramic sector. Based on the literature review, the methodology identifies, characterizes and compares the most common waste heat recovery technologies in this industry, delimiting their application scope.

It should be mentioned that in spite of the focus on the ceramic industry, the elaborated methodology for waste heat recovery incorporation is a rather robust instrument and therefore it can be easily tailored to other industries looking for energy saving solutions though consideration of waste heat recovery options.

In addition, the elaborated methodology was applied at one of the Portuguese ceramic factories – *TopCer* – that is specialized on manufacturing of ceramic tiles. The application of the methodology was restricted by the objectives and necessities imposed by the *TopCer* administration. Thus, there was explored the feasibility of only two heat recovery technologies (direct heat recirculation and Organic Rankine Cycle) applied to the one waste heat source – kilns. The case study has put into evidence the importance of waste heat recovery in ceramic industry as there were estimated significant reduction of energy costs, energy consumption and GHG emissions with the waste heat recovery technologies incorporation. However, the future research should be performed on *TopCer* in order to study spray-dryer and dryers as potential waste heat sources, analyzing the lack of available waste heat recovery technologies to improve energy efficiency of the factory.

2. Proposal for future research

The major result from the research performed for this dissertation consists in the development and application of the methodology for the efficient incorporation of waste heat recovery technologies in ceramic industry. As a proposal for the future research it is expected to develop an energy model that would cover a series of energy intensive industries where the waste heat recovery is an attractive choice.

Further, based on the developed energy model, it is believed that a decision support system (DSS) could be developed. The DSS would help on minimizing the time spent on the selection of cost-effective waste heat recovery technology from a wide range of steadily increasing and improving options in order to match with the necessities and realities of different industries. Besides, this tool would be able to facilitate implementation of the selected technology and assessment of the expected energy and costs savings.

