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PhD Thesis

RESEARCHES ON THE IMPLEMENTATION OF A REAL-TIME CONTROL AND MEASUREMENT SYSTEM FOR THE WORKING REGIME PARAMETERS OF DOUGH PROVERS

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PREFACE

Bread products consumption occupies an important place in Romania. The manufacturing industry is in an intensive process of automation, tehnologization and efficiency increase. Once with the technical and technological progress made in bread making industry, the qualified personnel for this field is continuously decreasing.

Although the proving process is the largest stage in the bread making process and leaves an important mark on the finished product's characteristics, this subject entered reaserchers attention only recently. Also, the appreciacion of dough fermentation level in bread factories is still performed mostly organolepticaly.

Therefore, automated control solutions for defining stages of bread making, with minimal human monitoring, becomes an increasing necessity.

The PhD thesis „ *Researches on the implementation of a real-time control and measurement system for working regime of dough provers*" presents o sinthesis of the research performed by the author regarding bread dough fermentation process evaluation and the possibility to implement a system which automately controls the proving process in any industrial prover.

The paper is structured in 6 chapters, developed in 225 pages and contains 188 figures and graphs, 101 mathematical relations and 235 references. It also contains a list with notations and simbols and a series of appendices (12 pages).

The general objective rearding the research theme of this project is the theoretical and experimental research in laboratory and industrial environment for the identification of an automated real time control solution for the working regime of dough provers, in permanent correlation with the desired characteristics of the finished product.

In **chapter 1** called „*General considerations regrding the bread making process*" are presented general aspects of the bread making process with the stages for bread making, the description of all operations needed for bread making, the influence of factors analysis and proving parameters presentation.

Chapter 2, called „ *Dough preparation methods. Final fermentation and air conditioning installations"* represents a synthesis of bread making technological lines and modern equipment manufacturing solutions which are necessary for a correct proving process. There are presented prover construction variants with accent on the modern models. There are also presented air conditioning units for provers and the complete proposed solution for air conditioning unit which uses the carbon dioxide concentration for proving parameters control in industrial prover. Next, it is presented the energy recovery system with thermal tubes, which recovers the heat released from the burnt gases of the bread oven. If integrated in the functioning logic of the air conditioning unit, the energy recovery system is a viable solution for energy consumption cost reduction.

In **chapter 3**, called „*Theoretical and experimental research synthesis regarding bread dough final fermentation*" are presented different methods and equipment for dough rheological properties determination as well as global theoretical and experimental research regarding dough proving evaluation. There are also presented in a concised and analytical way, the factors which influence dough's rheological properties in regard to the proving process (dough recipe, gluten and yeast quality). There are also analyzed different evaluation methods for the fermentation process.

In **chapter 4**, called „*Theoretical aspects and contributions regarding bread dough final fermentation*" is proposed a mathematical model for carbon dioxide specific volume determination which is released during dough proving process and which uses the pressure variation in a sealed container. This method is further validated with real time measurements of released carbon dioxide.

A mathematical model is proposed for the energy consumption during proving in industrial environment, for three operating modes and the results are validated with real time measurements of energy consumption.

It is also presented the tridimensional numerical simulation of air currents in a tunnel type prover with 4 floors and the influence analysis of recirculated air discharge grids dimensions on air speed and temperature distribution on the prover's floors. The prover's model was designed in solid Works program and the tridimensional simulation was run in ANSYS CFX Fluent.

Chapter 5, called „*Experimental research regarding bread dough proving process*" is structured in two main subchapters: experiments in laboratory and experiments in the bread factory, for which, in the first part equipment and methods are presented. The performed research experiments had the purpose of identifying, evaluating and establishing the optimal characteristics and the implementation of a better solution for the control of working regime parameters of bread dough provers.

The results of the experimental research for determination of carbon dioxide concentration are successively presented in a clear and objective manner, as a reference parameter in proving process evaluation and automate control of temperature and relative humidity parameters.

A conventional air conditioning system and the proposed solution were analyzed comparatively.

Experimental determinations were performed at reduced scale, in two industrial provers of similar construction but different capacities and in a spiral type prover.

The presented results approach two directions: the functioning mode of the systems in regard to the working parameters variations and their influence on the characteristics of the finished products (dimensions, volume, crumb porosity).

In **chapter 6,** called „*General conclusions. Personal Contributions. Future research directions"*, are presented the essential conclusions which resulted from the global research part but also the ones from the theoretical and experimental contributions. The accent was being put on the necessity of better understanding the influence of different factors in the proving process of wheat dough as well as the importance in identifying o complete solution for proving process control in the technical and technological context.

THEME IMPORTANCE AND PhD THESIS OBJECTIVES

The general objective of this PhD thesis is the theoretical and experimental study of bread dough proving process regarding the implementation of a system which automately controls the working regime of dough provers.

The specific objectives are:

- Identification of influence factors on dough proving process;
- Construction analysis of dough provers;
- Construction analysis of prover air conditioning units;
- Theoretical and practical research regarding rheological behavior of dough during proving;
- Air current distribution analysis in tunel type provers using dedicated software (Solid Works, Ansys);
- Mathematical modelling of the proving process using pressure variation in airtight container;
- Mathematical modelling of energy consmpution during proving in a tunnel type prover;
- Experimental research regarding the carbon dioxide concentration during proving in a reduced scale prover;
- Experimental research in the bread factory, regarding the implementation of a proving parameters control system in any prover;
- Experimental testing for the establishment of accuracy functioning level of the proposed system;
- Evaluation of proving parameters influence on the finished product;
- Mathematical models validation for the evaluation of the proving process.

SIMBOLS AND NOTATIONS

S – surface, [cm^2]

UB (UF) – Brabender units (pharinographic)

t – time, [s]

p – pressure, [Pa, bar]

V – volume, [m^3]

R – gas constant, [j/mol·K]

ρ - density, [kg/m^3]

v – speed, [m/s]

CHAPTER 1
GENERAL CONSIDERATIONS REGARDING THE BREAD MAKING PROCESS

1.1. THE TECHNOLOGICAL PROCESS OF BREAD MAKING

1.1.1. Bread making process evolution

The bread making process can be seen as o serie of aeration stages in which air bubbles are incorporated during kneading, expanded with carbon dioxide during proving and then the resulted aerated structure is stabilized during baking, [152].

Knowledge about the influence elements on dough fermentation process and systems improvement for better proving control are key points in obtaining superior quality products.

1.1.2. Bread making stages

In order to transform raw materials in bread products it is necessary to perform technological operations at well defined intervals. Each operations has a well established role and can not be omitted in order to obtain good finished products, [86].

These operations are: raw materials storage, in special bunkers or bags; raw material preparation (conditioning); dough preparation in one, two or three stages; dough work by dividing in desired pieces with the help of dough dividers and controlling dough weight based on the final desired mass and process lossess; final dough fermentation (proving) performed in closed spaces with treated air; dough pieces conditioning (slotting, wetting) with aesthetic role and to control the amount of released gas; baking until the core crumb of the bread reaches a minimum temperature of 92 °C; bread cooling until the core crumb reaches maximum 27 °C and is performed in cooling spirals; product packaging in crates if fresh or sliced and individually packaged with dedicated slicing machines.

1.2. BREAD DOUGH FINAL FERMENTATION PROCESS

1.2.1. Influence factors regarding bread dough final fermentation

Bread dough final fermentation process is conditioned by: the adopted technological process, bread recipe, dough temperature when entering the prover, proving parameters, gas holding capacity and forming, compounds accumulation as a result of alcoholic and lactic fermentation.

A) Raw materials used in the bread making process

Wheat flour is the most used type in the bread making process because is the only cereal capable of ensuring an aerated structure of the finished product, [23].

The quantity of added water to the bread recipe is defined by the hydration capacity (percentage reported to the flour quantity), meaning flour's property to absorb water.

The yeast used in bread making belongs to *Saccharomyces* gender, *Saccharomyces cerevisiae* species, being considered superior fermentation yeast through its enzymatic equipment. It's optimal development takes place around 25-30 ºC and optimally ferments around 35 ºC.

Salt (sodium chloride), next to its taste contribution, has great influence on dough's rheological properties by strengthening the gluten structure and stabilizing the fermentation process.

B) Processes that take place during dough fermentation

During dough fermentation complex colloidal, microbiologic and biochemical processes take place.

C) Dough capacity to form and retain fermentation gases

Capacity to form and retain gases is wheat dough's property which allows the release and retainment of a certain amount of gases, leading to volume increase and density reduction.

1.2.2. Dough pieces weight lossess during processing

Dough weight lossess during bread preparation is of great importance because of its direct financial impact on the averall bread making unit. Usually, weight lossess amount up to 14 %.

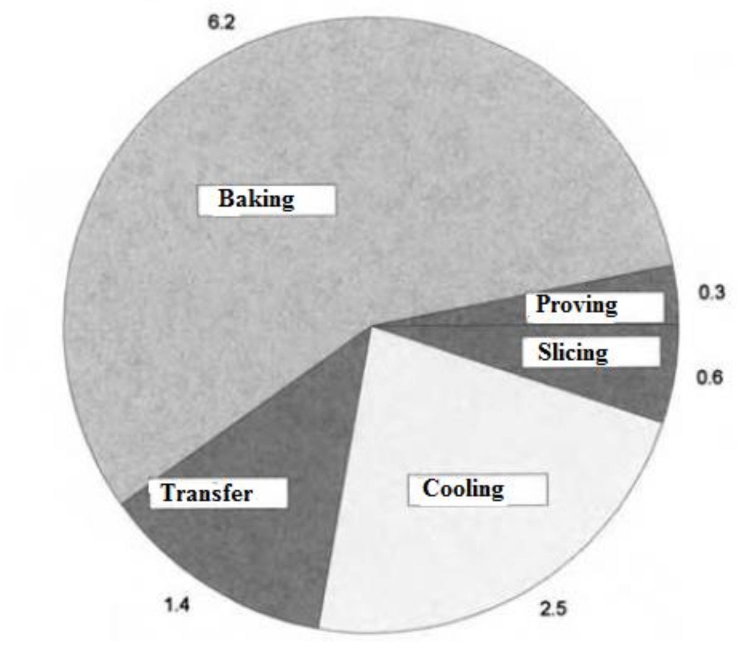


Fig. 1.12. Dough piece lossess during processing (%), [24]

1.2.3. Final fermentation parameters

Final fermentation parameters are fermentation time, temperature and air relative humidity. Being a porous medium, between the dough piece and environment heat and humidity transfer takes place.

