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Research Article

Digital industrial furnaces: Challenges for energy efficiency under VULKANO project

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Abstract: Under intensive industry, industrial furnaces must cope with new challenges to improve the efficiency, reliability and flexibility of their processes. As they need a great amount of energy to achieve the temperature required for heating and melting processes, many researchers have been focused on the minimization of the energy consumption. This energy optimization implies improvements, not only in the competitiveness, but also in environmental and cost performances of the process. This paper shows briefly the challenges for industrial furnaces under VULKANO project focused on the development of five approaches from the point of view of efficiency, flexibility, reliability and safety: improving refractories, investigating new recovery systems based on PCM, using alternative fuels, integrating advanced monitoring and control devices and, finally, developing a holistic tool to help the operator to make decisions. Besides, this paper describes the creation of a digital industrial furnace, regarding to digital twin term. Therefore, an analytical model comprising the burners system, the isolation structure, an energy recovery system, and the load to be heated is described. Each individual model provides the base for the development of future hybrid models, accurately parametrized through process variables, used to investigate the efficiency optimization and provide precise maintenance operation strategies.

Keywords: *Industrial furnaces, Energy efficiency, Control and monitoring system, Digital twin*

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Nomenclature		Nomenclature	
ADC	Analog-Digital Converter	IRENA	International Renewable Energy Agency
CFD	Computational Fluid Dynamics	ITPE	Industrial Thermo Processing Equipment
COP	Coefficient of Performance	LCC	Life Cycle Costing
COP	Conference of Parties	LCA	Life Cycle Assessment
DAC	Digital to Analog Converter	LCOE	Levelled Cost of Energy
EC	European Commission	LHV	Low Heating Value
EEA	European Economic Area	MD	Machinery Directive
EHSR	Essential Health and Safety Requirements	NG	Natural Gas
EMC	Electro Magnetic Compatibility	O&M	Operation & Maintenance
FMEA	Failure Mode and Effects Analysis	SCADA	Supervisory Control And Data Acquisition
HHV	High Heating Value	TRL	Technology Readiness Level
HS	Harmonic Standards		

1. INTRODUCTION

During the last decade, many countries [1–3] and international forums focused on the sustainability [4] have been promoting the reduction of greenhouse gas emissions with the aim of avoiding the global warming to fulfil the Kyoto protocol. In fact, there is a strong political commitment ongoing towards more efficiency and environmental targets as it was shown under the Paris Climate Agreement (COP21) [5]. For instance, in the recent years, the Chinese government is promoting renewable energy policies raising them to a national priority [1]. Also, according to the European Commission, an ambitious agenda is established to move forward a low-carbon economy. As it is indicated by Gökgöz et al. [3], some directives in the Climate & Energy Package announced by EC in April 2009 [6,7] have been aligned in the reduction or improvement of some targets. One of these targets is the increment of 20% of the energy efficiency. In this sense, the energy-intensive industry needs changes to reduce energy consumption and to reach a new scenario where a significant amount of energy will come from renewable sources, progressing towards sustainable production energy [8].

One of the most energy demanding sectors corresponds to industrial sectors focused on continuous and batch processes. In this sense, many types of research focused on the optimisation of the energy consumption for multiples sectors [9,10] and processes [11–15] have been led to address radical improvements in the competitiveness and energy, environmental, and cost performance at the system level. The achievement of minor enhancements in energy consumption signifies a considerable energy saving as can be demonstrated in previous references.

One of the most demanding energy-industry is related with the industrial furnaces in its diverse typologies. Regarding the source of energy used to produce heat, one can classify the industrial furnaces as electrical and chemical furnaces, where the last one is based on the combustion reactions implying the oxidation of hydrocarbons through the formation and destruction of intermediate chemical components [16]. Although the former sources of energy are the most used for industrial processes, some new technologies for heating furnaces are being developed to use renewable energy from the sun, called solar furnaces, that concentrate solar power to produce high temperature [17].

Delving into furnaces based on chemical reactions, their future designs should take into account the reduction of the fossil fuel consumption due to its non-renewable nature, introducing reliable and efficient alternatives. One option is the use of syngas, mainly composed by a mixture of methane, hydrogen, carbon monoxide and inert gases like nitrogen, water vapour and carbon dioxide, in proportions that are very different depending on the source. One of the most promising source for obtaining syngas seems to be gasification [16,18] affecting positively in the promotion of the use of renewable energy sources in existing combustion plants without implying very complex changes. Co-firing of Natural Gas (NG) and syngas in existing furnaces seems to be one of the high potential applications to implement in the short-medium term. It imposes the least requirements as to syngas purity, and it allows a direct and gradual substitution of fossil for renewable fuel [19]. Nevertheless, the impurities of the syngas must be studied in the burner behaviour and in the material to be heated or melted. In this sense, some efforts have been focused on the development of new burners to be able to combust syngas or a mixing fuel composed by NG and syngas [20–24], some of them focused on the flame stabilisation [21,23,25] and the reduction of the NOx emissions through the modifications in the diameters of the injector and the fuel rate [23]. However, the use of these fuels in existing furnaces is not widespread yet, and it remains at Technology Readiness Level (TRL) 4-5 since the actual implementation of the process would require a careful redesign to enable the system dealing with the differences that exist between the conventional and the synthetic fuel in terms of heating values and density properties. Fig. 1 shows the variations of most conventional fuels with the given density where the asterisk indicates fuels consisting of a mixture of several different compounds which may vary in quality depending on the season, influencing the heating values lower than 10% [26]. High Heating

Value (HHV) and Low Heating Value (LHV) represent the calorific value of the substance, associated to the heat released during the complete combustion under standard conditions.

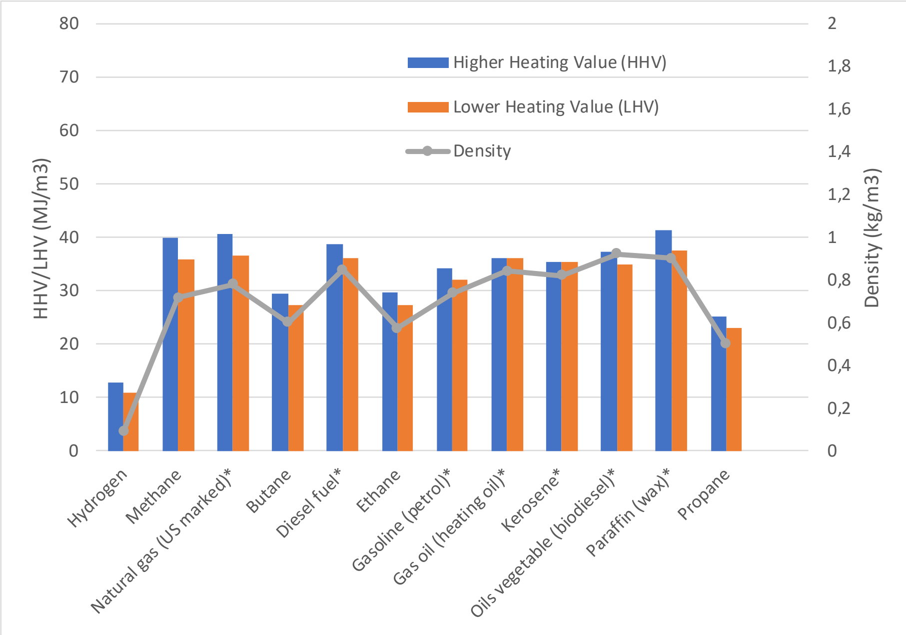

Figure 1. HHV, LHV and density of most ordinary fuels [26]

From a renewable energy perspective, in order to substitute the natural gas by syngas obtained from a biomass gasifier, an optimal monitoring and control system to regulate and supervise the status of the process and the new burners is required [27], as well as, a suitable adaptation of the existing ones.

