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SUMMARY OF DOCTORAL THESIS

Monitoring and Control of Modernized Electrothermal systems

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Contents:

1. Introduction

1.1 Statement of the Problem

Over the last years the outstanding technological progress has led to developing systems capable of producing practical solutions to more and more complex problem. Technological progress responds in actual fact to a global economic demand which is the ability to develop and deliver performant finite products at competitive price ranges. This fact is attained on several levels: high quality design of the final product, efficient design of the production means of final product, efficient automatization of production system and achieving a high production volume with minimal losses within time unit.

Factory automations become more and more complex from both an enhanced production performance perspective and energy saving perspective. It is known fact that the reliability of a system is in inverse ratio to its complexity and number of components it incorporates. This drags us into a vicious circle: we produce more and more highly performant automation systems, with a lower and lower power consumption rate; nonetheless, these systems require an increasing level on maintenance. In the end, all these aspects translate into a cost balance: is cost reduction due to high performance and energy saving greater than the maintenance additional costs that this approach implies? Within this context, this thesis aims to tackle the study of automation systems of industrial production machines as well as the way in which their development has led to the alteration of the general manufacture and implementation conception.

1.2 Purpose and Goals of the Research

The purpose of the research is the construction of two gas fired forging furnaces for titanium bars with a common heat recovery system from the automation perspective.

Contrary to general perception, a gas fired industrial furnace entails a more complex automation system than an electrical furnace due to the large number of required elements such as: measuring, control and supervision elements, implemented safety systems which are compulsory when working with gas, the required know-how. These additional acquisition costs are legitimate if we take into account the performance limitations of electrical furnaces. In fact they are finally counterbalanced by a much lesser primary energy cost. Currently, the vast majority of furnaces/boilers/systems in the heavy industry are gas fired.

The furnaces have been manufactured and commissioned at Zirom S.A. Giurgiu plant by Electro-Total S.R.L., and the person in charge with the design and implementation of all monitoring and control software systems was the author of the present study.

The implemented automation methods have enabled the construction of a type of furnace which can encompass the specific performances of both high and low temperature furnaces, all in one universal furnace. Until recently, design and conception of low temperature furnaces were completely different from those of high temperature furnaces. When the need of both high and low temperature furnaces arose, also meeting the requirement of certain temperature uniformity performances, the only available solution was the construction of two types of furnaces, each of them having a specific design and conception according to the working temperature.

In the present case, using a single heat recovery system for both furnaces has raised some challenges from the automation point of view which will be detailed and explained in this thesis.

The maintenance of systems as well as the auto diagnosis procedures have been incorporated into the management software system which is capable of taking automatic decisions regarding: safe operation, the possibility of the system running with a fault by automatically changing some parameters, undergoing maintenance operations, fault prevention, fault limiting actions, identifying faults before they occur, fault diagnosis using complex analysis methods of some measured parameters within the system.

Due to the increased market need for higher performance furnaces and as short as possible stop times caused by failures, there is a growing need for more reliable software implementation procedures with diagnosis purposes and managed preventive maintenance.

We will present methods and solutions for the thermal process control as well in these furnaces. The software implemented solutions aim to achieve a better temperature uniformity within the furnace, the possibility of choosing a more profitable hardware equipment from a cost control of initial investment perspective, the development of software control in order to achieve a universal temperature furnace suitable for both high and low temperature without the need of recirculation fans.

The goal of the research is the implementation of various monitoring and control methods which should overcome all challenges raised on accomplishing this new industrial furnace design.

1.3 Structure and Content of the Thesis

The present thesis has a structure comprised of 6 chapters:

Chapter 1 – Introduction
Chapter 2 – Present Situation
Chapter 3 - Presentation of the achieved electronic system
Chapter 4 - Diagnosis in automation and monitoring systems of industrial furnaces
Chapter 5 - Thermal process digital control systems for industrial furnaces
Chapter 6 – Achieved results
Chapter 7 - Conclusions. Personal contribution and developmental perspectives

In **Chapter 1** we present aspects regarding the evolution of automation systems over the last couple of years, the economic context which pushes the boundaries of technology toward achieving the lowest possible production costs, and the purpose of this study which is attaining an electronic control system which allows a more performant diagnosis and control of temperature together with other parameters in order to achieve a universal temperature furnace.

Chapter 2 showcases the present situation, present and usual methods used in this field.

Chapter 3 showcases the application as a whole in order to be able to understand all the aspects taken into consideration during design and accomplishment of the electronic control system. There is a brief description of the burning system structure, heat recovery system, measuring elements, actuating elements, power, automation and control system, SCADA system. The main technical specifications of the application are also described alongside with the system performances.

Chapter 4 presents the safety and auto diagnosis system of the application as well as the techniques involved.
In the first part of the chapter we showcase the security techniques given the inflammable gas handling. During the second part we present basic auto diagnosis techniques generally valid for any type of application and extended auto diagnosis techniques especially designed for the present application type. In the third part we depict the preventive monitoring and maintenance system which contributes greatly to cost reduction in maintenance and reduction of machine downtime.

Chapter 5 showcases the digital control system highlighting the inner temperature control system which made it possible to manufacture a furnace capable of maintaining temperature uniformity for both high and low temperatures without the need for recirculating fans. Within this chapter we show control techniques of the burners; these techniques enabled the achievement of this performance.
We also present various technical attributes of the control system in charge with the parameters of the main heat recovery system which services both furnaces.

Chapter 6 showcases achieved results from a double viewpoint: the diagnosis system and the control system. We submit measured results obtained in real-time working mode; these results are confirmed by tests in accordance to norms and technical regulations in effect such as: SAT, TUS, flue gas analysis reports, etc.

In **Chapter 7** we iterate the main conclusions of this implementation: the techno-economic advantage of this solution by eliminating the need for some expensive equipment in the general design stages, achieving performances which include these furnaces in the class 2 furnaces according to aviation standards, new design from the automation perspective which made it possible to manufacture some highly reliable universal temperature furnaces capable of uniformity performances at both high and low temperatures, thus contradicting the old premise according to which furnaces are designed according to temperature (high or low).

2. Present Situation

Currently, large capacity industrial furnaces used in the heavy industry for melting, forging, tempering, standard heat treatments, special heat treatments, etc. are not mass produced, but they are designed according to the technological process requirements specific to each individual factory, most of them being unique designs. For this reason replacement or upgrading process of these production units is an expensive and time-consuming enterprise which implies advanced knowledge in the field in order to improve their safety, efficiency and production.