Dough pieces *final fermentation time* varies within large limits of 15 to 90 min depending on several factors like: mass of dough piece, prover dimension (capacity), dough preparation technology.

Air temperature in the prover is determined based on proving time, bread recipe and the technological process, so as to control the fermentation speed.

Air relative humidity is established besed on the working temperature and air speed currents so as to avoid excessive moisture loss or the creation of a water film on the dough surface. The usual values are between 70-75%.

1.3. CONCLUSIONS

Dough fermentation is the longest stage in the bread making process, starting from kneading and continuing through the first baking part. It is mainly caused by alcoholic fermentation produced by bread yeast, which consumes a significant part of available sugars and releases carbon dioxide and ethylic alcohol, producing the volume increase of dough piece.

CHAPTER 2
DOUGH PREPARATION METHODS. FINAL FERMENTATION AND AIR CONDITIONING INSTALLATIONS

2.1. BREAD MAKING LINES

A technological bread making line is conceived starting from the desired specific of the products and the line's technical sheme follows the technological process's stages, [155].

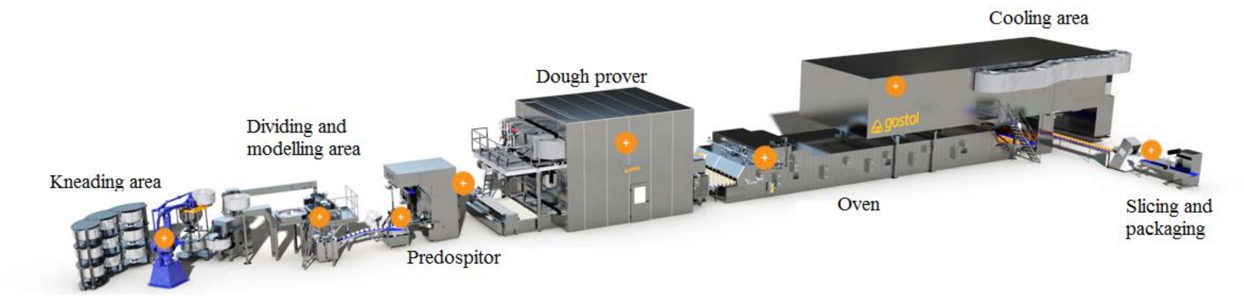


Fig. 2.2. Modern technological line for bread making with tank dough fermentation

Technological linea which use direct dough preparation are the most used types in bread making industry. All ingredients are mixed together and the resulting dough can be kept in the vat for 2 -4 hours or for a very short resting time of 10-20 min, in which case the yeast quantity needs adjusting for time compensation.

2.2. INSTALATIONS FOR DOUGH FINAL FERMENTATION

Final dough fermentation installations, called provers can function continuously or discontinuously.

Industrial load capacity is determined based on the surface occupied by a dough piece Δs, the distance between pieces, number of loaded pieces per time unit N_0 and final fermentation T_{Ff} for Δ_s and N_0 constant ($S=f(T_{Ff})$, $S = f(\Delta_s, N, T_{Ff})$).

Continuous provers are used in industrial spaces with high rate production in which the technological flux for bread making is mechanized, the operations are successive and connected.

Industrial provers are tunnel or with swings type. The modern model are completely automated and have operating systems with different setable parameters and alarms.

The working functioning principle can be divided in 4 phases: loading, fementation, discharge, drying and pockets disinfection.

2.3. PROVER PARAMETERS CONTROL INSTALLATIONS

Most industrial provers have an **air conditioning system** which ensures at least the minimum necessary temperature and relative humidity inside the prover.

2.3.2. Proposed solution for air conditioning of continuous dough provers

To treat the air in a prover an air conditioning unit like the one in fig 2.32 together with an air distribution system like the one in fig 2.33 is used. The air conditioning unit can function with recirculated air or can use mixed air (old with fresh).

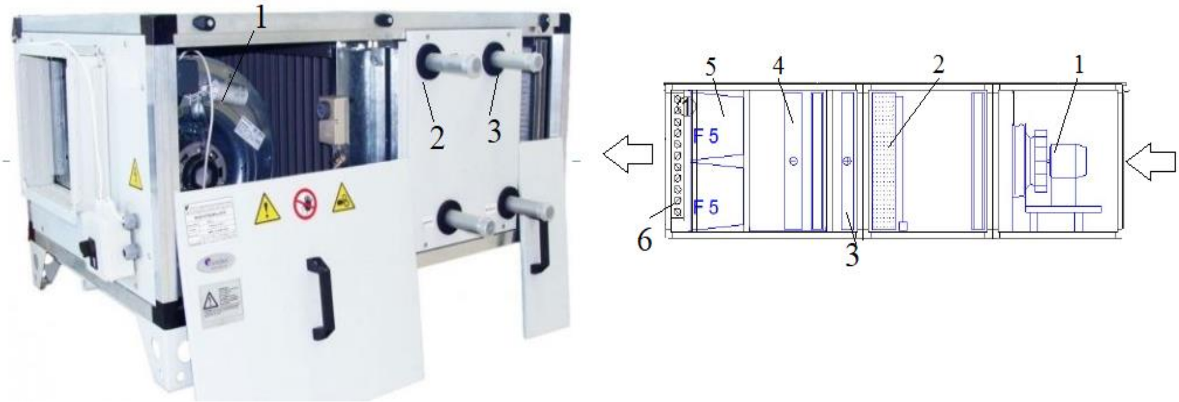


Fig. 2.32. Air conditioning unit for dough prover, [213]
ventilator; 2. drainer; 3. heat exchanger with cold water; 4. heat exchanger with hot water; 5. hepa filter; 6. grid flap

The air conditioning units for provers have heat exchangers with hot and cold water, water drainer, HEPA filter, a humidifier and a ventilator.

2.4. CONCLUSIONS

Modern provers are different from the classic models. The entire mechanical process is automated including the loading and dough discharging mechanisms and the proving stages are more efficient.

The air conditioning units connected to the prover ensure at least minimum values for temperature and relative humidity inside the prover. The most used air conditioning units function using treated air distribution in the proving chamber.

Bread making technological process optimization in relation to productivity increase and superior quality obtained products is a necessity for the present society.

CHAPTER 3
THEORETICAL AND EXPERIMENTAL RESEARCH SYNTHESIS REGARDING BREAD DOUGH FINAL FERMENTATION

3.1. APPARATUS AND METHODS FOR RHEOLOGICAL PROPERTIES DETERMINATION OF WHEAT FLOUR DOUGH

Mechanical dough behavior can be studied using rheological methods and equipment.

Wheat dough present the following rheological properties: elasticity, plasticity, viscosity and relaxation time. These influence the volume and final product structure, shell and crumb elasticity, [105,147].

The alveographic method analyzes stretching resistance of a thin foil of dough inflated until rupture with air pressure, [36,174,175,210].

The extensographic method measures the stretch resistance of a fermented cilindrical dough piece, [176,204]. The obtained results are useful for gluten strength determination and flour quality characteristics. The effect of fermentation time and additives on dough performance can also be evaluated.

Chopin Rheofermentometer (fig.3.5) measures dough characteristics during fermentation by measuring pressure variation in a known volume (fig. 3.6), [177,178].

The device develops a graph for gas forming and retention in dough as well as dough development in time, (fig.3.7).

Fig. 3.5. Chopin rheofermentometer, [196]
1-device; 2-fermentation chamber; 3-piston body; 4-dough piece

3.2. REASEARCHES REGARDING THE INFLUENCE OF BREAD RECIPE COMPOUNDS ON BREAD FINAL FERMENTATION

3.2.1. The influence of yeast type on final fermentation process

Voica D., in paper [151] studied dough behaviour during fermentation using Chopin rheofermentometer. Dough’s capacity to produce and retain fermentation gases was monitored.

According to the obtained results, in a three hour interval, gas production and gas retention registered higher values per time unit when using compressed yeast than any other type.

3.2.2. Influence of soluble fibers and antioxidant addition on dough fermentation

Due to a raising interest regarding nutritional food value and because bread is consumed in high quantities, insertion of fibres and antioxidants in bread products has increased lately, [67,135].

3.2.3. The influence of salt addition on carbon dioxide production

Luchian M and Canja C.M. (2010) studied the effect of adding salt on gas production in bread dough for a fermentation process of 100 minutes, using different qunatities of saline solution with 25 % concentration (0 %, 6 %, 12%, 20 %).

According to their results, doubling the salt percentage determines a decrease of over 30 % in gas production in the same unit time.

3.3. REASERCHES REGARDING BREAD DOUGH PROVING PROCESS EVALUATION

3.3.1. Carbon dioxide production in dough, using the risograph

G.E Rattin and colaborators, (2009) performed measurements of carbon dioxide production using a device called Risograph. The recipients are immersed in a water bath with controlled temperature.

The reaserch institute for bread making yeast, VH Berlin, (Versuchsanstalt der Hefeindustrie) tested an experimental device for fermentation capacity determination called ANKOM Gas Production System, using SOP H 04, method, according to ISO/IEC 17025:2005, [179]. The results were compared with the ones obtained using standard SJA phermentograph and Brabender method.

For performing the tests two recipes were used: a standard one with 300 g flour, 4.5 g salt, dissolved, 7.5 g of fresh yeast (one test enriched with sucrose – 45 g), also dissolved in water. For individual testing 350 g dough samples were used and for simulatenous testing 100 g of dough were used.

3.3.2. Monitoring of dough fermentation process using different measuring methods

A. Ktenioudaki and colaborators (2009) monitored dynamic dough density during final fermentation using three measuring methods: the register of apparent mass change in dough piece immersed in siliconic oil at 35 ºC, proving process monitoring in real conditions using structure lighting technique; fermentation process evaluation using Chopin rheofermentometer.