Among others, new points of interest to reduce the energy demanding in furnaces are leading through the investigation of new refractories [28,29] and the recovery of the heat from the flue gases of the process [30]. Some research on new refractories is focused on increasing the durability and support alkali dash deposits coming from biomass combustion processes in order to reduce erosion and corrosion problems, produced even in SiC refractories as it is reported by Olevano et al. [31]. The improvement of the refractories´ durability implies a reduction in operation costs. On the other hand, the supply of air combustion pre-heated by PCM based recovery system, not only improves the quality of the air combustion considering its smooth effect, but it has a potential energy saving around 12,9% as estimated by Nardin et al.

This paper presents the challenges of current and new coming industrial furnaces based on chemical reactions from the efficiency, flexibility, reliability and safety perspectives studied under the VULKANO Project. In addition, the manuscript goes into the concept of the digital twin, which represents a comprehensive digital representation of an individual product or process including their properties and conditions, with the aim to analyse the real-life behaviour through models and data [32,33]. Taking advantage of the model, the physical system can be simulated under other conditions in order to optimise the system or to find situations to foresee wrong behaviours allowing a safety actuation in advance. In this sense, the concept of digital twin models into the industrial furnace use case is addressed from the perspective of monitoring and control system. This writing proposes an analytical model of digital furnace divided into four sections: (i) burners system, (ii) isolation structure, (iii) energy recovery system, and (iv) load to be heated. This framework provides the foundation for a future hybrid model development to achieve higher efficiency levels of the production process, using an accurate parametrisation of operational variables which could offer in future, precise maintenance operation strategy to increase availability, extend the components live cycle and reduce the overall cost.

After the introduction, this paper is structured as follows. Section 2 describes the challenges of Digital industrial furnaces under the project focused on three aspects: Firstly, it analyses the energy efficiency increment by the reduction of the thermal losses and the improvement of the combustion through the use of a new recovery system of the flue gases based on Phase Change Materials (PCM). Secondly, the increase of the flexibility of different fuels supported by industrial burners is examined. Thirdly, to assess the right maintenance strategies the reliability of each industrial furnaces component is analysed. Finally, the last point of this section concerns safety issues related to this kind of furnaces. Section 3 presents the digital twin concept with the analytical models of each principal component in order to create a complete virtual model of a basic industrial furnace. Finally, section 4 offers a brief discussion highlighting the conclusions and possible directions for future work.

2. CHALLENGES OF DIGITAL INDUSTRIAL FURNACES UNDER VULKANO PROJECT

Industrial furnaces are continuously facing new challenges in order to increase their competitiveness through improving efficiency, reliability and flexibility of the process. Besides, the updating and upgrading of currently installed furnaces with specific retrofit actions are crucial to meet new demands. In this sense, the development of improved designs based on the installations of new materials, the use of alternative fuels and the integration of permanent monitor and control systems seem to be essential. All of these points are being investigated under VULKANO project (http://www.vulkano-h2020.eu/).

This project involves twelve companies from different European countries. The primary objective of the project is the design, implementation and validation of some advances retrofitting solution in existing preheating and melting industrial furnaces currently fed with NG to increase the energy and environmental efficiency. To reach those objectives, it requires the integration of new solutions based on high-temperature PCM recovery systems, new refractories, optimal co-firing systems, further advanced monitoring and control system and, on the top of them, a realistic and powerful tool able to optimize the integration of the solutions following a life cycle and cost thinking along the value chain. This type of new improvements is aligned with the key actions suggested under SPIRE Roadmap [34], promoted by EC. In order to assess the retrofitting solutions, they will be implemented in two real facilities in Spain and Slovenia, involving ceramic and steel sector, respectively, considering each company needs with the aim to reach TRL7. In addition, the solutions will be theoretically evaluated in the aluminium sector in a Turkish company.

In the following subsections, the previous indicated new solutions are studied under four aspects: efficiency, flexibility, reliability and safety.

2.1. Efficiency

It is widely known that nowadays most companies around the world are investigating their processes to be more competitive through improving their efficiency. In order to evaluate their efficiency one can use the Coefficient Of Performance (COP) widely used in heat transfer devices [35]. This coefficient is defined as the ratio between the useful heat introduced in the system (E_{in}) and the energy required (E_{out}), both measured in the same units, i.e., joules. Therefore, COP can be obtained as indicated in Eq. [1]:

$$COP = E_{in}/E_{out} \qquad (1)$$

The difference between energy introduced in the system and required are the energy losses. Therefore, Energy losses (E_l), is calculated as given by Eq. [2]:

$$E_l = E_{in} - E_{out} \quad (2)$$

Attending to the origin of the energy losses, they can be grouped into two main types: energy conversion losses and losses due to the energy exchange with the environment. The former one is due to non-ideal thermal isolation and the fact that there is a heat exchange between substances in contact. Hence, the environment absorbs part of the thermal energy as it is illustrated in Fig. 3 under a Sankey´s diagram.

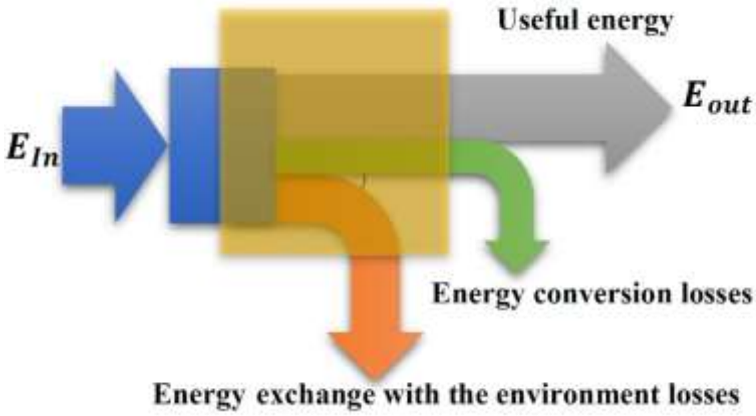

Figure 2. Conceptual definition of Efficiency

In a furnace, to reduce the heat absorption from the outside environment, some refractory materials having low thermal conductivity properties are assembled with the purpose to provide good thermal isolation. Lower the thermal conductivity of the entire wall, lower heat absorption from the outside environment. The choice of the refractory and isolation material depends on many variables, but mainly on the temperature and the materials with which come into contact. The last one is a critical issue because the refractory material must withstand high temperatures (up to 1400ºC depending on the process) without melting. Therefore, the refractory must keep its essential structural features under such normal working conditions.

Under the project, an improvement of 5% in the energy efficiency of the process is desired through the development and assembling of new alternative materials withstanding up to 1500ºC, keeping in mind a better behaviour for more extended periods of time, increasing its durability. Also, the new refractories must overcome some current problems related to reparability and recyclability. In this sense, the design of the refractories under the project are based on nano-particles containing aqueous suspensions to avoid technical and healthy handicaps. In fact, the addition of this colloidal binders provides, among other advantages, faster drying, good mechanical strength at intermediate temperatures and better thermomechanical properties at high temperatures [28,29].