In Romania there are furnaces operating for more than 50 years without having undergone any upgrading process, except for current maintenance works in order to ensure their functioning. These furnaces benefit from primitive adjustment and control methods, in the best case scenario they use discreet regulators and a relay logic. Safety features (flame supervision, tightness control, temperature protections, etc.) as well as system auto diagnosis are virtually inexistent. According to current norms and standards these furnaces shouldn't even be in operation; nevertheless the same norms and standards state that furnaces must be aligned with current safety requirements only when they undergo an upgrading process. As long as they work according to the initial project and norms they have the right to operate for an undetermined time period, so legally speaking their operation cannot be stopped even thought it can be life-threatening.

The main groups of heavy industry factories are beginning to reach the conclusion that in order to stay competitive on the international market, they are forced to upgrade the production process in order to increase performance, save energy, reduce flue gas emissions. Furthermore, even their clients have developed more and more restrictive audit procedures which cannot be catered for by an aging technology.

Following this trend the majority of factories which wanted to remain competitive started a large scale modernization process for existing machinery and also acquiring new and modern machinery. With this being said an opportunity emerged for furnace production companies to bring new innovations and methods in order to lower production losses.

The main players on the international furnace manufacturers' market are: Otto Junker – Germany, Ipsen – Germany, Aichelin – Germany, Loi Thermoprocess – Germany, Olivotto – Italy, Danieli – Italy, Cometal – Italy, Fergal – Italy, Seco/Warwick – Poland, Ebner – Austria, Codere – Switzerland, Elmetherm – France. Each of them is specialised on certain types of furnaces.

Form a working temperature viewpoint, furnaces are divided into 2 large categories: low temperature furnaces and high temperature furnaces which due to the thermal transfer taking place inside them (convection or radiation) have completely different project designs, used equipment and burning and temperature control methods. To that effect, the major different between low and high temperature furnaces is the fact that low temperature ones are equipped with recirculating fans in order to achieve temperature uniformity inside them. The current design model for these furnaces is manufacturing a low temperature furnace for low temperatures and a high temperature furnace for high temperatures even in situations where the technological process requires usage of both temperature holdings (low and high) within the same factory/division.

Furthermore, each of these furnaces uses a standard temperature adjustment control which is either a continuous control, or an On-Off control; they also use standard air/gas ratio control methods for the burners either via mechanical ratio controllers, or via electronic flow.

Diagnosis methods generally used belong to primary diagnosis that is the fault is signalled to the operators the moment it occurs; there are no pattern analysis methods of certain values, logic analysis of several parameters within the system, preventive maintenance methods, all of which are integrated in the system further presented in this thesis.

From an energy saving and exhaust heat recuperation point of view, generally, each furnace is designed with its own heat exchanger, by contrast with the system presented within this thesis.

3. Presentation of the Achieved Electronic System

It refers to the electronic system implemented at Zirom SA Company and designed by SC. Electro-Total SRL in order to achieve automation of 2 gas fired forging industrial furnaces for titanium bars with a common heat recovery system.

Technical specifications:

Inner work space: 3000x2000x5000mm
Insulation: ceramic fibre
Power: 2.5 MW /furnace
Maximum temperature: 1300 °C
Maximum temperature of preheated air: 400 °C
Nominal capacity: 15 t /furnace
Temperature control zones: 2 per furnace
Number of burners: 8 per furnace (4 per zone)
Temperature rise: max. 150 °C/h, min. 20 °C/h
Average gas consumption: 90 Nm3/h /furnace
Average electrical power consumption: 22.5 kWh /furnace
Monitoring and control system level 1: PLC
Monitoring and control by the operator level 2: SCADA system

The burning system comprises of 8 burners on each furnace separated in 2 temperature adjustment zones (4 burners/zone), zone 1 covers the front side of the furnace, zone 2 the backside. Considering the chamber type furnace configuration with trap door on the front and flue gas exhaustion at the back, we opted for this specific configuration in order to achieve a better temperature uniformity within the internal volume of the furnace.

The burners are impulse burners with flat flame and high gas speed. Their flame enters max. 20cm inside the furnace and it takes a petal-shape form which develops on the embrasure. In this way, the material inside the furnace (titanium) never enters into direct contact with the flame, thus avoiding undesired chemical reactions. Furthermore, thanks to flame development on a large radiant surface, we achieve a better temperature uniformity inside the furnace.

On the common route of the flue gasses we installed a heat exchanger in charge of preheating the combustion air via the heat exchange with the flue gasses, thus saving the methane gas.

The automation system comprises of:

1. Power cabinet
2. Automation control cabinet with PLC and HMI
3. Actuating elements
4. Measurement elements
5. PLC system
6. SCADA system

3.1 Power Cabinet

The power cabinet consists of:

- General switch
- Motor protection switches
- Control contactors
- Variable frequency drive 55kW
- Energy analyser
- Lights, buttons, switches, horn

3.2 Automation and Control Cabinet

The automation and control cabinet consists of:

- General switch
- Power supply protection switches
- Control contactors
- PLC
- HMI
- Lights, buttons, switches, horn

3.3 Actuating Elements

Actuating and control elements on each furnace:

- Combustion air fan with a star-delta starter
- Exhaustion fan powered by a variable frequency drive
- Flue gas dilution fan
- General gas 1 electro valve
- General gas 2 electro valve
- Exhaust gas electro valve
- Bypass gas electro valve
- Double electro valves for burners 1,2,3,4,5,6,7,8
- Gas motorised butterfly valve zone 1
- Gas motorised butterfly valve zone 2
- Air motorised butterfly valve zone 1
- Air motorised butterfly valve zone 2
- Flue gas motorised butterfly valve
- Air dilution motorised butterfly valve 1
- Air dilution motorised butterfly valve 2
- Hot air exhaust motorised butterfly valve
- BCU burners 1,2,3,4,5,6,7,8

3.4 Measuring Elements

Measuring and monitoring elements on the furnace:

- Temperature thermocouple zone 1
- Temperature thermocouple zone 2
- Temperature thermocouple for furnace protection
- Gas temperature thermocouple (dilution 1)
- Temperature thermocouple 1 for heat exchanger protection
- Temperature thermocouple 2 for heat exchanger protection
- Air combustion temperature thermocouple – heat exchanger outlet
- Flue gas temperature thermocouple (dilution 2)
- Pressure gauge on the furnace
- Methane gas flowmeter zone 1
- Methane gas flowmeter zone 2
- Combustion air flowmeter zone 1
- Combustion air flowmeter zone 2
- Thermocouple temperature on item contact
- Gas analyser – flue gas O_2 concentration
- Gas analyser – flue gas CO concentration
- Minimal gas pressure controller
- Maximal gas pressure controller
- Pressure controller – tightness test
- Compressed air pressure controller
- BCU burners 1,2,3,4,5,6,7,8
- Methane gas meter
- Energy analyser

3.5 PLC System

The PLC program is designed in ladder and structured text language depending on the complexity of the performed routines. Generally, ladder language is used for logical sequences (start, stop, conditions, etc.), whereas structured text is used for math operations (if, for, while, etc.)