These methods can be used for dough proving process evaluation but the applied techniques influence in some measure the obtained results and this aspect must be taken into consideration when using the presented methods, [49, 79, 136].

3.3.3. Using ultrasounds for the study of dough proving process

The use of ultrasounds and the application of the presented methods represent viable mechanisms for dough behavior evaluation during proving in relation to rheological, structural aspects and also to lead to the identification of a better control method for bread making.

3.3.4. The study of proving process in terms of gas cell expansion

Gas cells distribution and stability changes throughout the bread making process are caused by two fundamental mechanisms: disproportionation and coalescence. As the gas cells are expanding, the toal number of gas bubbles are diminishing, by way of coalescence, [159].

3.3.5. Mathematical modelling of carbon dioxide individual cell development during proving process

Gas bubbles development during proving is influenced by four factors: carbon dioxide production facilitated by yeast content; dough's gas retention capabilities; carbon dioxide diffusion into the liquid phase in the gas bubbles; bubbles coalescence rate.

The mathematical model proposed by Shah and colaborators describe the development rate taking into consideration the mass transfer rate into the cell *Q*, in terms of the effect on moles number of the existent gas, *n* and so of gas bubble dimension, [132]:

$$Q = \frac{dn}{dt} = f\left(\frac{dD}{dt}\right) \tag{3.7}$$

3.3.6. Studies regarding pressure variation during proving process

The most frequent way of evaluating the industrial fermentation process is measuring the carbon dioxide flow which leaves the fermentation enclosure, [39,51].

Erfan Mohagheghian and colaborators (2015), in paper [101], developed a mathematical model to determine the carbon dioxide compressibility factor, in a statistical program (least square support vector machine –LSSVM), using the least squares method (MCMMP).

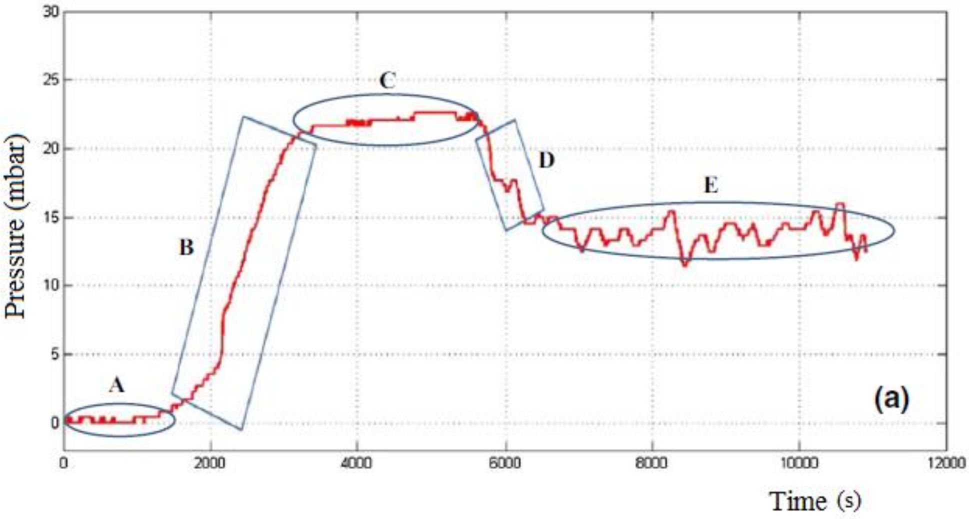


Fig. 3.36. Pressure variation during dough proving: A. lag period; B. development time (gas production); C) stability period; D) falling period (gas loss)

From the experiments 5 transition dough phases were identified during final fermentation, based on pressure variation measurements, presented in fig 3.36 and compared with experimental determinations using Chopin alveograph and rheofermentometer in similar conditions.

3.4. CONCLUSIONS

Recent approaches on the study of dough's structural modifications during final fermentation imply the use of ultrasounds and magnetic resonance.

The most visible effect of proving is the volume growth of the dough piece but there are also rheological and flow changes.

The desired volume of femented finished bread products is obtained only if the dough ensures the right conditions for yeast multiplication and fermentation process development from which results carbon dioxide and in the same time, the dough posseses the gluten matrix capable of retaining as musch of that released gas as possible.

The air molecules instroduced into the dough during kneading represent the bubbles in which carbon dioxide accumulates during fermentation determining dough's expansion.

The carbon dioxide in dough diphuses from the liquid phase in the gas cell and the phenomenon do not necessitate the suprasaturation of the liquid phase with carbon dioxide.

A difference of +10 °C can double the speed of the fermentation process and the gas production.

CHAPTER 4
THEORETICAL ASPECTS AND CONTRIBUTIONS REGARDING BREAD DOUGH FINAL FERMENTATION

4.1. 4.1. EQUIPMENT AND APPARATUS USED FOR THEORETICAL RESEARCH

A) Construction of tunnel prover with 4 floors TCH, Technobit Automatizari, Romania

This prover model was used for the tridimensional simulation in air current distribution analysis and for energy consumption determination during proving. The prover has a capacity of 4000 buc x 0.36 kg/h, the air conditioning unit can ensure a temperature parameter up to 40 °C and a relative humidity up to 80 %. Based on the speed of the conveyors, correlated with the oven's, the proving time can vary between 60 to 90 min, [195].

B) The energy recovery system

The bread making line from ALX ROM, Rusanesti, Olt, has the prover described at point A) and a bread oven which uses pellets as primary fuel source and it is built by J4 company, Czech Republic which are connected to 2 energy recovery systems bult by Biotehnologicreativ Company, Romania, [55], (fig. 4.3), [138].

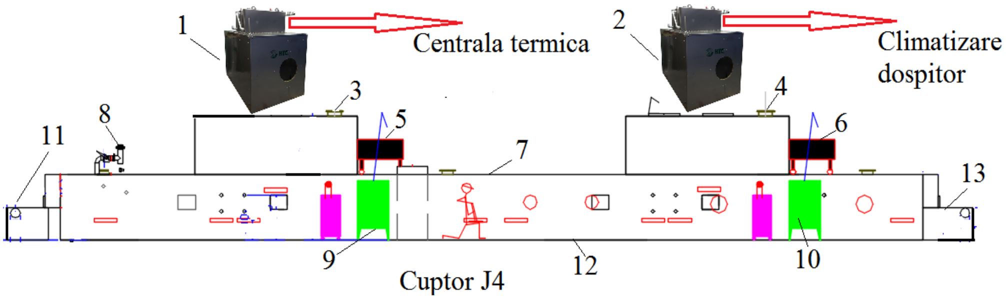


Fig. 4.3. Energy recovery systems mounted on J4 oven

1. gas-water recovery system in first baking area; 2. gas-water recovery system in second baking area; 3. area 1 burnt gases evacuation tunnel; 4. area 2 burnt gases evacuation tunnel; 5. area 1 pellets burner; 6. area 2 pellets burner; 7. operator; 8. steam intake; 9,10. Area 1 and 2 pellets reserves

4.2. SIMULATION OF AIR CURRENT DISTRIBUTION IN THE PROVER USING FINITE ELEMENT METHOD

CFD has been applied in food industry just in the last decade and a half, [11].

The computational program for tridimensional simulation, Ansys Fluent is used in a two part simulation of air current flow during dough proving. In the first part of the simulation the tridimensional model is applied to one floor of the prover. In the second part of the simulation, the model is applied to prover's real scale, using the values determined in the first part.

The following hypotheses with which the model was run and finally generated were applied: the entire free space in the enclosure is full with air at constant pressure, p=101325 Pa. The air is introduced in the prover using the left grids and aspirated through the right grids with an air speed individually defined for each grid. Simulation was run at three air speeds: 0,2, 0,4 and 0,6 m/s respectively, [70].

The prover has an air conditioning system which uses a fan with a capacity of 2200 m³/h and an air distribution system, (fig. 4.10).

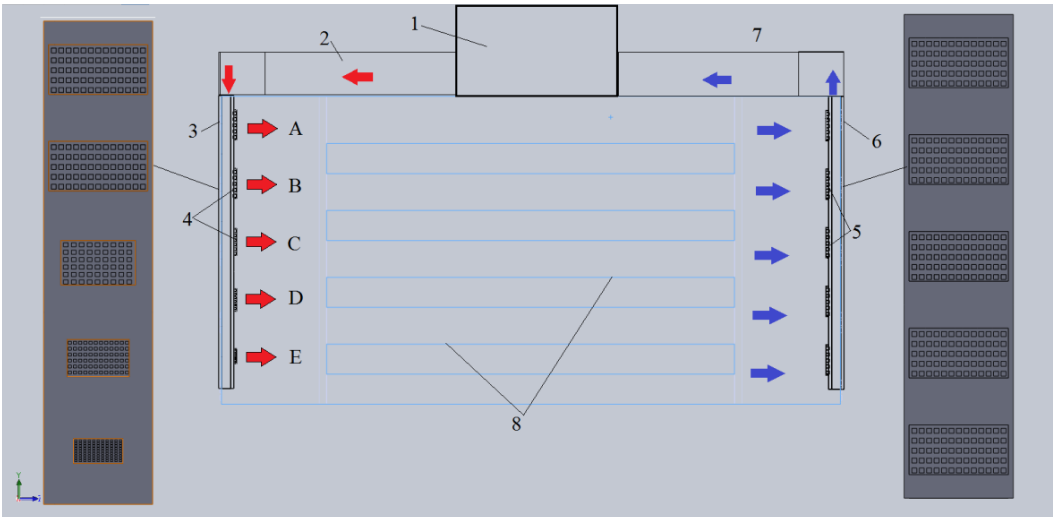


Fig. 4.10. The air distribution system design: 1-air conditioning system; 2-exterior pipes for air discharge; 3-interior pipes for air discharge; 4-air discharge grids; 5-air charge grids; 6-interior pipes for air charge; 7-exterior pipes for air charge; 8-prover floors

The air is blown through one side of the prover and aspirated through the other side, after it passes (charged with temperature) through the floors of the prover. The exterior charge (2) and discharge (7) air pipes have 0.09 m² diameter and are connected to 12 internal discharge (3) and charge (6) air distributers placed on the entire prover length, from 2 to 2 meters. Each internal distributor has 5 grids (4, 5), one for each floor and one for the space between the ground floor and the base of the prover. There are no registered differences for air speed through the grids placed on the length of the prover, [70].