Another point to be analysed in order to increase the efficiency of the process is related to the recovering energy discharged to the environment as flue gases. Currently, heat exchangers are installed in chimneys with the aim to recover thermal energy to be used for increasing temperature of the combustion air, mixed with the fuel in the burner. According to the classification of heat recovery technologies [2], under passive techniques there are phase change materials to store heat. This technique is very useful not only due to the advantages related to the accumulation of the latent heat of fusion (reflected in the smoothing of the combustion air heated by the PCM), but due to low investment and operation costs of this technology, with minor modifications in the plant [30]. In this point, the challenge concerns to the use of a PCM recovery system facing up with temperatures up to 1500ºC, with the aim of increasing the combustion air temperature more than 100ºC in relation to the currently achieved. The control of the associated motorised valves in order to manage the load and unload of the stored heat effectively and efficiently in the PCM is another critical issue.

2.2. Flexibility

Independently of the type of energy source, industrial furnaces need the energy to heat the chamber and the load at the required temperatures. As it was mentioned in the introduction section, there are some policies promoted by governments of different countries with the aim to use more renewable energy instead of fossil fuels. In this sense, according to the International Energy Agency (IRENA), one of the primary renewable sources able to generate fuel to be combusted is the biomass. This energy source is being economically assessed during the last decades regarding the levelled cost of energy (LCOE) and compared with other primary renewable energies like geothermal, hydropower, solar photovoltaic, solar thermal or on-shore/off-shore wind. The LCOE is a rate between the entire cost of infrastructure over the lifetime and the amount of generated energy over the same period, measured in €/kWh or USD/kWh. The LCOE of different renewable technologies for the period 2010-2017 is compared in Fig. 3 meanwhile Fig. 4 shows the bioenergy installed capacity trend in its various ways (source www.irena.org). As it can be seen in the first figure, the LCOE of Biomass has decreased in the last years, and it is under the fossil fuel power cost, being one of the lowest maximum cost. In addition, every year the installed capacity of the Bioenergy is steadily growing as illustrated in Fig. 4. Both, biogas and syngas can be used to be combusted to generate heat. Biogas composition differs depending on the substrate composition and the anaerobic process conditions. In spite of that, in most of the biomasses, its main component is Methane exceeding 50% in molar composition [36], which has a high HHV compared to some other fuels (see Fig. 1). Syngas, another conventional biofuel generated from biomass wastes, is also produced through gasification and anaerobic digestion processes. In this case, the molar composition, after effective purification, includes 15–20% H_2, 15–20% CO, 1–5% CH_4,10–15% CO_2 and the balance N_2, providing a HHV around 6 MJ/Nm3 [36].

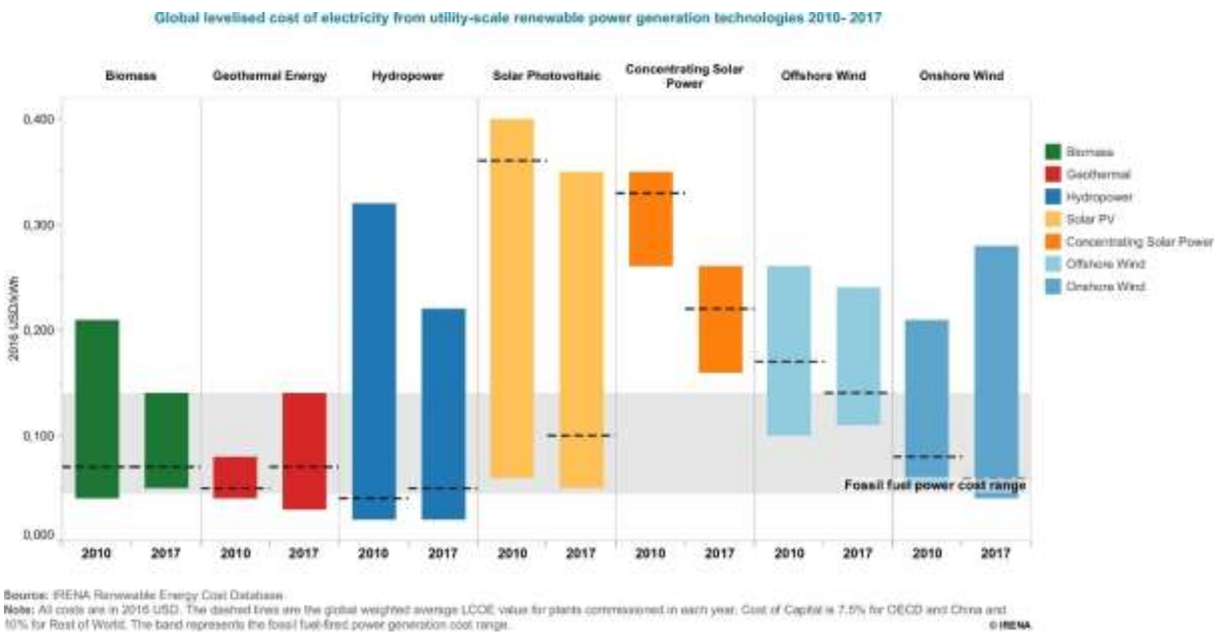

Figure 3. LCOE (Period 2010-2017). Courtesy of IRENA

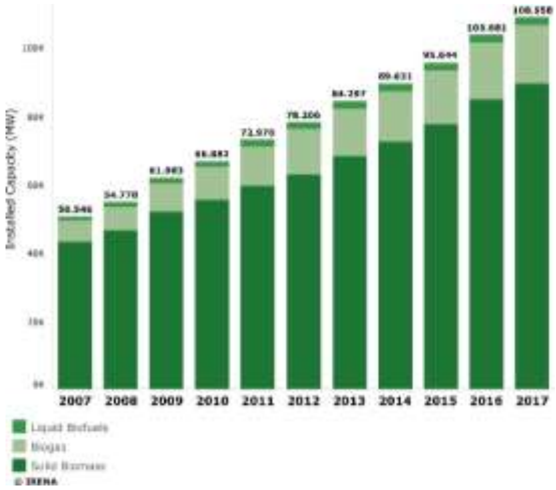

Figure 4. Trends in Installed Capacity of Bioenergy (Period 2010-2017). Courtesy of IRENA

Taking into account the effect of economic factors, mainly related with the fluctuation of raw material prices in short times, i.e. NG prices, the industrial furnaces based on combustion reactions must be flexible in order to use alternative fuels like biogas or syngas. Therefore, some new concepts like co-firing, involving the combustion of different fuels, or the burning of previous alternative fuels can minimise the impact of the energy prices fluctuation in the cost of producers.

Under the project, the utilisation of syngas from biomass gasification has been chosen by practical issues. In this case, the challenge consists in designing new burners able to combust the fuel generated by the plant gasifier. Moreover, the mixture between the fuel (typically identified as the reductant in an exothermic redox chemical reaction) and the oxidant (typically heated air passing through a recovery system) is critical to ensure a complete combustion. So, the control of the associated motorised valves, as well as the monitorization of the primary process signals like temperatures and pressures, will be challenging since the relationship of the reductant and oxidant must be managed in an optimised and safe way.

Another strategy conferring flexibility to industrial processes comes from the use of holistic tools. These kind of tools consist in applications able to support operator´s decision during the process, basing the decision on Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) indicators [37]. Through some algorithms, these indicators take into account the direct impact on furnace performance as a consequence of modifications in critical parameters of the process. Since the tool needs real data of the process, it is required a good acquisition system for saving and analysing the essential parameters identified in the process. Once the vital parameters have been identified and registered in a database, the tool could predict the performance evolution of the furnace, providing flexibility to engineers for optimising the critical variables, supporting operator to make decisions about the modification of specific variables, and in addition, to reduce the risk of damages to increase the lifetime of the installation.