The HMI panel is used for local monitoring and control of the furnace from the automation cabinet located near the furnace

PLC configuration:

- Motherboard 1
- Motherboard 2
- Processor
- Ethernet Module
- RS485 Module
- Module 16 analogue inputs 4-20mA x 2
- Module 8 analogue inputs 4-20mA x 1
- Module 8 analogue outputs 4-20mA x 3
- Module 16 digital inputs x 8
- Module 16 transistor digital outputs x 4

3.6 SCADA System

The SCADA system is composed of 2 computers operating on redundant basis.
The system is used for viewing, controlling, monitoring, diagnosis, storage and analysis of the data, and it was designed in Visual Studio.

4. Diagnosis in Automation and Monitoring Systems of Industrial Furnaces

Taking in consideration the current industrial economic context which puts high pressure on production efficiency and lowering production costs, one of the most important points in this process is avoiding production losses and maintaining a high availability of machinery. By implementing an automatic modern monitoring system of diagnosis and maintenance, we greatly reduce the machine downtime and the maintenance intervention time by prescribing the operations to be undertaken by the service team. In this way we avoid altering the production flux and we drastically cut the specific cost of the finite products.

4.1 Diagnosis Procedures and Safety Functions

4.1.1 Double Tightness Test for the Main and Secondary Gas Trains of the Burner

Gas train tightness test is a safety and diagnose feature. It is performed each time the furnace starts after a standstill period and it is compulsory for combustion systems with a power higher than 1200 kW according to EN 746-2:2010.
Double tightness test is subdivided into 2 tests:

- First test determines if either of the main gas valves have leakages
- Second test determines if either of the burner valves have leakages

The main risk with faulty motorised butterfly valves is gas accumulation in the furnace chamber which can lead to massive explosions on ignition of the burners.
As a safety measure, this test is automatically performed by the PLC software during the start-up phase of the furnace. If it fails, the furnace enters into lockdown mode which prohibits the starting of the burners.

Logical sequence of the 2 tests:

- First test between V1 and V2 main valves
- Test OK -> carry on ; Test Fail -> lockdown
- V2 = open
- Second test between V1 and burner valves
- Test OK -> carry on ; Test Fail -> lockdown

Pmax = maximum supplied gas pressure
Pt = test pressure (for equal sensitivity transition from 0->Pmax or Pmax ->0 Pt=Pmax/2)
V1 = main motorized butterfly valve 1
V2 = main motorized butterfly valve 2
Tfill = necessary time for gas filling the pipe between V1 and V2
Tmeasure = waiting time for pressure changes

The PLC tightness test program is written in ladder diagram mainly due to the use of logical sequence.

It mainly uses logic chains of conditions, timer functions, arithmetic operations, functions, different types of conversions and memory set and reset, pulse transitions, etc. in order to run all the steps mentioned in the logical diagram

Inputs for tightness test routine:

- Pressure controller signal – confirms pressure existence between the points where the test is carried out
- Reset command – restarts the test if previous test fails
- Start command – start the test
- Filling time – the required time for gas filling the pipe section to be tested
- Test time – the required time to detect pressure drops

Outputs for tightness test routine:

- Command for motorised butterfly valve 1
- Command for motorised butterfly valve 2
- Tightness fault signal at valve 1
- Tightness fault signal at valve 2
- Ok signal valve 1
- Ok signal valve 2
- Command fault signal at valve 1
- Command fault signal at valve 2
- Test running signal for valve 1
- Test running signal for valve 2
- Test first step signal
- Test second step signal
- Test third step signal
- Test remaining time

To sum up, by performing this test before furnace start-up, we eliminate the risk of explosion caused by gas accumulation inside the furnace as a result of faulty tightness in the motorised butterfly valves on the gas. This test is compulsory according to the directives in effect and it ensures a safe operation.

4.1.2 Furnace Pre-ventilation

Furnace pre-ventilation is a safety feature (the last one in the safety chain) that can prevent an explosion due to gas accumulation inside the furnace. Pre-ventilation is carried out before each start-up as a last resort in preventing situations which are not covered by the other safety measures. For example, a furnace has registered a tightness fault on the gas valves after a long standstill period. This fault has led to gas accumulation inside the furnace. The fault was identified during the tightness test

causing the automation system to lockdown the furnace. The service team has identified and remedied the fault and then attempted restart. At this point, the furnace would pass the tightness test once the valves have been fixed, but there is still a gas accumulation inside from the previous failure.
In this case, pre-ventilation would wash the interior of the furnace with air, exhausting the methane gas through the stack. According to EN 746-2:2010 standard, the atmosphere inside the furnace must be altered minimum 3 times before start. In order to determine pre-ventilation time, the determined interior volume figure of the furnace is divided by the maximum air flow of the combustion air fan.

$$T_{pre\text{-}ventilation} = 3 \text{ x } V_{int.\ furnace} / Q_{max\ VAC}$$

Pre-ventilation sequence:

- Ventilation of minimal combustion air pressure controller
- Maximum opening of the combustion air valves on the burners
- Maximum opening of the flue gas exhaust valves
- Fan maximum speed
- Pre-ventilation time waiting

Pre-ventilation in performed simultaneously with the tightness test and is integral part of the safety lockdown protocol of the furnace.

4.1.3 Burner Start-up and Flame Supervision

Furnace gas burners are ignited by a spark electrode and supervised by an ionization electrode or an UV sensor depending on the output power of the burner.

The flame supervision in gas fired furnaces is a safety condition especially when the furnace is operating bellow the methane gas auto ignition temperature. During this type of operation flame supervision is mandatory. Flame supervision eliminates the danger of gas pocket accumulation inside the furnace chamber which can lead to explosions.

Bellow it is shown a logical diagram of the burner supervision routine which achieves the following:

1. Safety lock chain verification in furnace start-up before this step
   - Safety lock if a previous operation of the safety chain failed during start-up
2. Check for flame presence without start command
   - Possible valve tightness fault
   - Possible flame detection fault
   - Possible relay command fault
   - Possible cables fault
3. Start sequence of the burner
   - Open gas valve
   - Turn on spark ignition for a predetermined time
   - Check for flame presence
4. Operator independent auto restart sequence management
   - The automation is allowed to execute a maximum of 3 unsupervised burner ignition attempts after a flame failure during a 90 min period of time
   - If there are more than 3 flame failures during a 90 min time period all without successful re-ignition, the automation activates the safety lock
   - After a successful re-ignition due to flame fault and after every 30 minutes period of continuous operation without flame fault the automation increments +1 the allowed auto restart tries value to a maximum limit of 3
   - After carrying-out all the auto restart tries the automation activates the safety lock
   - After safety lock activation the automation permits a maximum number of 10 supervised manual restart tries before activating the whole safety lock chain

5. Flame fault management
   - Close gas motorized butterfly valve
   - Safety lock activation
   - Fault signaling

4.1.4 Fault Detection on Temperature Measurement

The temperature measuring system mainly consists of thermocouples mounted in different areas of the furnace chamber according to the number of control zones, flue gas piping areas (in/out heat recovery system, air dilution), combustion air piping areas (preheated air temperature), etc.