For the dough to be less affected by the air currents in the prover, it is very important to determine the minimal values at which the recirculated air ensures the temperature gradient required for the proving process and as uniformly dispersed as possible, (fig. 4.11).

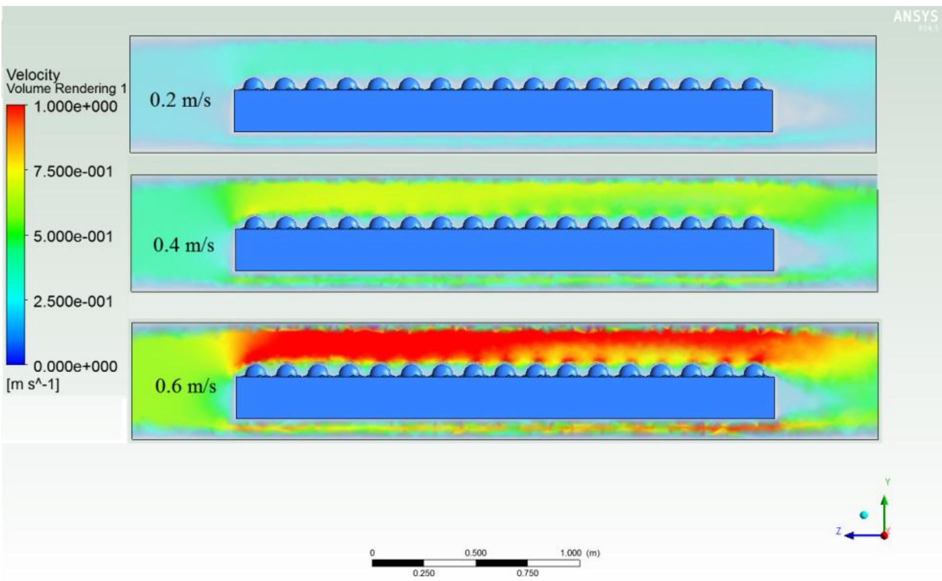


Fig. 4.11. Air speed distribution in the proving chamber based on the air speed

Optimization tests were performed for air flow inside the prover using different discharge grid sections until good results were obtained

In the first case, the discharge grids had the same dimensions: L=400mm and w=200mm. Simulations were performed for three air flow values. The air flow was modified through the variation of fan frequency. All the air charge grids had: L=400mm and w=200mm.

In the second case, the air discharge grids had the following dimensions (top to bottom): A- L=400mm and w=200mm; B-L=400mm and w=200mm; C- L=300mm and w=180mm; D- L=250mm and w=150mm, E- L=200mm and w=100mm. The air charge grids had equal dimensions: L=400mm and w=200mm. Simulations were performed for 4 different air flow values. The air flow was modified through the variation of fan frequency. There was also analyzed the influence of air flow change from 20 to 70 Hz, each 10 Hz interval.

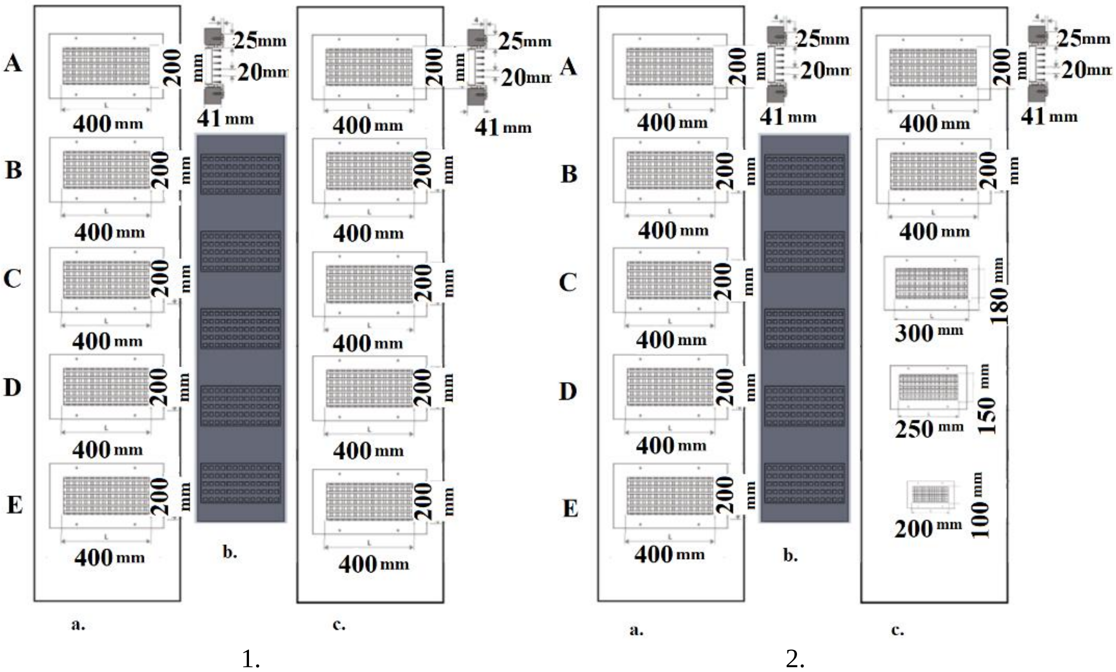


Fig. 4.13. 1.First case – a) Interior charge grids, b) Interior discharge grids designed in Solid Works, c) Interior discharge grids; 2. Second case – a). Interior charge grids, b) Interior discharge grids designed in Solid Works; c) Interior discharge grids

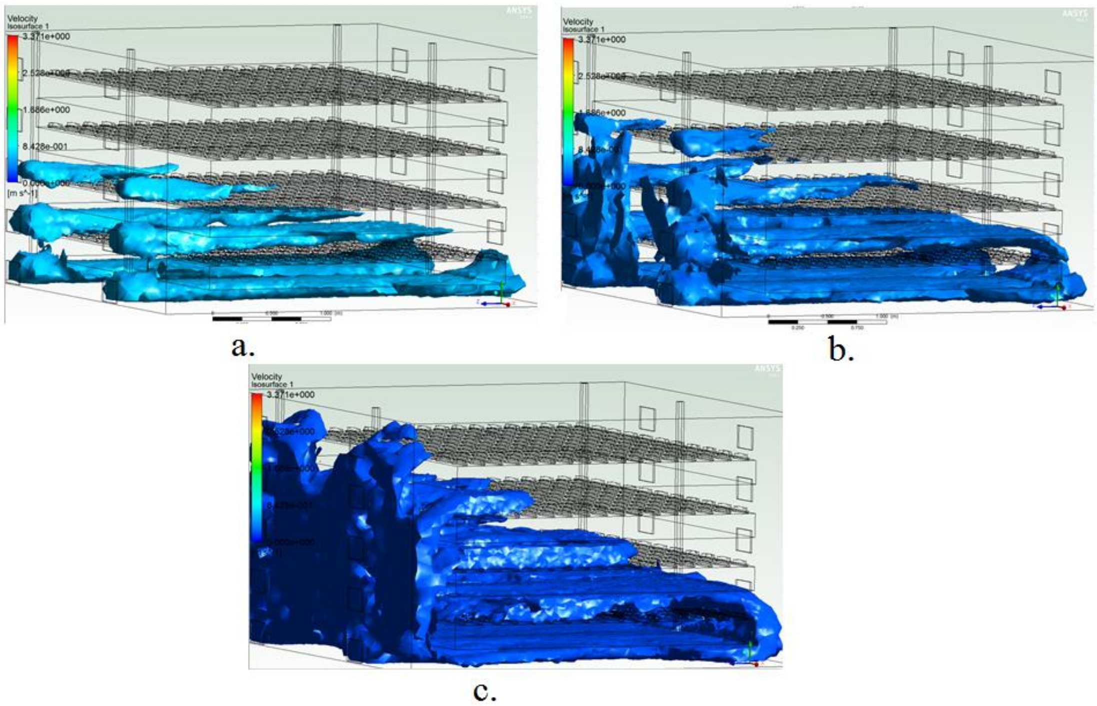


Fig. 4.14. Air speed distribution in the points where it reaches 0.6 m/s: a) fan working at 50 Hz simulation; b) fan working at 60 Hz simulation; c-fan working at 70 Hz simulation

At 50 Hz, the fan has an air flow of 2200 m³/h. By increasing the air flow, the air currents are higher in the lower part of the prover (D and E grids). In grid E, the registered air speed has a value of 3.4 m/s and much lower on the superior grids, (fig. 4.14).

For further verifications, simulations were run at different air flows, starting from 1650 m³/h (at 20 Hz fan frequency) to 2200 m³/h (50 Hz fan frequency) at 10 Hz interval. The results are presented in figure 12.

In all 4 simulations, it was observed a gradual increase of the points in which the air speed reaches 0.6 m/s. The best results were obtained when the fan works at 50 Hz and the measured air flow is 2200 m³/h.