2.3. Reliability

The global efficiency can be enhanced by lowering maintenance costs from the perspective of Operation & Maintenance (O&M). In this sense, the selection of good maintenance strategies is a key to increase the availability of the heating process and to ensure the process reliability. From the perspective of O&M there are three main approaches: reactive or corrective maintenance, preventive maintenance and condition-based maintenance.

Generally speaking, the first one, reactive or corrective maintenance strategy, lies in keeping the process under operation until a component is broken, not doing any scheduled maintenance. This strategy is adopted when the number of failures is residual, the repair cost is low and the availability of the machine is not determining.

Secondly, a preventive maintenance strategy comprises scheduled conservation actions based on a specific period of time, generally associated with the experience of the O&M team. To minimise the impact of the production, typically, these maintenance tasks are scheduled out of the production time. Although this strategy does not entirely prevent malfunctions during production time, these actions attenuate the probability of incidents.

Thirdly, condition-based maintenance strategy is built on the basis of satisfying specific rules to carry out particular maintenance actions. This strategy requires a wide-range monitoring system with different features to acquire, register and analyse data. The process and the physical signal obtained determine the requirements of the computational system in relation with the type of data capturing system to be used (voltage or current analog input signal), the sample rate and resolution required, among others. This continuous analytic process conducts a diagnostic algorithm over time to detect, isolate and identify current failures. Also, it executes a prognostics analysis to predict future shortcomings with the purpose of performing maintenance activities at the right time [38].

To reduce the entire O&M costs, a correct maintenance strategy must be chosen and successfully applied [39]. Fig. 5 compares these three strategies as a function of total cost [39,40]. As it can be seen in the figure, the optimum point is accomplished when the sum of preventive and repair cost is minimum.

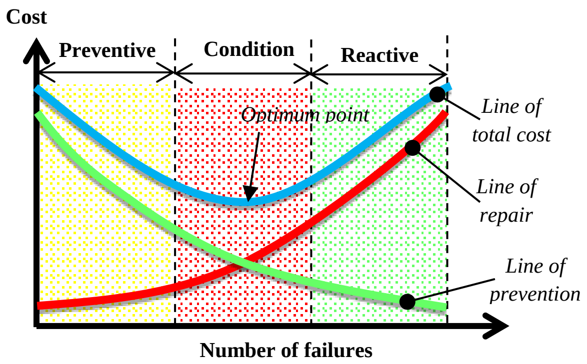

Figure 5. Costs associated with traditional maintenance strategies [39,40]

The economic impact of each component failure is not equal. Failures are critical when the production process is impossible to continue. The Failure Mode and Effects Analysis (FMEA) is a methodology that involves a review of components and assemblies to identify failure modes (occurring in the present) as well as their causes (happen in the past) and effects (that will occur in the future) [41].

In the case of industrial furnace processes, several factors can provoke the non-availability of the system (for example actuators or sensors broken). However, following efficient maintenance strategies founded on condition-based strategy, the downtime can be significantly reduced and the lifetime of the system can be increased. Besides, proper maintenance scheduling utilises production orders information to plan future preventive actions with the purpose of performing these activities, i.e., when customer orders are lower than usual. All of these strategies increase the availability of the system.

2.4. Safety

The incorporation of the challenges of VULKANO project included in previous sections must fulfil safety requirements. Under European Union, industrial furnaces are products subject to safety legislation covered by Machinery Directive (MD) 2006/42/EC. Consequently, their design and construction must satisfy all the applicable Essential Health and Safety Requirements (EHSRs) of this regulation. In addition to the MD, a second Directive that also applies to this industrial equipment is the Directive 2014/30/EU on Electromagnetic Compatibility (EMC), which is expected to increase its role shortly due to the progressive and unstoppable digitization of European industry.

The MD establishes mandatory EHSRs, while the safety technical specifications for their compliance are described in the European Harmonized Standards (HS). The application of HS for the design of industrial furnaces is voluntary - the manufacturer can choose these or other technical specifications to satisfy the legislated requirements - but their use confers presumption of conformity with the EHSRs they cover. Some of these HS include the series of standards EN 746 "Industrial Thermo Processing Equipment (ITPE)", which specifies the safety requirements (mechanical, electrical, thermal, etc.) to be met by the manufacturers of industrial furnaces to satisfy the EHRSs of the MD, ensuring people, property and the environment safety during the whole life cycle. The main standards of this series are currently under review to incorporate the contents of the ISO 13577 series "Industrial furnaces and associated processing equipment", more advanced and where the experts of the sector include their standardization efforts.

This former international standard sets some recommendations about protective system and its relationship with other furnace equipment or subsystems like heating system and process control system. This relationship, included in Fig.6 (ISO 13577-4) pays attention to the safety-related electrical control system, which integrates components like sensor(s), logic solver(s) and actuating elements, among others. Required sensors to carry out the safety-related functions of the industrial furnace concerns to, i.e., monitoring gas pressure, flame status, air/gas ratio or temperature limits of critical devices. Moreover, this standard provides the designer four alternatives to implement a protective system and their respective building blocks.

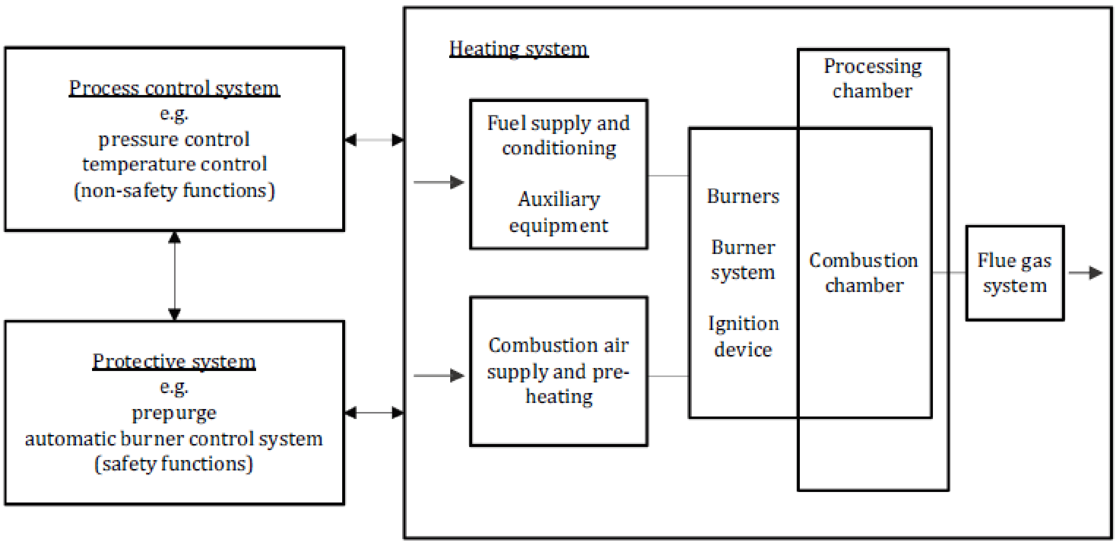

Figure 6. Block diagram of control and protective system (Source ISO 13577-4:2014)

Finally, the use of new industrial furnaces in workplaces by workers also poses additional challenges related to compliance with European legislation on safety and health at work (national transpositions), basically the Framework Directive 89/391/EEC on safety and health of workers at work and Directive 2009/104/EC, concerning the minimum safety and health requirements for the use of work equipment by workers at work.