The thermocouples output signals (mV) are locally converted by an mV to 4-20mA converter and sent to the PLC.

Temperature fault detection methods:

4.1.4.1 Internal Loop of a Thermocouple is Open

If the internal loop of the thermocouple opens the 4-20mA converter will send the full 20mA current signal to the PLC thus engaging the high temperature alarm

4.1.4.2 Open Loop 4-20mA between the PLC and Convertor

The 4-20mA signal is scalable to the temperature domain of the thermocouple, 4mA->min domain value, 20mA-> max domain value.

If the 4-20mA loop opens, the current signal will drop to 0mA thus triggering a PLC alarm of open loop.

4.1.4.3 Control and Protection Thermocouples

The interior furnaces chamber is equipped with 1 thermocouple/control zone and 1 protection thermocouple for the whole chamber.

The protection thermocouple is used for over temperature protection in case control thermocouples mall function; it has a safety loop PLC trigger to emergency shut down the furnace

4.1.4.4 Redundant Thermocouples

There are certain areas of measurement points which are critical regarding high cost equipment protection or critical technological process values.

For example, the input temperature of the heat exchanger (heat recovery system) is equipped with 2 thermocouples for measuring the same value. The PLC software permanently monitors the measurement difference between the 2 and if it exceeds a certain value it triggers an alarm. The input temperature control of the heat exchanger (heat recovery system) is very important to be maintained within the built material limits in order not to damage it.

The value taken in consideration is the worst one between the 2 values in terms of safe further processing.

In other cases when using 2-point redundancy the value taken in consideration is determined by plausible values when possible according to Art. 3.2.

There are also cases when we use a 3-point redundancy and the value taken in consideration for further processing is the average value from the 2 points which have the closest values. This method is rarely used because of cost effectiveness low ratio, but can be demanded in very specific cases when the outcome can prevent major failures or technological losses.

4.1.4.5 Alarms Logic and Scaling Routine of the Measured Values in the PLC

The purpose of this PLC routine is to incorporate all the processing sequences of the analogic values acquired from the field of sensors. Every analogic value of the furnace is passed through this software routine.

The routine achieves the following:

- Scaling the value acquired by the PLC A/D converter to engineering values
- Filtering any jitter and outputting a stable value
- Alarm and fault management by predetermined values and delays
- Resetting and acknowledging an alarm/fault
- Option for only scaling values without alarm management
- Output value for establishing current state of alarm/fault transmitted to level 2 SCADA system
- Status value – for internal routine diagnosis used only for software troubleshooting by the software engineer

The routine is written in structured text code and assembled as a functional block with input and outputs. The routine is called by the software for each individual analogic value at every program scan cycle and it has input/output parameters assigned for each individual analogic value.

The parameters are determined according to equipment safely limits, process safety limits or technological process limits and they are usually adjusted during the commissioning phase of the project and can be readjusted from level 2 SCADA whenever needed.

4.2 Preventive Maintenance Procedures and Functions

4.2.1 Alarm Recurring Frequency

Alarm frequency recurrence is a diagnosis method used for preventive maintenance. The PLC routine detects when a certain alarm frequency is starting to exceed the average occurrence frequency of the past days/month depending on the routine setup.

For example, it is quite common in gas fired furnaces to have a few burner flame faults during a 24-hour working time, but when this frequency occurrence is starting to rise, this could signal an abnormal functioning and the forming of a much greater defect in the burner system itself.

After identifying the rise of an alarm frequency occurrence, the PLC will signal this event using a specific alarm which alerts the maintenance department.

The main advantage of this function is that the system can be maintained/repaired before a full system malfunction/shutdown occurs that disturbs the production flow and causes production losses.

4.2.2 Logic Comparison and Plausible Values in Various Temperature Measuring Points

Throughout the whole route of the flue gases and air combustion piping inside the furnace the PLC continuously compares different measurement values in key points of the furnace in order to determine if certain values are plausible or if they signal a possible fault in one of the measures or in the system itself.

A simple example would be the comparison between the input and the output flue gas temperature of the heat exchanger (heat recovery system). In this instance the input temperature value should always be much higher than the output value. If the measurements are not as described above this could indicate a possible fault. The automation system signals through an alarm a discrepancy measure value in this part of the furnace which should be inspected.

If temperature measurements mentioned above are correct, the discrepancy could signal for instance clogging of the heat exchanger, damage to transfer convective piping, etc.

Occurrence of these improbable values in various points indicates for certain a failure in that zone of the system. That zone should be without a doubt inspected by the maintenance personnel regardless of the real cause of the fault.

Thus, the diagnosis system has alerted the maintenance department with regard to a problem on the furnace even though none of the acquisitioned measurement values has reached the alarm/fault threshold.

4.2.3 Value Decrease/Increase Pattern

The classic alarm routine of an analogic measured value from the field of sensors consists of an alarm value of the measure, fault value of the measure, hysteresis value, minimum trigger occurrence time and others. This way the abnormal functioning is detected when it occurs.

The analysis of the pattern means the automation system can calculate based on past data base values if a measured value tends to increase or decrease to the alarm/fault value and roughly calculate when it will hit these values.

For example, all the large fans in this furnace (air combustion fan and flue gas fan) are monitored through vibration sensors. When the automation system detects an increase pattern of the vibration values it calculates and signals the possible date/time when these values will exceed the alarm/fault values. This way the maintenance department can organize and schedule its maintenance for replacing the fan bearings, cleaning the fan and dynamic balancing of the fan.

The main advantage of this technique is that an alarm/fault will not take the maintenance department by surprise but it can be prevented from occurring in the first place. This translates into better availability figures for the furnace.

4.2.4 Scheduled Maintenance Monitoring

Scheduled maintenance is the part of the automation system which monitors all the equipment and maintenance operations which are to be done.

Usually all equipment has scheduled maintenance operations described in the technical manual; they are introduced in the SCADA software.

The automation systems monitor the operating hours/time from last maintenance and alerts the operator with a predetermined time in advance that some maintenance operations should be done.

All maintenance operations are thoroughly registered in SCADA database system resulting in an excellent traceability of maintenance works.

5. Digital Control Systems for Thermal Process in Industrial Furnaces

Gas fired heat treatment/forging furnaces have evolved over time. These types of furnaces are generally divided in 2 categories: high temperature furnaces and low temperature furnaces, both categories are designed with specific hardware and software control according to the type of heat transfer.

One of the most important performance parameters is the temperature uniformity inside the furnace chamber which has to be maintained in a specific range according to the utilization of the furnace.