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ATTACHMENT

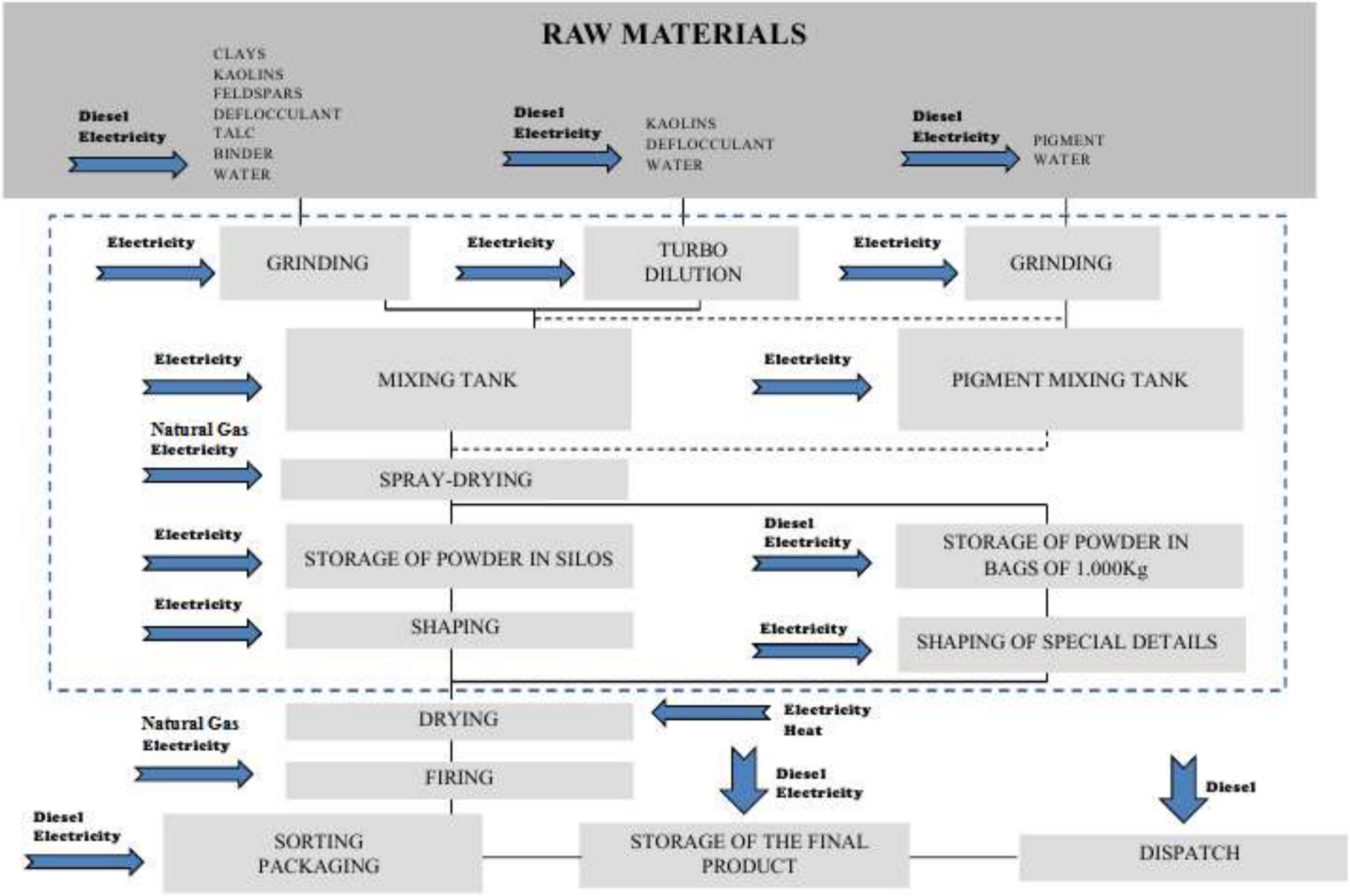

Figure 1A - Flowchart of the ceramics production process in *TopCer*.

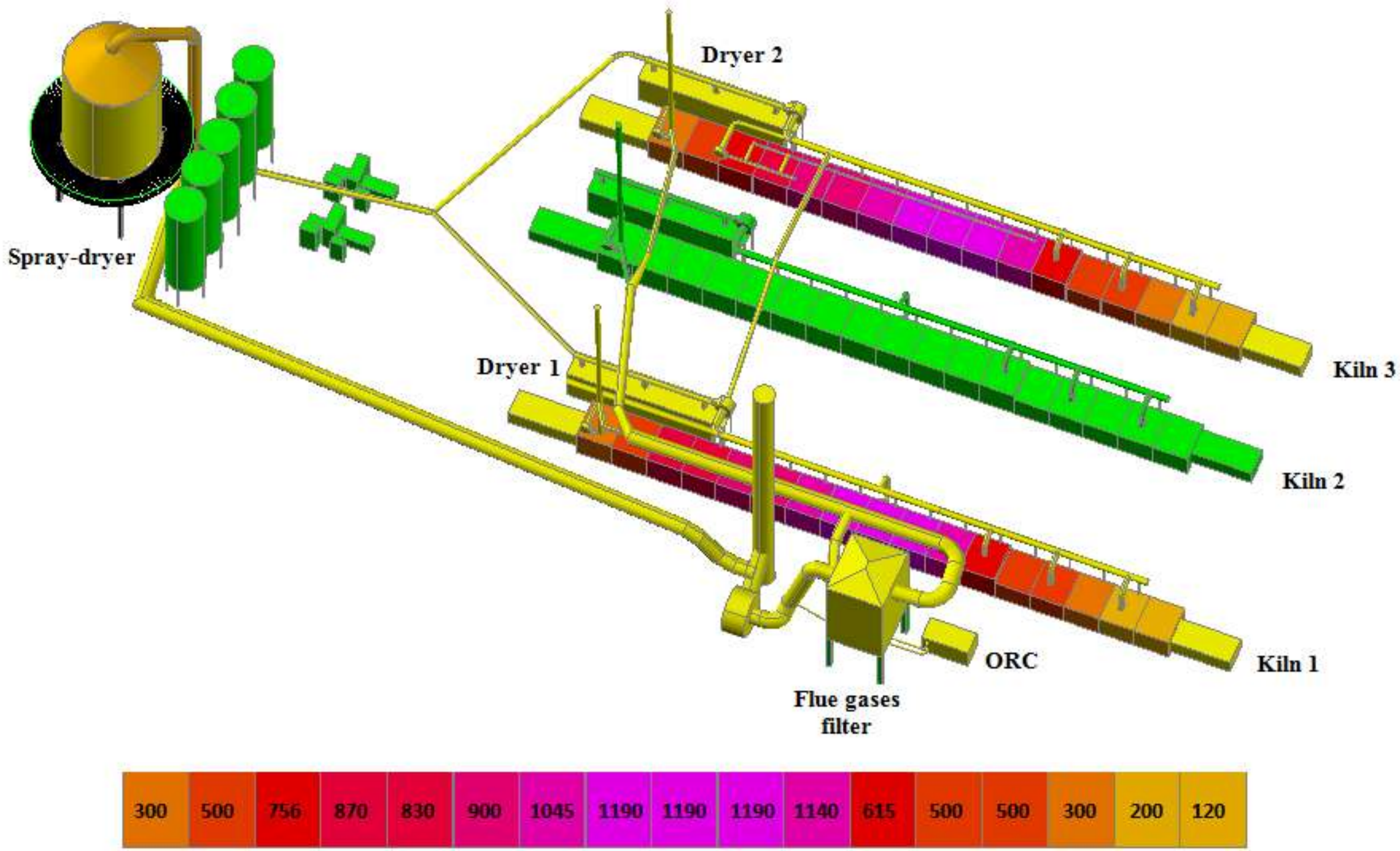

Figure 2A - Scheme of ducts installation on the factory with indication of temperatures of kilns' functioning (°C).