3. DIGITAL INDUSTRIAL FURNACES

In the last years, the combination of the information provided by any system with low cost and powerful technology able to analyse and model the system itself, have enabled the ideation and use of the so-called Digital Twin. Some authors define a digital twin of a production process as the collection of all digital parts linked with relevant generated data during the production process [32]. In the opposite side, other authors identify the digital twin with a linked collection of only relevant data and models [42]. In any case, it is conceived from generated information during all stages of a process: design, development, operation and services [42]. The information provided to the digital twin includes properties, conditions and behaviour of the physical components of the specific system through models and data that can be simulated.

From the simulation point of view, digital twin is considered as a newly improved step in simulation technology due to the possibility of evolving physical systems in more complex entities by adding software functions in some parts, i.e. drives and sensors, and enforcing the connectivity (Cyber-physical Systems) [42]. These steps are identified in Fig. 7. Under the digital twin concept, three different aspects are comprised: physical twin, digital twin representation and digital twin abstraction. The first one refers to the virtual image of the conceptual model geometry, normally called Skin Model [43]. This representation shows the current aspect of the future geometrical variations. The second aspect, is the set of components in the real world beneath study, highly monitored and integrated with Internet-based services with monitor and control purposes [44]. The last aspect, Digital twin abstraction, is an abstract model comprising all characteristics, adequately describing the physical twin at a conceptual level throughout the whole product life-cycle [45]. Experiments performed through Digital twin abstraction permits the capture of spurious events, simulate different scenarios, and understand physical twin behaviour. However, it requires fulfilling scalability, interoperability, expansibility and fidelity properties.

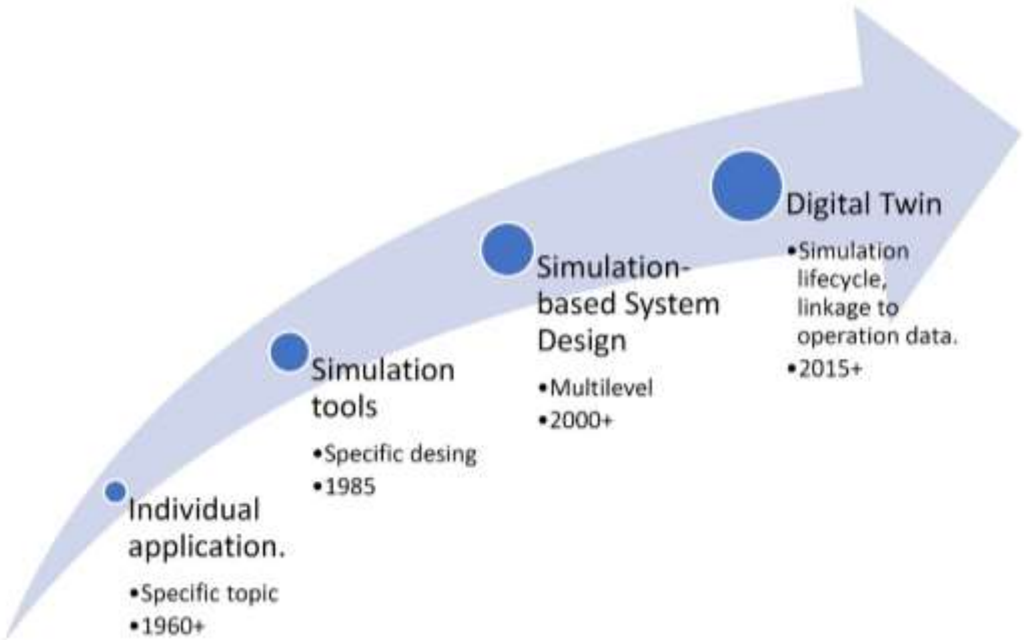

Figure 7. Evolution in simulation technology. Based on [42]

Taking into account that the ultimate purpose of a digital twin is to optimise operations during the production process, increase the variability of supported methods to process and improve maintenance operations during entire lifetime [42], this representation is able to recover the facets indicated in section

2: efficiency, flexibility and reliability of a specific process. The following subsections describe two fundamental aspects of the digital twin: data acquisition system and the hybrid model.

3.1. Data Acquisition System

As it was introduced before, the digital twin technique representing an industrial furnace requires accurate reproduction of all the physical components in an advanced computer. This reproduction involves a transversal data acquisition system to acquire and register data from different sources, represented in analogue or digital signals. It is a complex task due to integration with existing devices. Additionally, problems related to synchronisation issues between sensors from third-party controllers appear. Besides, diverse technologies must exchange data using intermediate devices, in some cases poorly documented and not very friendly, increasing the difficulty to achieve a suitable Supervisory Control and Data Acquisition (SCADA) which monitors all signals and actuates on the process. SCADA links the physical and the virtual industrial furnace, conceptually represented in Fig. 8 as two phases: observation and prediction.

Observation phase involves a set of elements, generally in the basis of individual and interchangeable input and output cards, responsible for capturing real-world physical conditions and converting them into data able to be analysed under the computational domain. This process, performed by a data acquisition system, can be divided into four steps represented in Fig. 9, where the observation phase of an industrial furnace under a conceptual scheme is illustrated. The first step identifies the physical properties that describe the physical system state, such as pressure, temperature or flow, among others. The second step installs the electronic hardware able to capture each tangible property transforming them into an electrical signal, commonly voltage or current. This electronic hardware typically requires an electrical excitation. The third step prepares the electrical signal before starting the Analog-Digital Converter (ADC) process through a signal conditioning step. Some conditioning processes involve filters to remove noise in order to obtain the precise signal required. Also, sometimes, the electrical signal needs to be amplified to get a better signal matching ADC features. The fourth step transforms the electrical signal into a digital signal using an ADC device. Computers understand digital signal, and it can be easily shared and exchanged between them. Similarly, the acquisition & control system can generate signals to manage the actuators included in the process, typically, drives controlling the aperture or closing process valves.