Heat transfer for low temperature furnaces (at temperatures below 500°C heat transfer is exclusively achieved via convection, in the temperature range of 500-800°C heat transfer input through radiation increases with the temperature value to the third power) is mainly achieved by convective transfer. In order to achieve good uniformity results inside the chamber there is a need for installing recirculation fans in order to mix the furnace atmosphere.

Heat transfer for high temperature furnace (at temperatures above 800°C heat transfer input through radiation greatly exceeds the one through convection, rendering it negligible) is mainly achieved by radiation transfer. Due to radiation heat transfer there is no need for recirculation fans in order to achieve good uniformity results.

The main challenge is to design and build a universal furnace that can deliver both good uniformity results in low and high temperature. The main problem in this case is that the recirculation fans which work very well in low temperatures are prone to failure in high temperature and have a very high acquisition and maintenance cost.

Other challenges of the adjustment system were: a very stable air/gas ratio on the burner, using and controlling the working parameters of a single heat exchanger designed for both furnaces, precise temperature control inside the oven.

5.1 Technological Performance Demands for Furnaces

The technological demands were:

- ±5°C temperature uniformity for both 650°C and 1250°C temperature holding
- a very accurate control of burner air/gas ratio in order to obtain a slightly reduction atmosphere in the furnace chamber (oxidizing atmosphere is prone to develop unwanted chemical reactions in the titan bars)
- using and controlling a single heat recovery system for both furnaces for better gas consumption efficiency and cost reduction of initial investment

5.2 Solution for Maintaining the Demanded Temperature Uniformity for both Low and High Temperature without Recirculation Fans

The furnace was equipped with high velocity flat flame burners without furnace atmosphere recirculation fans. This hardware configuration represented a challenge regarding the temperature and burner control in order to achieve good uniformity results.

5.2.1 Alternating Control Types on the Burners

Each furnace has 2 temperature control zones (front and back), each zone being serviced by 4 burners.

The temperature control is implemented with software PID controllers using 3 types of control:

- continuous control for high power demands
- burner alternation on-off subzone control for low power demands with 4 ignited burners (2 for each zone)
- full on-off control for very low power demands

The advantage of changing the control type during operation is that regardless of the temperature inside the furnace the temperature uniformity can be maintained in the desired limits especially at low furnace temperature where the heat transfer is mainly convective. Using short bursts of high-power ignition burner periods achieves a very good result in mixing the furnace atmosphere by the high velocity of burner flue gases.

The furnace power domain output of the PID temperature control is divided in 3 ranges:

- 0-10% output – full on off control
- 10-25% output – subzone alternation control
- 25-100% output – continuous control

The full on-off control means that all of the furnace burners are ignited for the ON time period and turned off for the OFF-time period.

The ON time and OFF time are established by a pointer which glides through the time base accordingly to the PID output which sets a greater ON time or a greater OFF time.

The subzone alternation control works in the same manner as the ON-OFF control but the main difference consists in the fact that the pointer controls the variable time when the burners will changeover.

The continuous control works with all the burners ignited and the temperature is controlled by modifying the zone burner's power by adjusting the flow of methane gas and air.

The implementation of subzone alternation and on-off control was necessary both for temperature uniformity and temperature accuracy as follows:

- temperature uniformity at low power demands and temperature holding is improved by short bursts of high-power flame from the burners which will result in mases of air movement. These mases of air movement will improve the convective heat transfer thus resulting in a better temperature uniformity
- generally, all burners have a minimum constructive operating power for which they can maintain a stable flame without flame failure. If the necessary power demand in order to maintain the desired furnace temperature is below the minimum burner constructive power the temperature will continue to increase above the desired temperature when using continuous control. Therefore, by using subzone alternation and on-off control the temperature accuracy is improved especially at low temperatures but also at holding high temperatures once the furnace reaches a constant working mode.

5.2.2 PID Parameter Alteration during Operation

The thermal response of the furnace (thermal inertia) is different when operating in low temperatures (convection heat transfer) then operating in high temperatures (radiation heat transfer).

In order to further optimize the temperature control accuracy, we implemented 3 sets of PID parameters (Kp, Ki, Kd) as follows:

- first set for low temperatures (convection heat transfer)
- second set for borderline temperatures
- third set for high temperatures (radiation heat transfer)

The automation system will automatically switch between the 3 sets of PID parameters according to the furnace temperature therefore achieving a more precise control adjusted to the furnace needs.

When there is a need for an even more precise control there is also an option for measuring and controlling the temperature directly on the material that is being heated by a contact thermocouple and an additional PID that will cascade the PID atmosphere. This option can be activated or deactivated by the furnace operator in the SCADA system.

5.3 Solution for Maintaining an Accurate Control of the Burner Air/Gas Ratio

For controlling the burner air/gas ratio, a flow measurement and a motorised valve are installed on each control zone (2 per furnace) both for air and gas.

Moreover, considering that the furnaces are equipped with a heat recovery system, the air combustion temperature is measured in order to compensate the air density and calculate the equivalent air volume regardless of its temperature. This is a necessary measure in order to maintain a correct ratio between the number of oxygen molecules and the air debit introduced in the burner.

An oxygen sensor is installed on the flue gas pipe in order to measure the precise O_2 concentration in the flue gases and marginally adjust the air gas ratio value.

This translates into a two-stage air/gas ratio control. The first and primary stage of control is based on the measured flow of the air and gas that enters the burners and is maintained at a stoichiometric ratio of 1 to 10. Furthermore, the information of the O_2 concentration of the flue gases is processed by the O_2 PID (secondary stage control) which can fine adjust the desired ratio (the air SV PID) in a restricted interval from 1/8 to 1/12 for safety reasons. Generally, the desired O_2 concentration in the flue gases should be anywhere from 1% to 3%. Using this method, we obtained a more precise air gas ratio control which is capable of compensating any flow measurement errors in order to obtain a better control.

Taking in consideration that the worst-case scenario is having an oxidizing atmosphere which can cause some unwanted chemical reactions in the titan bars, we opted for a cascaded PID controller with the master loop command on the gas valve. Using this method, the master temperature PID commands the burners' gas flow and the slave PID commands the burners' air flow. This method known as "the air follows the gas" reduces the risk of having excess oxygen in the furnace.

Considering the fact that the gas and air control of the burners is simultaneous adjusted on the whole zone consisting of 4 burners with only 1 execution element (1 motorized valve for air and 1 for gas), the automation system also has a specific routine that will take in account the number of active burners in order to readjust the air flow.