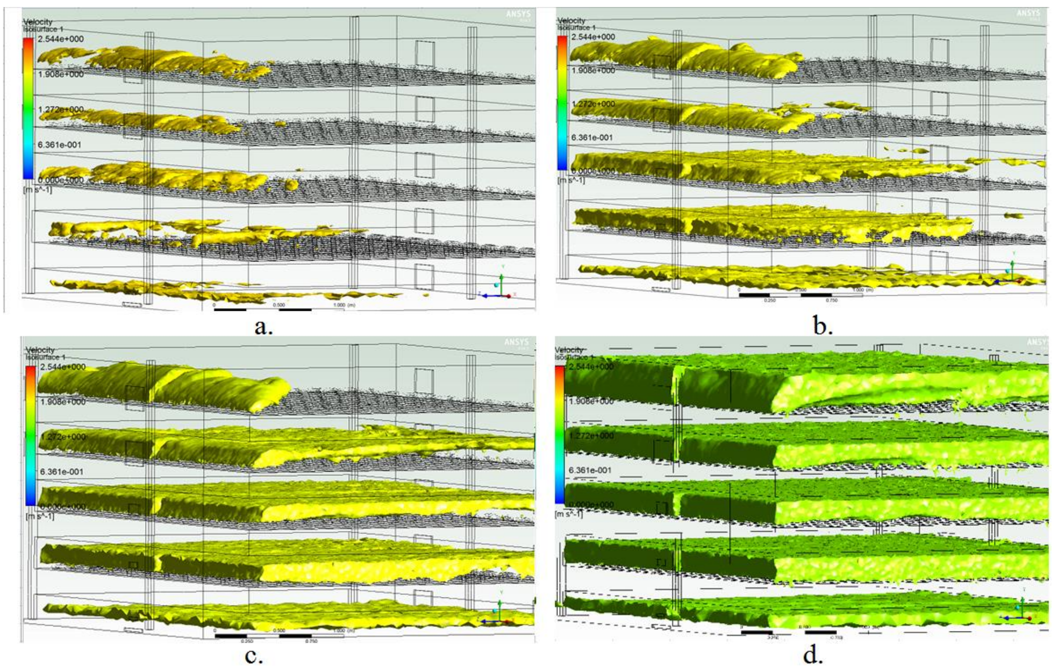


Fig. 4.17. Air speed distribution in all points where it reaches 0.6 m/s: a) simulation with fan functioning at 20 Hz; b) simulation with fan functioning at 30 Hz; c) simulation with fan functioning at 40 Hz; d) simulation with fan functioning at 50 Hz

It can be seen a much better air speed uniformity throughout the entire prover. Higher speeds are still registered at C, D and E grids but the maximum reached speed is 2.1 m/s and the maximum speed which passes over the dough pieces is 0.8 m/s. This air speed does not affect the proving process in any way.

4.3. MATHEMATICAL MODELLING OF ENERGY CONSUMPTION DURING PROVING

For energy consumption determinations during proving in industrial provers, an alghoritm was developed using Mthcad software for a 4 stories tunnel prover, with 4000 dough pcs *0.36 kg·$^{h-1}$ capacity. The following were determined: the necessary air and humidity flow to raise the temperature with 15 °C and 20 % RH; the air flow necessary to maintain a constant set temperature and to heat the prover's structure plus losses; the air flow necessary to raise the temperature in the piece dough with 6°C.

The general relation for enthalpy (h), based on absolute air humidity (x),is written as, [45,71,193]:

$$h = c_{pa}t + x\left(r_v + c_{pv}t\right)\text{ , kJ·kg dry air}^{-1}, \tag{4.5}$$

where: specific dry air heat is cpa=1.004 kJ·K $^{-1}$; water vaporizing latent heat at 0 °C is rv=2500 kJ·kg $^{-1}$; specific heat of overheated water vapours is cpv=1,863 kJ·K $^{-1}$.
The heat and humidity flow is determined with, [45,71,195]:

$$\dot{Q_{12}} = \dot{m} \cdot \Delta h\text{, W,} \tag{4.8}$$
$$\dot{G_{12}} = \dot{m} \cdot \Delta x\text{, kg·s}^{-1} \tag{4.9}$$

The determined values for the power consumption necessary to ensure optimal parameters in a prover for a 20 hour working cycle are: prover heating-15.85 kW; metallic structure heating-10.5 kW; wall losses-0.29 kW; floor losses-0.1 kW; total consumption for first hour-26.7 kW; Maintaining temperature setpoint and structure-12.79 kW; dough temperature increase with 6 °C-4.56 kW; hourly necessary for continuous working-17.35 kW; steam consumption in the first hour-12.06 kW; steam consumption for continuous working-8 kW. The obtained values were compared with real measurements of power consumption for ensuring the necessary parameters of temperature and relative humidity in a 20 hour working period., [71].

4.4. MATHEMATICAL MODEL FOR CARBON DIOXIDE CONCENTRATION RELEASED DURING PROVING PROCESS IN LABORATORY

The proposed mathematical model for determining the specific volume of carbon dioxide uses the pressure variation in a hermetically sealed enclosure, following the release of carbon dioxide during the fermentation process under controlled conditions. To develop the mathematical model, we started from the thermal equation of state of real gases, which uses the compressibility factor Z, dependent on pressure, temperature and nature of the gas.

Therefore, the real gas law can be written as, [1]:

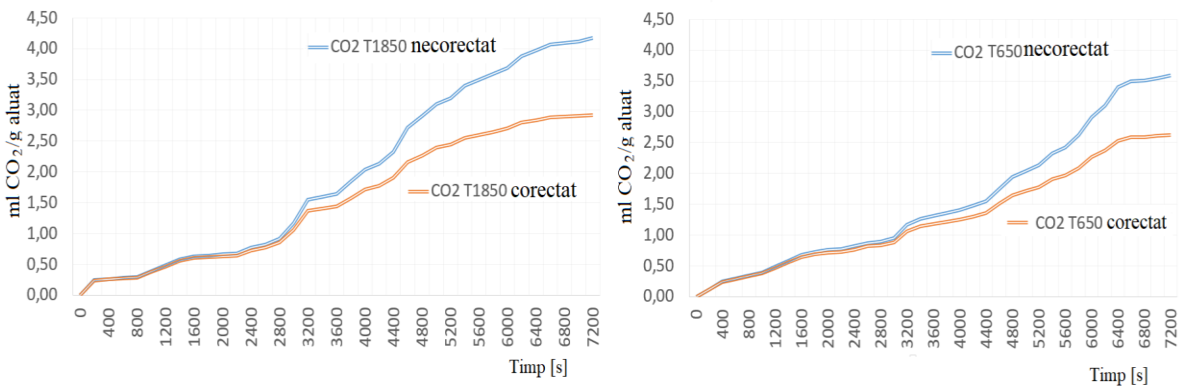
$$pV = ZnRT \tag{4.18}$$

To calculate the specific volume of carbon dioxide from the transformation of the pressure formed in the reactor, the equation was used:

$$V_{CO_2} = \frac{P_{CO_2} \cdot V_g \cdot M_{CO_2}}{RT} * 1/Z \tag{4.24}$$

In fig. 4.19 is presented the comparative analysis of the specific volume of carbon dioxide calculated for the doughs in flour FA1-650, respectively FI-1850, fermented at 40 ° C, using the ideal gas equation (uncorrected values), respectively with the addition of the compressibility factor, Z.

The specific volume of carbon dioxide calculated in the 7200 s using only the ideal gas equation gave a result of 4.17 ml CO2 / g dough for FI-1850 flour, respectively 3.59 ml CO2 / g dough for FA1-650 flour. The values calculated using the compressibility factor were 2.92 ml CO2 / g dough for FI-1850 flour, respectively 2.62 ml CO2 / g dough for FA1-650 flour, [73].



a. b.

Fig. 4.19. Comparative analysis of the volumes of carbon dioxide calculated when using FA1-650 and FI-1850 flours, respectively, in the fermentation process at 40 ° C, with and without the introduction of the compressibility factor, Z, [73]

4.5. MATHEMATICAL MODELLING OF ENERGY CONSUMPTION DURING PROVING USING Π THEOREM

For the mathematical modeling of the energy consumption druing proving , the theory of dimensional analysis was applied. From the theory of dimensional analysis was applied the theorem Π, stated by Buckingham, [139]. According to this theorem the number of independent criteria in the criterion function is given by the difference n-r, where n is the number of variables and dimensional constants, and r is the rank of the dimensional matrix, which is equal to the number of fundamental quantities according to which the variables taken can be expressed. The number of fundamental quantities is relatively small and depends on the complexity of the phenomenon. From the theoretical and experimental researches of the fermentation process, a number of 7 main parameters that influence the fermentation process were considered in the study:

- proving energy consumption, E ($kg \cdot m^2/s^2$);
- proving time, t (s);
- dough mass, m (kg);
- dough density, ρ (kg/m^3);
- dough pieces height, h (m);
- prover conveyor speed, v_b (m/s);
- CO_2 volume accumulated in dough, V_{CO_2} (m^3);
- proving relative humidity, u_r (kg abur/kg aluat);

A simplified variant of the equation is:

$$E^{a-1} = k^* \cdot \rho^a \cdot V_{CO_2}^{a-\frac{1}{2}b-\frac{1}{3}c} \cdot v_b^{2a+b-2} \cdot t^b \cdot h^c \cdot u_r^d \cdot m^{-1} \tag{4.77}$$

Notating:

$$\alpha = a - \frac{1}{2}b - \frac{1}{3}c \ ; \beta = 2a + b - 2 \tag{4.78}$$

Results:

$$E^{a-1} = k^* \cdot \rho^a \cdot V_{CO_2}^{\alpha} \cdot v_b^{\beta} \cdot t^b \cdot h^c \cdot u_r^d \cdot m^{-1} \tag{4.79}$$

4.6. CONCLUSIONS

The three-dimensional numerical simulation allowed the analysis of the distribution of air currents in the 4-stage tunnel prover in terms of determining the required air velocity and the correct sizing of the discharge grids to ensure the most uniform temperature distribution on all floors of the prover.

The numerical simulation program can be used to design more efficient air conditioning systems, because you can immediately see effects on energy transport in the prover when it changes: pipes, prover geometry, discharge sections, etc.

The closed container pressure variation can be used to evaluate the fermentation process and calculate the amount of carbon dioxide produced, using the ideal gas law and the compressibility factor, Z.

With the help of this reactor the interdependence between the production of carbon dioxide during the fermentation process of the dough and the pressure, temperature, humidity to which it is subjected can be analyzed, a study that can represent the precursor of the mathematical modeling of an industrial fermentation process.

The calculation of the proving energy consumption in the three stages revealed the hourly energy required to obtain the leavened bakery products. The calculation algorithm presented for determining the energy consumption during proving with respect to ensuring the parameters of temperature and relative humidity, can be used for all existing types of provers, by replacing the initial parameters necessary to run the algorithm in the Mathcad program.