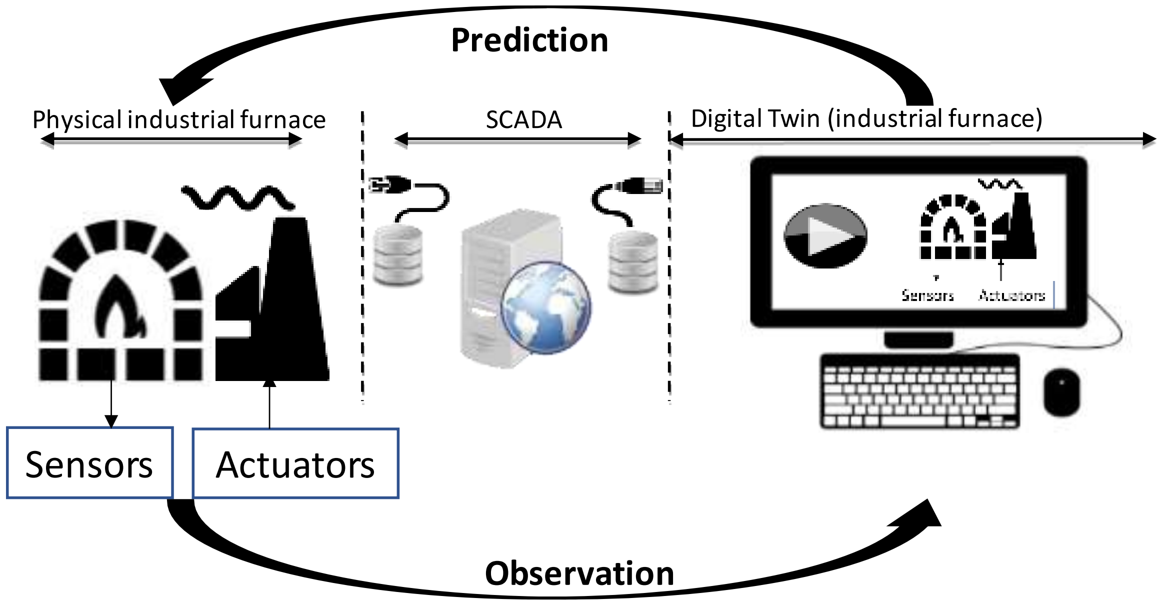

Figure 8. An industrial furnace as a digital twin

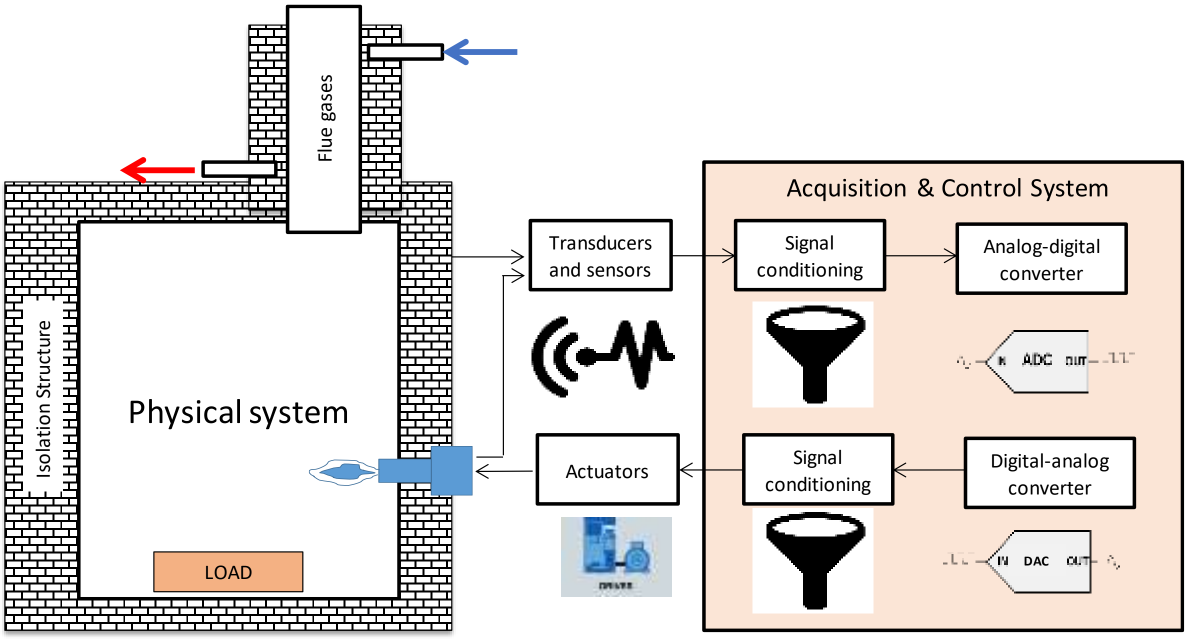

Figure 9. Data acquisition system schema

Regarding the observation phase, the signals obtained through a suitable acquisition system are the basis for developing the industrial furnace hybrid models. Physical twin information flows continually to adjust in real-time hybrid models according to the physical twin current status. Respect to prediction phase, simulations of hybrid models allows estimating the physical twin behaviour through certain scientific assumptions to deal with uncertainty. These hybrid models based on physical laws are explained in detail in the next subsection.

3.2. Hybrid Models

Assuming an unidirectional heat transfer and a steady state in which the thermophysic features keep constant, any thermal system can be represented as an equivalent electrical circuit using thermoelectrical analogy [46]. In this sense, electric current, electric potential difference (voltage), electrical capacitance and electrical resistance correspond to rate of heat fluxes in Watt, temperatures in Kelvin, heat capacity in joule per kelvin and thermal resistance in Kelvin per Watt, respectively.

Thermal problems can be divided into a considerable number of nodes to perform steady-state analysis using finite element software to model. Hence, solutions are obtained when thermal flows remain constant over time. Basically, the thermal furnace model can be divided into few isothermal nodes presented in Table 1 and illustrated in Fig. 10.

Table 1. The main nodes of node analysis

Node #	Description
0	Ambient
1	Burner system (near to the flame)
2	Air inside the chamber
3	Lateral walls of the combustion chamber
4	Roof walls of the combustion chamber
5	Floor walls of the combustion chamber
6	Inlet/outlet air
7	Load

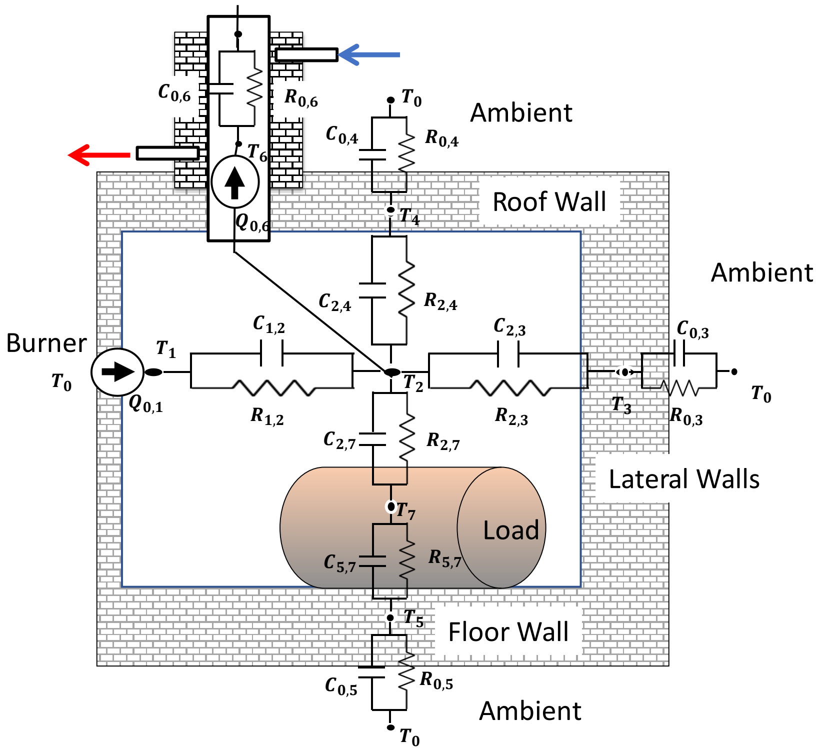

Figure 10. Model representation using thermoelectrical analogy.

The temperature in each node is represented as $\{T_i \ / i \in [0,7]\}$. Each temperature represents the mean value of the conceptual part associated.

Note that this model includes only the heat transferred along the system by conduction and convection, and any heat exchange that might take place is neglected. Bearing in mind the maximum temperature to be reached in one furnace (below 300ºC), it is considered that this approach is accurate enough to assess the overall thermal behaviour of the system and to develop, therefore, an efficient tool for the analysis of the variables involved. Considering higher temperature of the chamber, other terms related to radiation heat transfer should be included.