For example, if one burner is malfunctioning, it will be switched off resulting in the fact that all the measured gas flow that was distributed evenly through the 4 burners is now distributed to only 3 of them resulting in a 33% increase of gas flow per burner. However, in the same time the air flow remains at the same flow level because only the burner gas has a shutoff valve. This behaviour will lead to an incorrect air/gas ratio. In order to correct this massive error, the automation will compensate the air flow calculation according to the number of burners that are online, thus increasing the airflow to the remaining burners by the proportion between all the existing burners and the online ones. Following this adjustment, the air/gas ratio of each individual functioning burner will be sufficient in order to obtain a satisfying flame stability. Taking in consideration that the burner that is malfunctioning will still inject air in the furnace, the overall furnace chamber atmosphere will be altered. For sorting this matter the oxygen sensor will detect an increase in its O_2 level that will be sent to the O_2 PID which will readjust the desired overall air/gas ratio of all the burners resulting in a correct atmosphere in the furnace chamber.

As we can see here this is another advantage of using the secondary stage control for the air/gas ratio using the O_2 and cascaded O_2 PID.

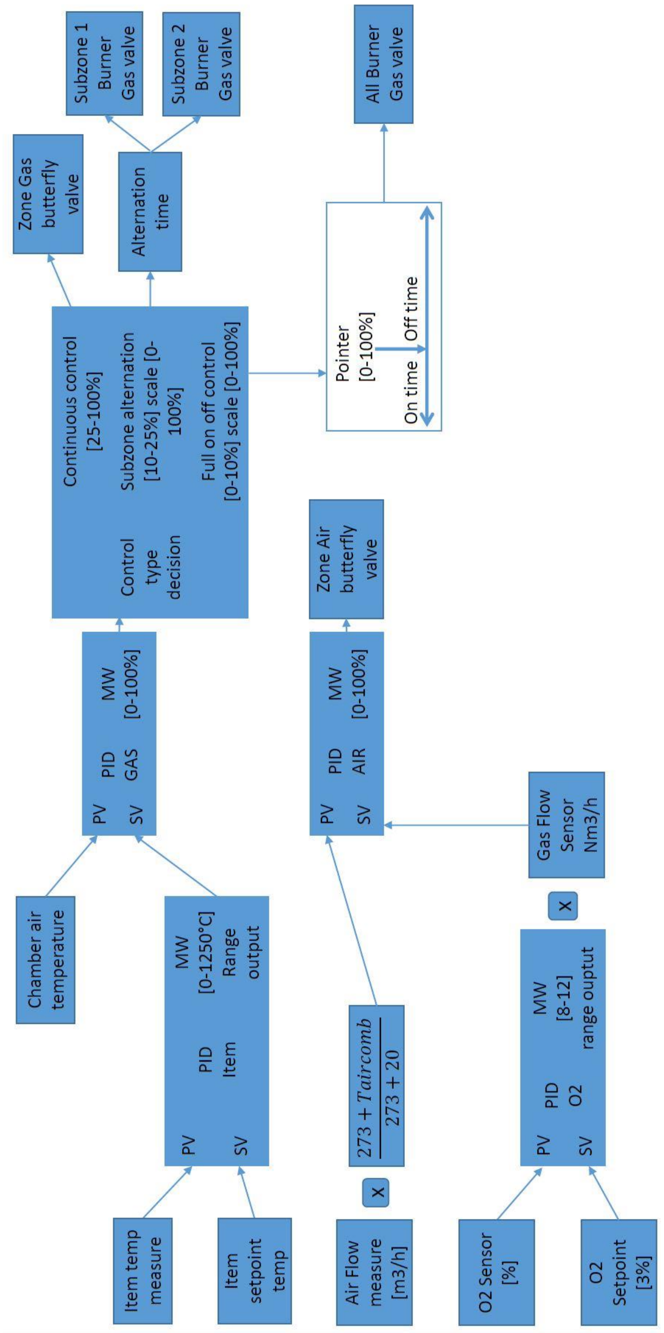

Fig 1. Logical diagram for controlling the temperature

5.4 Solution for Controlling the Inside Pressure of the Furnace Chamber for Both Furnaces with Only 1 Exhaust Fan

The flue gas piping execution elements are:

- butterfly valves at each furnace exhaust
- central exhaust fan equipped with a variable frequency drive mounted after the common central heat recovery system

The furnace pressure monitoring elements are:

- differential pressure sensors for each furnace (between chamber pressure and atmosphere pressure)

Regulating the inside chamber pressure, it is very important for it to be maintained to a slightly positive value (1-2mbar). Taking in consideration the fact that a furnace chamber cannot be totally tight, this control is necessary in order to eliminate any infiltrations of false air in the furnace chamber or any furnace atmosphere leaks outside the chamber through any chamber tightness defect. These leaks can occur depending on the excessive negative or positive value of the pressure.

The negative effects of false air infiltration (excessive negative pressure) are incorrect furnace atmosphere (excess O_2 resulting in an oxidizing atmosphere) and excessive gas consumption resulted from the unnecessary heating of the infiltrated air.

The negative effects of atmosphere leaks (excessive positive pressure) outside the furnace are human poisoning with CO which is life-threatening.

Taking in consideration the unique design of these furnaces with a central common heat recovery device and exhaust fan, the technical difficulty is implementing a control system that uses 2 measurement elements with 3 execution elements which have to work both individually and together.

The solution is the following:

- PID controller for furnace 1 pressure:
  PV1 = pressure sensor 1
  SV1 = desired pressure for furnace 1
  MW1 = butterfly valve 1

- PID controller for furnace 2 pressure:
  PV2 = pressure sensor 2
  SV2 = desired pressure for furnace 2
  MW2 = butterfly valve 2

- PID controller for central exhaust fan:
  PV = MAX (MW 1, MW 2)
  SV = 80%
  MW = exhaust fan speed

Using this 3 PID configuration will result in the following operating mode:

When the pressure for furnace 1 is exceeding the desired set value the furnace 1 pressure PID will increase the opening of the butterfly valve. If the effect on the inside pressure is not satisfactory until 80% opening, beyond this value the PID for the exhaust fan will start increasing the fan speed in order to keep the response of the furnace 1 pressure PID below 80%. Presuming that furnace 2 pressure was in a steady state operation before this pressure alteration on the common exhaust pipe, the result is decreasing the pressure in furnace 2 chamber. Following this pressure modification, the furnace 2 pressure PID will decrease the opening of the butterfly valve 2 in order to keep the pressure in the desired limit.

The 80% set value of exhaust fan PID represents the point in which the PID pressure butterfly valves of each furnace signal the PID exhaust fans that they need a greater negative pressure on the common flue gas exhaust piping in order to cope with the desired value of the furnace pressure.
The fixed 80% value was chosen in accordance with the specific flow curve of any butterfly valve. The butterfly valves have a specific “S” type nonlinear opening/flow curve which means that at an opening greater than 80%, it results in a smaller increase of the flow. For this reason when the butterfly valve reaches the opening point in which the effects on increasing the flow become minimal, the exhaust fan will increase its speed in order to help the PID pressure of the furnace.