CHAPTER 5
EXPERIMENTAL RESEARCH REGARDING BREAD DOUGH PROVING PROCESS

5.1. EXPERIMENTAL RESEARCH OBJECTIVES

The general objective of this PhD thesis is the development and implementation of an automatic control system for the working regime of dough provers, using the concentration of carbon dioxide released in the proving chamber to control the final fermentation process of dough pieces.

Among the specific objectives, we can mention:

- identification of the optimal values of the CO_2 concentration released during fermentation process for the manufactured bread assortments;
- identification of optimal values for parameters of temperature and relative humidity for the fermentation of each assortment of bread manufactured on an existing technological line;
- increasing the stability of the entire fermentation process by ensuring an individual proving program, specific to the target assortment;
- monitoring the fermentation process through an appropriate computer-assisted program.

5.2. APPARATUS AND EQUIPMENT USED IN LABORATORY EXPERIMENTAL DETERMINATIONS

The experimental determinations were performed both in our own laboratory, developed together with the company Mg Biotech (Bucharest, Romania), and in the Panifcom bakery factories, - Iași and ALX-ROM, - Rusănești, Olt.

5.3. METHODOLOGY OF EXPERIMENTAL DETERMINATIONS FOR LABORATORY RESEARCH

The working scheme for obtaining experimental data in laboratory is illustrated in figure 5.8.

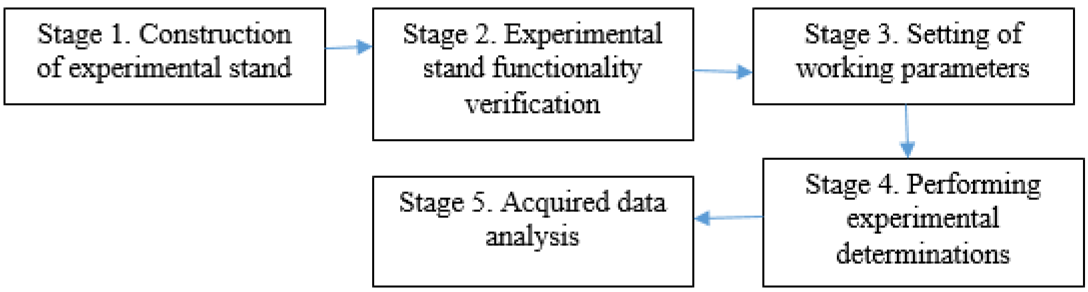


Fig. 5.8. The steps of obtaining experimental data using the experimental stand

5.3.1. Methodology of experiments performed in the laboratory, using pressure variation

Through the experimental determinations performed at different temperatures and with different types of flour, the possibility of developing a method of analysis of the fermentation process under controlled conditions was followed.

Two sets of experiments were performed:

a) measuring the pressure in the airtight container in which a piece of dough with a standard recipe (flour, water, salt, yeast) was introduced, as a result of the fermentation process;

b) measuring the concentration of carbon dioxide released during the fermentation process, under the same conditions, using a dedicated device.

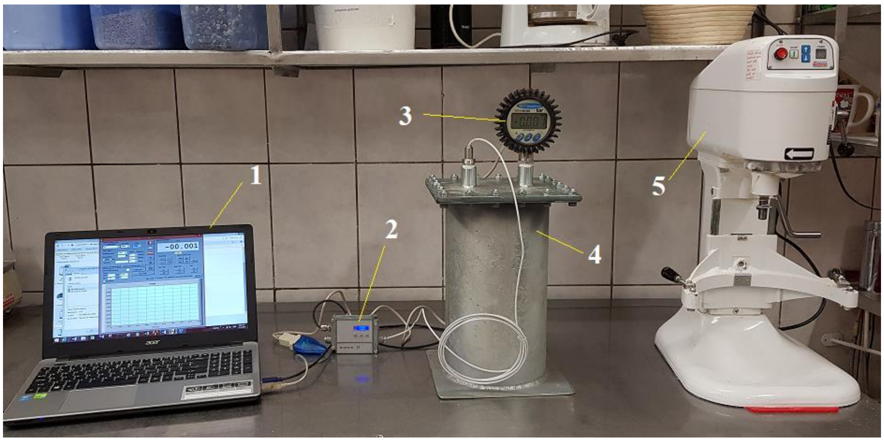


Fig. 5.9. Experimental stand for the fermentation process study of dough

1. laptop; 2. infrared measuring device and temperature recorder; 3. pressure measuring and recording apparatus; 4. cylindrical container; 5. mixer

The role of the fermentation process analysis using the experimental stand from fig. 5.9 was to establish the possibility of correlating the measured pressure in the reactor with the specific volume of carbon dioxide produced by the piece of dough subjected to the experiment, under certain controlled conditions of temperature and humidity.

5.3.2. Methodology of experiments performed in the laboratory using the concentration of carbon dioxide

The evaluation of the fermentation process of wheat flour dough in terms of carbon dioxide concentration was also carried out on a small scale, using the Miwe Aeromat oven with a capacity of 10 trays, dimensions 400 x 600 mm, with prover and integrated temperature control panel and humidity. Carbon dioxide measurements were performed with the Trotec CO2 BZ25 device (Trotec, England). The working temperature and relative humidity were additionally monitored, using a metrologically verified thermo-hygrometer. The equipment is shown in fig. 5.11, [72].

Each fermentation experiment was performed for 3600 seconds, at a controlled temperature, during which time the CO2 measuring device recorded the concentration values in the fermentation chamber every 10 seconds. The carbon dioxide concentration was first measured without charging the prover. At each experiment, the initial measured concentration was 586 ppm.

Also, the dimensions of the finished products obtained were determined, immediately after baking and their volume, using the Fornet method, according to STAS 91-83, 4 hours after baking.

5.4. APPARATUS AND EQUIPMENT USED IN BREAD FACTORY EXPERIMENTS

The experimental determinations from the Panifcom bread factory, Iași, Romania, were performed in March - June 2020 using the provers from the factory (one spiral prover, Tecnopool, Italy, two plate provers, Werner Pfleiderer, Germany). Also, various measuring and control equipment was used, as well as the air conditioning system, designed and developed by the author for the application of the “MACDA” method, together with the company Mg Biotech, Romania.

5.4.1. Provers used to perform experimental determinations in the factory

The fermentation process of bread dough was analyzed in two Werner provers of the same type, but with different fermentation capacities, 2500 pcs / h and 3750 pcs / h, respectively. The difference in capacity is given by the number of plates. Each plate can hold 24 pieces of dough of 0.300-0.565 kg.

A) The Tecnopool spiral type prover (Italy), (fig.5.12), has a capacity of 2500 pieces x 0.300-0,500 kg / piece of dough / h, and the fermentation time is 60 minutes.

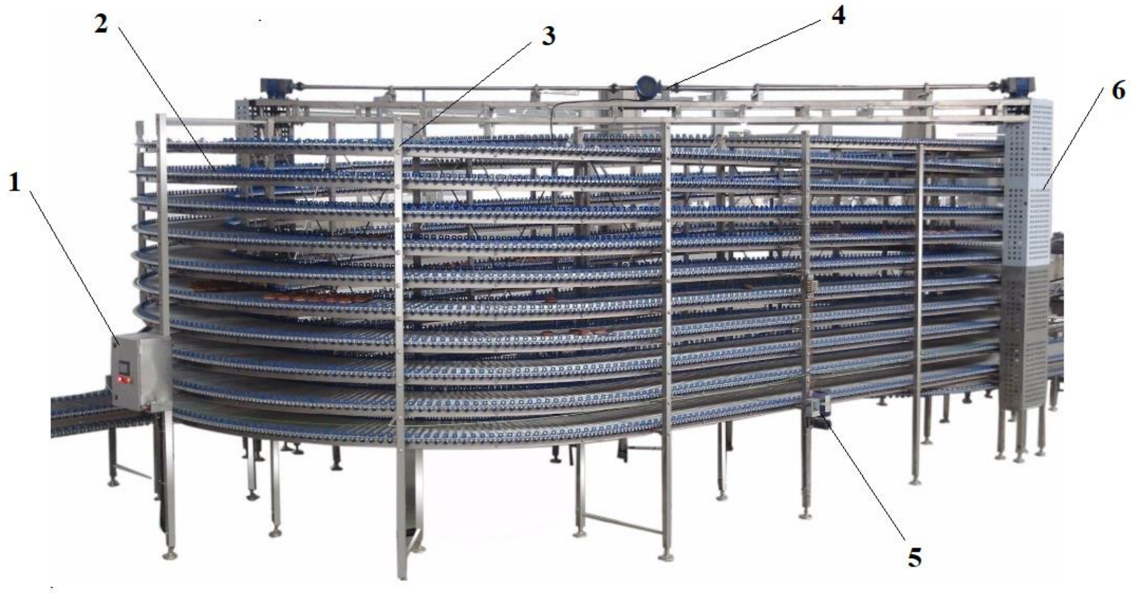


Fig. 5.12. Spiral-type prover, Tecnopool, [183]
1. control panel; 2. conveyor belt; 3. frame; 4. horizontal transmission; 5. belt chain lubrication system; 6. vertical transmission

B) Prover Werner Pfleiderer, Germany, [215] has different working capacities, depending on the model.

Fig.5.15. Werner Pfleiderer plate prover, [215]

1. proving chamber; 2. touch screen for viewing the prover's parameters; 3. control panel; 4. shaper for long dough

Specific system for controlling the concentration of carbon dioxide in leaveners

The experiments for determining the possibility of automatic control of dough fermentation process were performed with an air conditioning system, which is of original design and which is the subject of patent no. 133450 dated 11/27/2020, granted by OSIM Romania, [108].

In fig. 5.17 and 5.18 are schematically presented the component parts of the system and the logical operating system.