Following the Kirchhoff's first law, the rate of heat flow in each node must be null as expressed in Eq. [3]. Each rate of heat flow from node i to another node j can be represented as $Q = \{Q_{i,j} \ / \ i,j \in [0,7] \ \wedge \ i < j\}$ where. The matrix Q represents all possible cases of heat flow rates regarding the nodes identified in Table 1.

$$\sum_{j=0}^{j=7} Q_{i,j} = 0 \quad where \quad i \in [0,7] \tag{3}$$

$$Q = \begin{bmatrix} Q_{0,1} & Q_{0,2} & Q_{0,3} & Q_{0,4} & Q_{0,5} & Q_{0,6} & Q_{0,7} \\ & Q_{1,2} & Q_{1,3} & Q_{1,4} & Q_{1,5} & Q_{1,6} & Q_{1,7} \\ & & Q_{2,3} & Q_{2,4} & Q_{2,5} & Q_{2,6} & Q_{2,7} \\ & & & Q_{3,4} & Q_{3,5} & Q_{3,6} & Q_{3,7} \\ & & & & Q_{4,5} & Q_{4,6} & Q_{4,7} \\ & & & & & Q_{5,6} & Q_{5,7} \\ & & & & & & Q_{6,7} \end{bmatrix} \tag{4}$$

There are some particular heat flow rates defined. The first one is the heat flow rate provided by the burner, characterised by $Q_{0,1}$. The value of this heat flow rate can be defined at each instant by the monitoring and control system explained in detail in subsection 3.2.1.

The second one is the heat flow rate as a consequence of the not ideal heat exchanger system due to input/output air renewal movement. This heat flow rate source is mainly represented by $Q_{0,6}$ and it is defined in subsection 3.2.3.

Regarding Fig. 10, the thermal resistance can be identified, denoted as $R = \{R_{i,j} \; / \; i,j \in [0,7] \wedge \; i < j\}$. It is a measurement property of a component that indicates the difficulty of heat flow movement in Kelvin per wats. Similarly, to electrical circuits, thermal resistances satisfy circuit laws for simplification of resistances in series and parallel. The thermal resistances identified in the model are the following ones, denoted by Eq. [5].

$$R = \begin{bmatrix} R_{0,1} & R_{0,2} & R_{0,3} & R_{0,4} & R_{0,5} & R_{0,6} & R_{0,7} \\ & R_{1,2} & R_{1,3} & R_{1,4} & R_{1,5} & R_{1,6} & R_{1,7} \\ & & R_{2,3} & R_{2,4} & R_{2,5} & R_{2,6} & R_{2,7} \\ & & & R_{3,4} & R_{3,5} & R_{3,6} & R_{3,7} \\ & & & & R_{4,5} & R_{4,6} & R_{4,7} \\ & & & & & R_{5,6} & R_{5,7} \\ & & & & & & R_{6,7} \end{bmatrix} \quad (5)$$

Another element identified in Fig. 10 is the heat capacity. It is defined as the ratio of heat transferred to or from the system and the resulting variation in temperature in the system, expressed in Joules per Kelvin. In the same way as thermal resistance, the heat capacity is indicated as $C = \{C_{i,j} \; / \; i,j \in [0,7] \wedge \; i < j\}$.

$$C = \begin{bmatrix} C_{0,1} & C_{0,2} & C_{0,3} & C_{0,4} & C_{0,5} & C_{0,6} & C_{0,7} \\ & C_{1,2} & C_{1,3} & C_{1,4} & C_{1,5} & C_{1,6} & C_{1,7} \\ & & C_{2,3} & C_{2,4} & C_{2,5} & C_{2,6} & C_{2,7} \\ & & & C_{3,4} & C_{3,5} & C_{3,6} & C_{3,7} \\ & & & & C_{4,5} & C_{4,6} & C_{4,7} \\ & & & & & C_{5,6} & C_{5,7} \\ & & & & & & C_{6,7} \end{bmatrix} \quad (6)$$

Eq. [7] shows the transient behaviour of temperature and heat flow rate over time of a thermal capacitance, c.

$$q(t) = c \cdot \frac{dT}{dt} \quad (7)$$

Using one dimension of heating equation, the Eq. [8] system must be fulfilled.

$$Q_{i-1,i} = \frac{T_i - T_j}{R_{i,j}} + C_{i,j} \cdot \frac{d\left(T_f - T_0\right)_{i,j}}{dt} \quad where \quad i,j \in [0,7] \wedge \; i < j \quad (8)$$

where T_f and T_0 are final and initial temperature in node i,j, respectively. Using Eq. [8] and solving it at each instant, temperatures notation in each node can be calculated over the time, knowing thermal resistances and capacitances between nodes.

Therefore, the following subsections describe each of the main subsystems-burner, isolation structure, energy recovery system and the load to be heated- describing a digital industrial model of a furnace.

3.2.1. Burner system

Burner system is in charge of generating a controlled flame used to heat the furnace inner chamber. Usually, the flame is generated by igniting a mixture of fuel and combustion air, normally preheated in a recovery system, typically named as heat exchanger. The higher the temperature of the preheated combustion air, the lower the energy required to heat the chamber of the furnace.

Different burner typologies such as conical burner are designed to combine this air/fuel mixture [47]. This component is responsible for flame stabilisation and the combustion efficiency depends on its design. Therefore, researchers are motivated to explore diverse geometric designs possibilities using Computational Fluid Dynamics (CFD) simulation [48] of the combustion process to maximise combustion efficiency, reduce pollutant emissions and decrease the risk of thermal damage [49]. However, CFD techniques require substantial computational resources to provide useful information, being more suitable for obtaining information in steady states instead of transition ones [50]. Because of that, the model of a burner to be implemented on the digital industrial furnace top model cannot require so high detailed definition of the flame.

Burner control system provides the desired heat through the regulation of the fuel and combustion air flows. In some cases, this regulation between both components is performed by only one actuator which manages the combustion air while the fuel valve is mechanically adjusted. In case of cofiring burner, the regulation of fuel and combustion air is more complicated as consequence of the difference in chemical composition of fuel gas over time. Besides, the balance of inlet combustion air influences this proportion, mainly the oxygen percentage, but it can be considered constant. To maintain the heat supplied in the furnace chamber under a specific value, some sensors are installed to monitor the flame status, real flow of fuel and combustion air, the temperature and pressure in the combustion chamber, with the purpose of providing data to setpoint flow controllers. The block diagram of cofiring burner is presented in the Fig. 11.

Using this block diagram, an independently regulation of combustion air and fuel gas flow is performed with the aim to maintain the combustion process stable and safe, insufflating a specific heat flow rate. Based on the information provided by the combustion chamber sensors and the algorithm implemented in each controller, the aperture of the valves will be regulated, keeping the required ratio between fuel and air combustion flow, in order to reach the temperature setpoint inside the chamber. Despite previous paragraphs, the heat supplied by the burner, $Q_{0,1}$, can be assumed as a constant heat flow rate source manipulated by a suitable control algorithm controlling the temperature of the chamber.