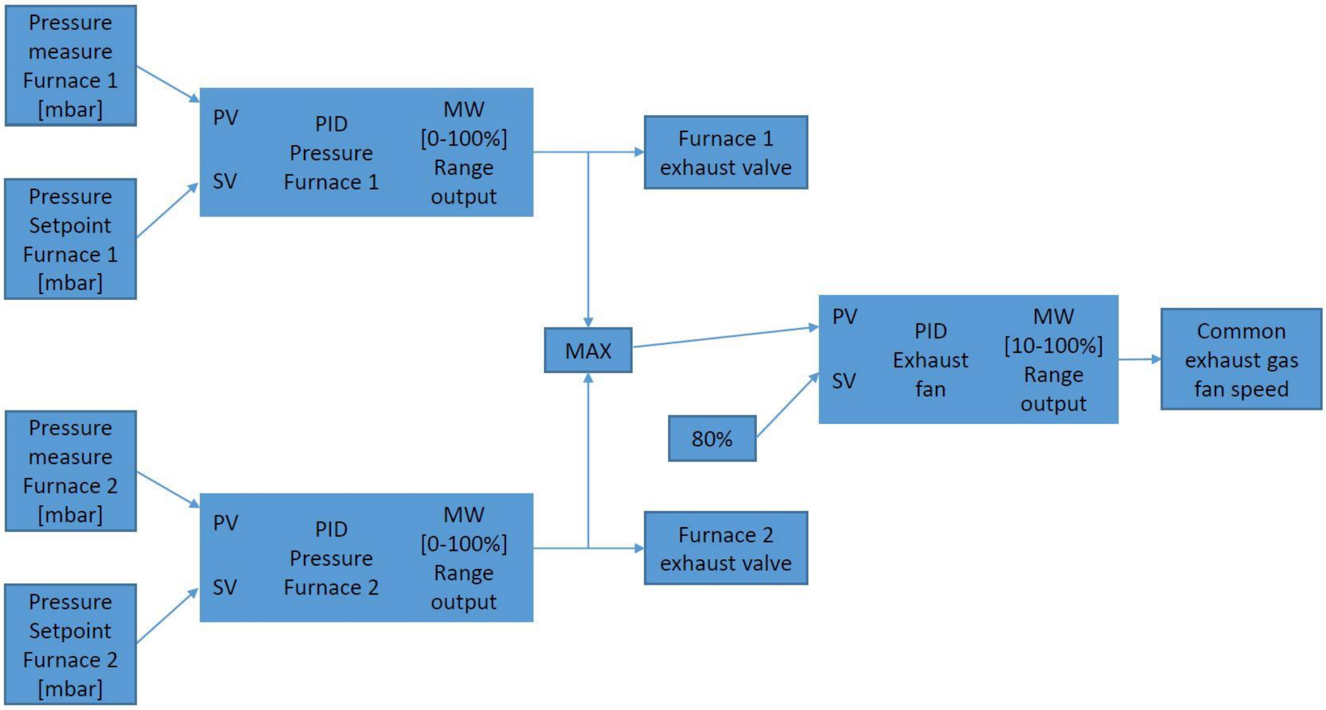

Fig 2. Logical diagram for controlling the inside pressure of both furnaces

6. Obtained Results

Working the task at hand, the author has designed, implemented, tested and commissioned the diagnosis and control systems integrated into the overall project. The innovating elements have been published in articles of relevant literature.

6.1 Advantage for Using the Implemented Diagnosis Procedures

Results of this implementation are:

- Increased production availability
- Automatic fault detection within the system
- Better and more rationalized inventory of maintenance operation
- Higher percentage of concluded scheduled maintenance operations
- Traceability of maintenance works
- Traceability of faults and failures
- Cost reduction of finite product and specific energy saving
- Cost improvement of maintenance works due to an early problem detection
- Fewer unscheduled stops of the furnaces as a result of unanticipated failures

6.2 Maintaining Temperature Uniformity inside the Furnace

In order to confirm the temperature uniformity inside the furnace the TUS test is performed (temperature uniformity survey).

The regulating standard AMS 2750 for the TUS test states that in accordance with the usable volume inside the furnace and its graded class a certain number of measurement points should be determined and positioned inside the chamber. In our case, we required a frame with 12 thermocouples to be disposed evenly and introduced inside the chamber volume.

Temperature uniformity is the difference between the values of the hottest and the coolest points within the 12-thermocouple frame.

Temperature uniformity inside the chamber furnace of ±5 °C according to the TUS test

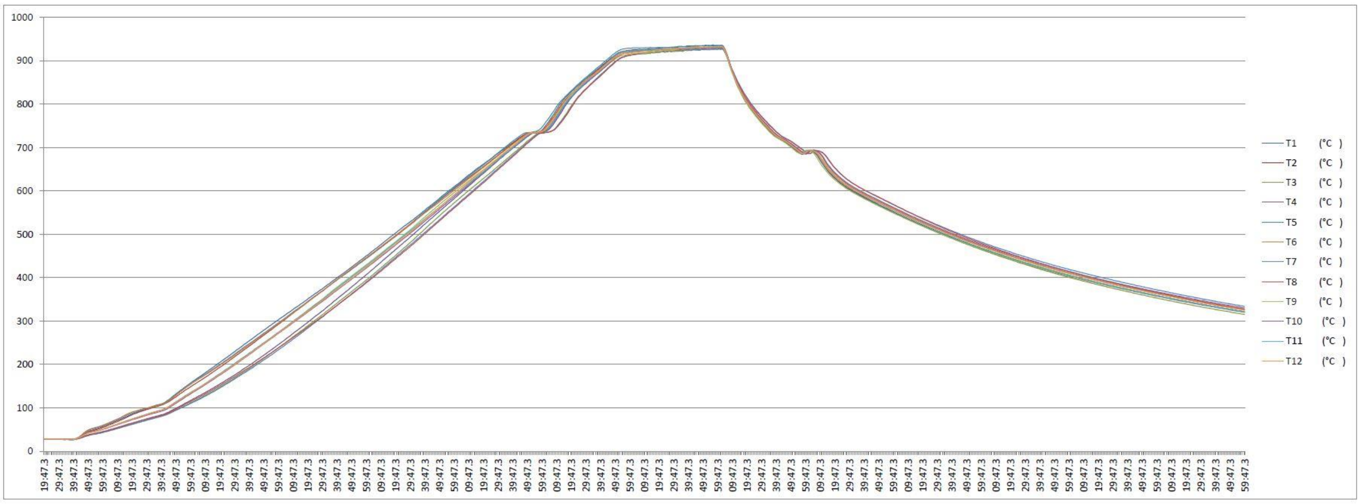

Fig 3. shows the graphic of temperatures evolution for all the 12 thermocouples during the TUS test.

6.3 Temperature Holding for Both Low and High Temperatures

We achieved a stable temperature holding both at low and high temperatures (650°C and 1250°C).