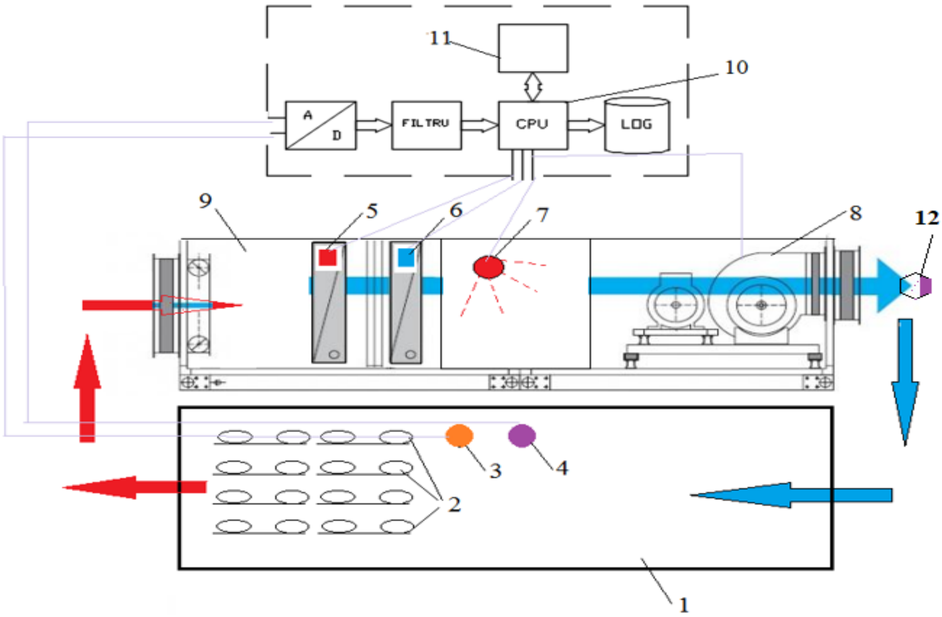


Fig. 5.18. Components of the air conditioning system for the control of the concentration of carbon dioxide in provers, [74]

1. proving chamber; 2. pieces of dough; 3. temperature sensor; 4. humidity sensor; 5. heat exchanger for hot water; 6. heat exchanger for cold water; 7. carbon dioxide measuring sensor; 8. fan; 9. air treatment plant; 10. PLC; 11. touch screen; 12. humidifier

The system refers to a method of controlling the proving process of bread dough (adjusting the level of fermentation of dough pieces) in continuous flow industrial provers, by changing the temperature and relative humidity depending on the measured CO_2 concentration. To correlate the fermentation level of the dough pieces (using the external dimensions and texture), the method uses a CO_2 sensor (7) which is located in the air exhaust pipe from the prover in order to obtain an average concentration value of carbon dioxide inside the prover. At the same time, the relative temperature and humidity values are automatically changed to an average value set in the work program.

A) Air conditioning system for controlling the concentration of carbon dioxide in leaveners. Transducers are peripheral equipment whose role is to take electrical signals and transmit the measured quantities to a PLC. The system uses the following types of transducers: SACO2 CO_2 sensor, (Siemens, Germany, fig. 5.19).

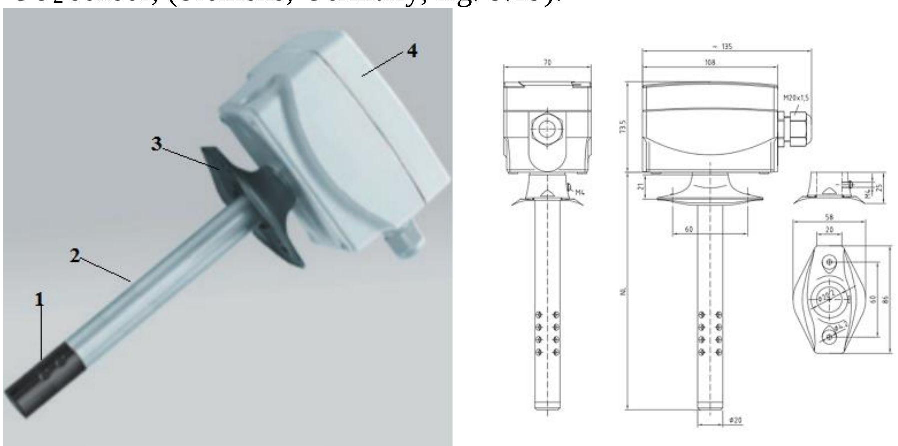


Fig. 5.19. SACO2 CO_2 sensor, (Siemens, Germany), [224,225]
1. the sensor for measuring the concentration of CO_2 in the air recirculated in the prover; 2. the rod of the transducer that is mounted in the piping; 3. sealing element; 4. the housing of the electronic components that transmit the measured data in real time

B) Siemens QFM 2171 temperature and relative humidity sensor, Germany (fig. 5.20).

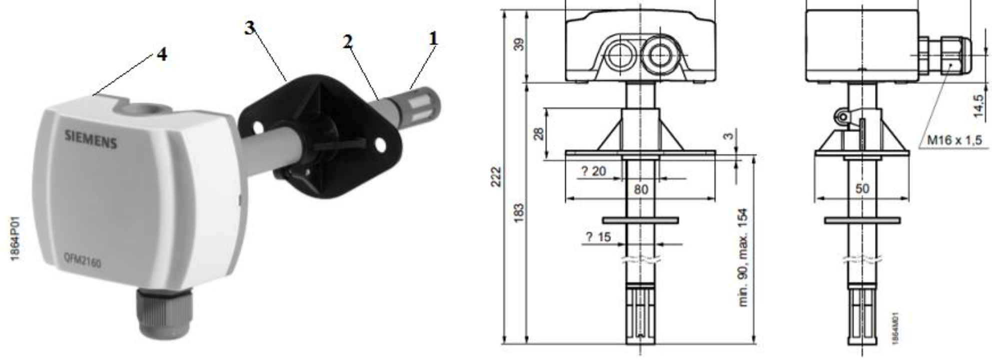


Fig. 5.20. Siemens QFM 2171 Relative Temperature and Humidity Sensor, Germany, [226]
1. temperature and humidity transducer from the air recirculated in the prover; 2. the rod of the transducer that is mounted in the piping; 3. sealing element; 4. electronic components housing

An air conditioning unit is used to control the temperature and relative humidity inside the prover. The air conditioning unit (CTA), mounted on the analyzed provers, which heats, cools, filters and humidifies the air is built by the company Biotehnologicreativ, [214].

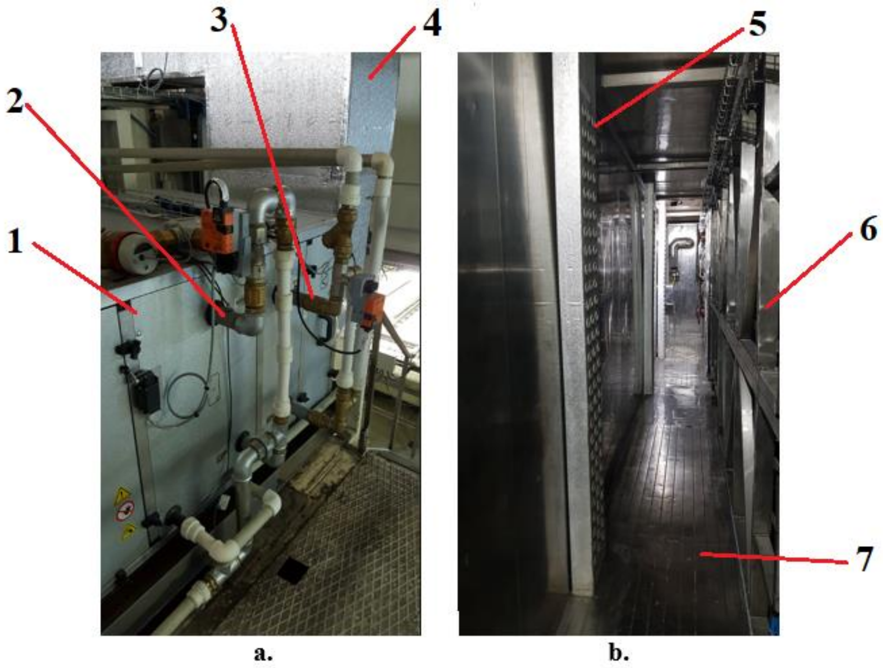


Fig. 5.25. Construction elements of the air conditioning system
a. hot and cold water supply of CTA; b. internal piping of the prover:
1. air conditioning unit (CTA); 2. heat exchanger for hot water; 3. heat exchanger for cold water; 4. prover air duct; 5. air discharge pipes inside the prover; 6. frame; 7. inside fermentation chamber

A) Process description regarding the control of carbon dioxide concentration in the prover

Figure 5.29 shows the main interface of the system's control panel, which displays the following sub-menus and parameters:

1. Manual (28) or automatic (1) mode selection button. In manual mode, the operator sets the temperature and humidity in the section of the work programs and the installation ensures these parameters, through the touch interface of the control unit of the air conditioning system.

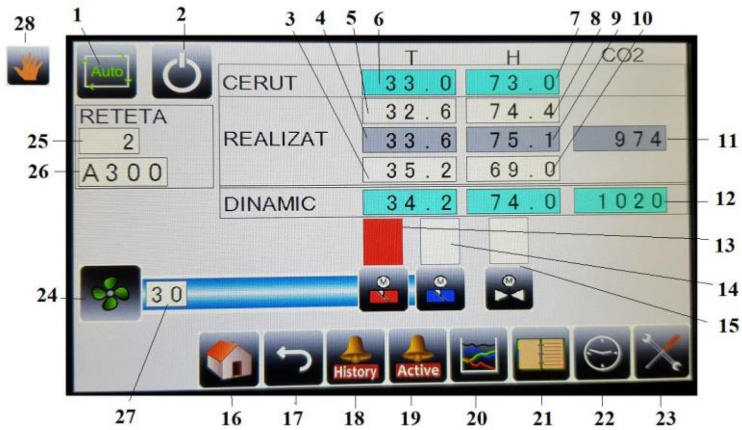


Fig. 5.29. Dynamic dough fermentation control plant control screen

In the automatic mode, the operator sets the value of the concentration of carbon dioxide released in the prover during the fermentation process, correlated with the desired volume of the product concerned. Depending on this value, the system dynamically changes the working values of the temperature and relative humidity parameters.