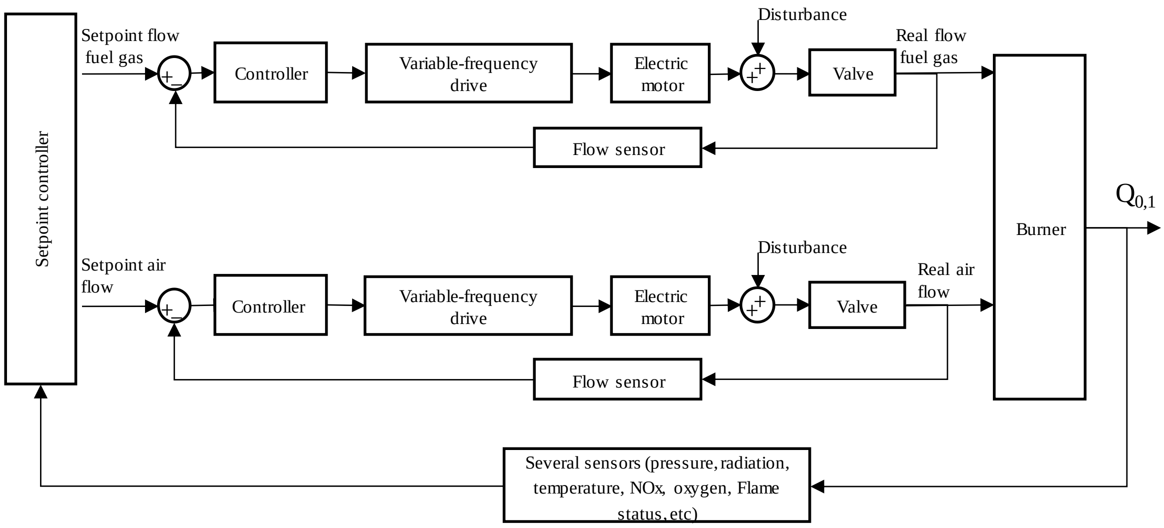

Figure 11. Block diagram of the burner system

3.2.2. Isolation structure

Due to that the combustion process occurs inside the combustion chamber, it is the primary thermal isolation structure of the industrial furnace. Hence, it is generally covered by refractory materials with specific extreme features like thermal shock resistant, low coefficient of thermal expansion, chemically inert and low thermal conductivity. The current challenges existing in refractories are related to withstanding high thermal fluctuations, operate at higher temperatures and for more extended periods of time, and replace the damaged material more efficiently.

Regarding the node analysis, the schema of the equivalent thermal circuit of a wall component is presented in Fig.12. Note that $R_{2,3}$ and $R_{0,3}$ take into account the conduction across the wall and the natural convection to the ambient respectively.

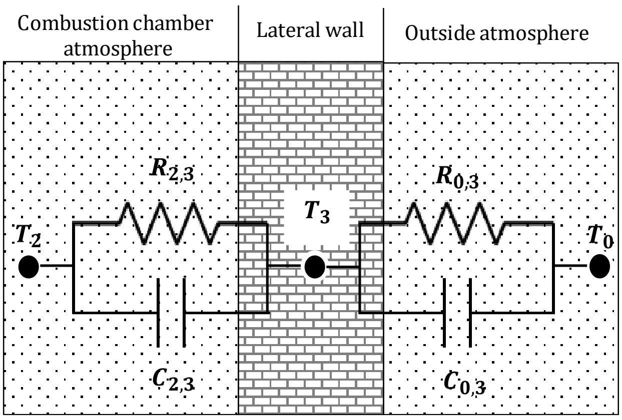

Figure 12. Thermal schema of burner system

3.2.3. Energy recovery system

Regarding the node analysis, the schema of the equivalent thermal circuit of an Energy Recovery System can be represented as heat flow rate, $Q_{0,6}$, resulting from the difference between the energy released by the flue gases and the energy recovered increasing the temperature of the combustion air as it is indicated in Fig. 13. Note that T_0 and T_6 corresponds to the temperature of the ambient and the temperature of the flue gases respectively.

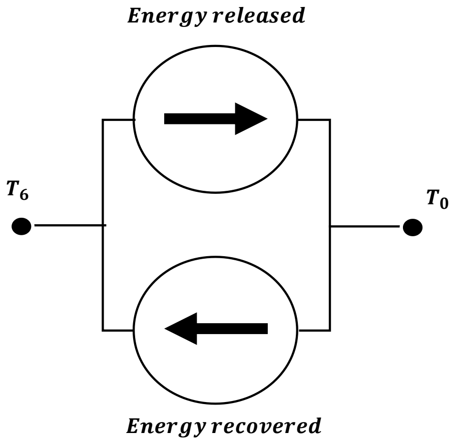

Figure 13. Thermal schema of an Energy Recovery System system

In this case, thermal resistance $R_{0,6}$ and heat capacity $C_{0,6}$ can be neglected due to that heat flow rate is the main component.

3.2.4. Load

Regarding the load-wall region, Fig. 14 shows the assumed schema. In this case, the heat in the furnace chamber flows by convection to the Load, by conduction from load to floor wall and by convection, again, to the ambient. A perfect contact condition can be assumed between the load and the floor wall. $R_{0,5}$ includes both the conduction across the wall and the natural convection to the ambient.

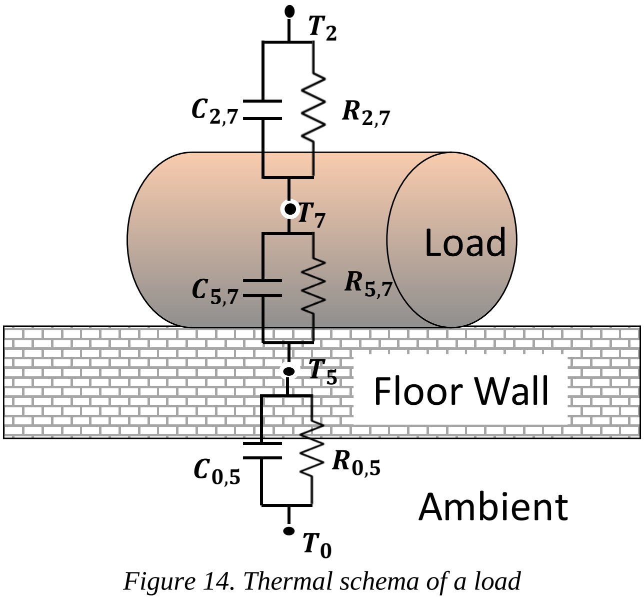

Figure 14. Thermal schema of a load

4. CONCLUSION and FUTURE WORK

This paper has presented the challenges of industrial furnaces under the perspective of efficiency, flexibility, reliability and safety studied on the VULKANO project. The challenges are related firstly, to the development of new refractories based on nano-particles containing aqueous suspensions. Secondly, assembling a new recovery system based on PCM exchangers. Thirdly, including the possibility to use an alternative fuel like syngas in conjunction with NG, developing a new burner. Fourthly, including new acquisition and control system able to manage all new signals needed to control and supervise the behaviour of the new approaches. All data obtained with the acquisition system will be used to develop algorithms to be included in a holistic tool with the aim to support operator´s decision keeping in mind the improvement of the efficiency, flexibility, reliability and safety of the furnace.

Related to these new challenges is the concept of the digital twin term. This paper also has introduced general ideas for a digital industrial furnace through the use of the digital twin term. Therefore, briefly, the concept of a furnace model using thermoelectrical analogy is described through four subsystems: burner, isolation structure, recovery system and the load to be heated. This model will be a part of a future hybrid model including real data obtained with the new acquisition system.

Future work will be held focused, on the one hand, on the development of a precise analytical model using the parameters and conditions of a real case. This model will include a complete monitoring and control system with controller design using the operational variables optimised by a precise metaheuristic algorithm. On the other hand, the newly manufactured components like refractories, recovery system and syngas burner will be assembled in a real case of study having the possibility to test under operational conditions.

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