Fig 4. Temperature holding at 650°C and 1250°C

The achieved temperature uniformity is remarkable taking into account that it applies to both low and high temperature within a furnace with no recirculation fans. These results were enabled by the advanced control system regulating the burners and the burning process.

6.4 Temperature Accuracy Regulation

In order to confirm temperature accuracy a SAT test (system accuracy test) was performed.

The temperature accuracy achieved is of: ±1.5°C

6.5 Lowering the NOx Emissions

The reference regulations regarding the NOx content within exhaust flue gases is the PT A1-2010 technical prescription which states the following admissible maximum values:

NOx = max 350 mg/Nmc
CO = 100 mg/Nmc

Following a correct analysis of the flue gases using a calibrated CHEMIST 600X gas analyser we obtained the following average values:

CO = 34 mg/Nmc (maximum CO level according to UE regulations is: 100 mg/Nmc normalized at 3% O_2)
NOx = 113 mg/Nmc (maximum NOx level according to UE regulations is: 350 mg/Nmc normalized at 3% O_2)

In appendix 4 we present the rest of the analysis reports of flue gases which have been checked and validated by an authorised company.

6.6 Atmosphere Type inside the Furnace

Following a correct analysis of the flue gases using a calibrated gas analyser we obtained the following values:

O_2 = 1.7%
λ = 1.08

It can be well noted that the atmosphere inside the furnace is very slightly oxidizing.

7. Conclusions. Personal Contribution and Developmental Perspectives

7.1 Conclusions

7.1.1 Preventive Diagnosis and Maintenance System

Diagnosis and maintenance procedures implemented within the software can be classified in:

- Basic maintenance procedures are usual procedures that can be implemented regardless of the application type (ex: open loop detection, measured value increase beyond safety limit, etc.). Using this type of procedure, we can identify mainly the faulty equipment on the installation.
- Extended diagnosis implies specific procedures custom designed to the particular features of each and every application (ex: logic comparison of plausible values, pattern analysis, etc.). Using these types of procedures, we can identify faulty equipment and also more complex problems like inadequate automation response to system feedback, PID loop parameters out of tune, etc.

- Preventive maintenance can identify faults that are about to happen, equipment that is prone to malfunction, and also keep track and signal scheduled maintenance operations for each individual equipment according to the manufacturer maintenance program.

7.1.2 Automation and Control System

- The achieved temperature uniformity of ±5°C according to the TUS test is compliant with the international aviation standards for temperature control in titan forging class 2 furnaces AMS 2750D and AMS H81200. This performance is obtained both for 650°C and 1250°C temperature holding without the need of recirculation fans due to the advanced temperature control system implemented in the PLC.
- The achieved temperature regulation accuracy at very low temperatures and power demands of ±1.5°C according to the SAT test is compliant with aviation standards for class 2 furnaces AMS 2750D.
- Eliminating the atmosphere recirculation fans achieves a reduction in the initial investment cost and a better reliability of the entire system.
- The precise control of the O2 concentration in the furnace atmosphere is obtained by introducing a flue gas analyser value in the control loop which can precisely adjust the air gas ratio resulted from the flow ratio control, thus managing to obtain the correct furnace atmosphere in relation to titan forging.
- The use of one heat recovery system for both furnaces was made possible by the advanced control software routines previously presented which lead to a reduction of initial investment costs of the overall project and a better fuel economy.

The overall conclusion of this project is that the use of advanced software routines made it possible to design and build a furnace that is able to maintain a holding temperature within the aviation standards for both high and low temperature regimes without the need for recirculation fans.
Till now furnaces were built to answer specific temperature holding regimes (specific design for low temperature and specific design for high). If a factory needed both high and low temperature regimes with a specific temperature uniformity the only solution was to build 2 types of furnaces that would answer the specific demands of each individual process.

The constructed furnaces presented in this thesis can be considered universal furnaces for both high and low temperature, in contrast to the way furnaces were built in the past.

7.2 Personal contribution

In elaborating the doctoral thesis, the author values his personal contribution to be innovative from both a conceptual and practical perspective:

- Design of the diagnosis and control system

The stepping stone in designing the diagnosis and control system was the initial performance demands of the system. This played an essential role in tossing aside the old and elaborating and adopting a new technical solution both on a hardware (mechanical, electric) and software (PLC, HMI, SCADA) level.

- Designing the hardware structures

The design of the hardware structures was closely connected to the new system conception which enabled the elimination of certain hardware equipment compensated by an advanced software diagnosis and control system.

- Design of application software

This software includes all advanced control and diagnosis routines, procedures, methods with considerable advantages and performances in application as presented in this thesis.

- Implementation and testing

Given the novelty of the pursuit: a better temperature and burner control resulting in a better temperature uniformity, implementation and testing of the new system was concluded step by step, in stages until the final version was adopted and confirmed with performance tests.

- Practical capitalisation

At present, the 2 furnaces are in production in Zirom S.A. Giurgiu plant attesting the high performance and reliability of the system.

- Communicating the achieved results in publications and conferences.

The achieved results are very important in supporting the idea that old standard conception and design of furnaces can be perfected with a new general solution which implies many advantages as opposed to the old conception. These advantages are:

- Performance (temperature uniformity for low and high temperature regimes) was greatly improved by replacing the old temperature control concept.
- Cost reduction of the initial investment by excluding some redundant equipment and using a single heat exchanger for both furnaces
- Increasing system reliability by using new auto diagnosis solution and methods
- Reducing maintenance costs by excluding some sensitive, malfunction high-risk equipment that requires constant supervision and maintenance.

As an observation on the development of this project, we discovered that the complexity of software routines is constantly evolving leading to hardware replacement and very good working results, as shown in this thesis. This contributes to the engineering progress by developing better solutions on all levels (performance, costs, etc.) which meet the industry demands.

7.3 Developmental Perspective

7.3.1 Diagnosis System

In the future, new extended diagnosis techniques can be developed based on a better understanding and approach of the specific technological process and functions of the furnaces. My proposal is designing a specific routine that can calculate a global unique value for the operating state of the furnace [0-100%] based on all measured parameters, alarm/fault analysis (faults can be divided into several categories according to the level of impact on the general operating state and availability of the furnace: minor, medium, serious, emergency lockdown).

Based on this global value, the automation system will be able to anticipate the approximate date when an impending capital repair should be carried out, or when the furnace should be shut down for required maintenance works.

The main difference brought by this technique is that scheduled capital repairs and maintenance shutdowns are no longer inflexible, but they can be adjusted in real time by the automation system based on the global functioning state value. This results into a better availability of the furnace and a reduction in maintenance costs.

7.3.2 Control System

In the future, a more performant temperature control system can be developed, based on more temperature control zones. This can lead to a better temperature uniformity.

7.4 List of Figures

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8. Appendices