2. The OFF / ON button stops or starts the installation; when the system is operating, the fan (24) on the screen is flashing;
3. Temperature measured in the prover for the lower level; the temperature sensor that is mounted on the ceiling of the first proving floor transmits the measured value to the control panel, and this is displayed on the touch screen in real time;
4. Temperature measured in the prover for the intermediate level; the temperature values measured by the sensor mounted on this level are used for reference;
5. Temperature measured in the prover for the upper floor; the temperature sensor mounted on the ceiling of the last proving floor transmits the measured value in real time;
6. The set temperature for operating in manual mode;
7. The relative humidity for operating in manual mode;
8. Relative humidity measured in the prover for the upper floor;
9. Relative humidity measured in the prover for the intermediate level; the measured values of relative humidity at this floor are used for reference;
10. Relative humidity measured in the prover for the upper floor;
11. The concentration of carbon dioxide measured in the prover;
12. The carbon dioxide concentration set for a given work program;
13. Control for hot water solenoid valve;
14. Control for cold water solenoid valve;
15. Control for steam solenoid valve;
16. Home menu (basic interface) (fig. 5.29);
17. Back key;
18. Alarm history;
19. Active alarms;
20. Diagrams of temperatures, humidity and carbon dioxide for the last 2 hours of prover operating (figure 5.30);
21. Menu for creating and storing work programs;
22. Time and date set;
23. Icon indicating the operation of the installation when the fan is flashing;
24. Name of the work program;
25. Work schedule number;
26. The frequency at which the fan operates;
27. The icon that shows the operating status of the installation;

The values of temperatures, relative humidity and carbon dioxide are recorded every second and stored on an external card.

In figure 5.32 is presented a work program example. When the measured carbon dioxide value reaches 1500 ppm, the cooling demand of the system is 100% and the heating demand - 0%. When the measured carbon dioxide value reaches 1100 ppm, the cooling demand of the system is 0% and the heating demand - 100%. When the measured value of carbon dioxide reaches 1300 ppm, both the cooling demand of the system and the heating demand is 50%.

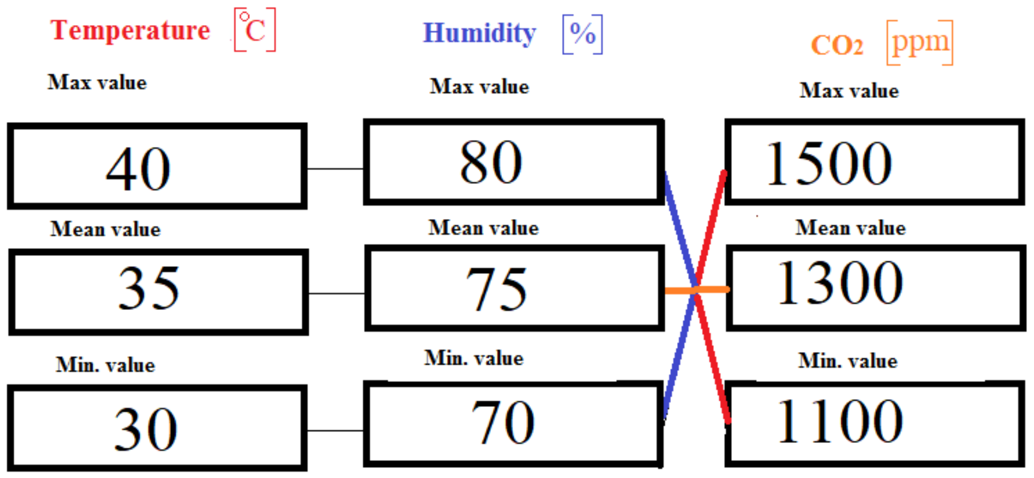


Fig. 5.32. Example of work schedule

5.4.3. Methodology of experiments using the air conditioning system to control the concentration of CO_2 in the prover

The working scheme for obtaining the experimental data using the fermentation plant for the application of the MACDA method is presented in figure 5.33.

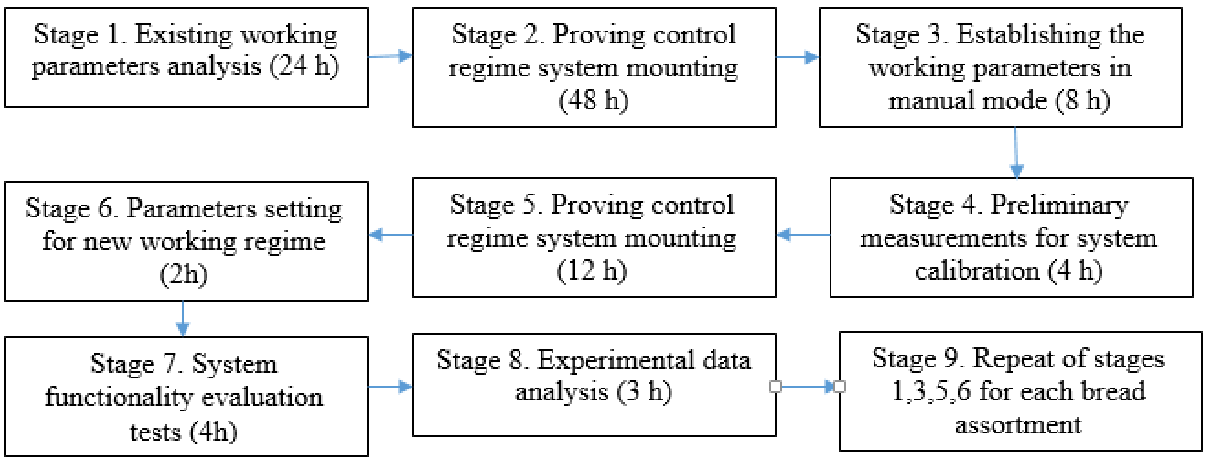


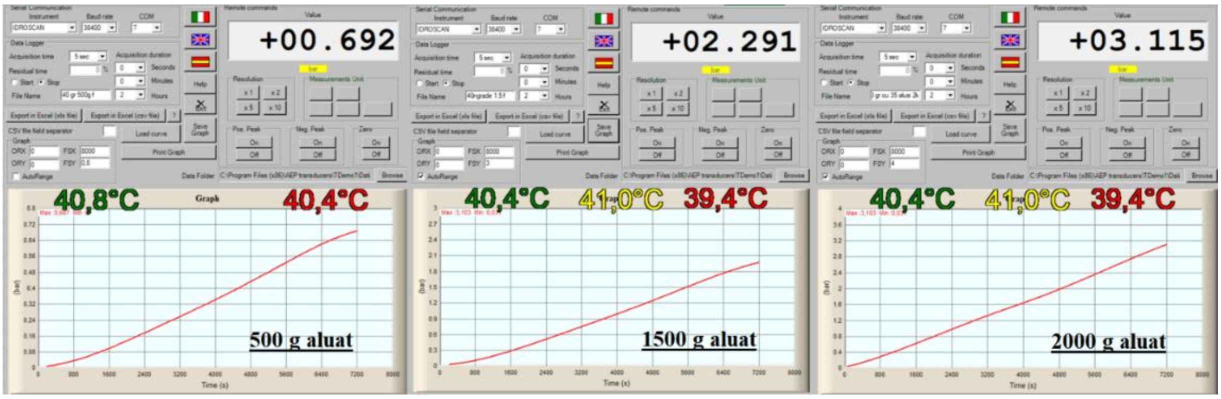
Fig. 5.33. The stages of implementing the control installation of the parameters of the proving work regime

5.5. EXPERIMENTAL RESEARCH REGARDING BREAD DOUGH PROVING PROCESS

5.5.1. Laboratory research using pressure variation in enclosed space

The study presents the comparative analysis between the pressure diagrams and those of variation of the released carbon dioxide, obtained after measuring two fermentation processes performed with doughs of wheat flour with different extraction, type FA 650, respectively FI 1850 (whole wheat). The measurements performed were used to verify a mathematical model for determining the amount of carbon dioxide produced during fermentation, using the increase in pressure in a sealed container (reactor), presented in chapter 4.

Figure 5.35 shows that as the amount of dough increases, so does the final pressure at which the experiment is stopped at 7200 seconds,which varies between 40 and 120 minutes.



a) b) c)

Fig. 5.35. Variation of pressure in the reactor for three different amounts of dough
a-500 g dough 5s; b-1500 g dough; c-2000 g dough

The following tests were performed with a quantity of 2000 g of dough to obtain an amplified response of the results, but at the end of the experiments a mass of 350 g of dough was used for standardization, as it corresponds to the mass of dough usually divided into bakery factories for the assortment of white bread type bagel.

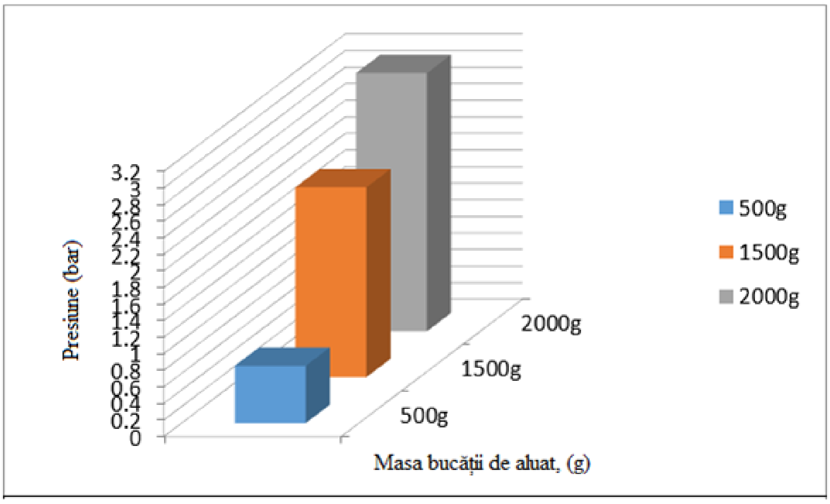
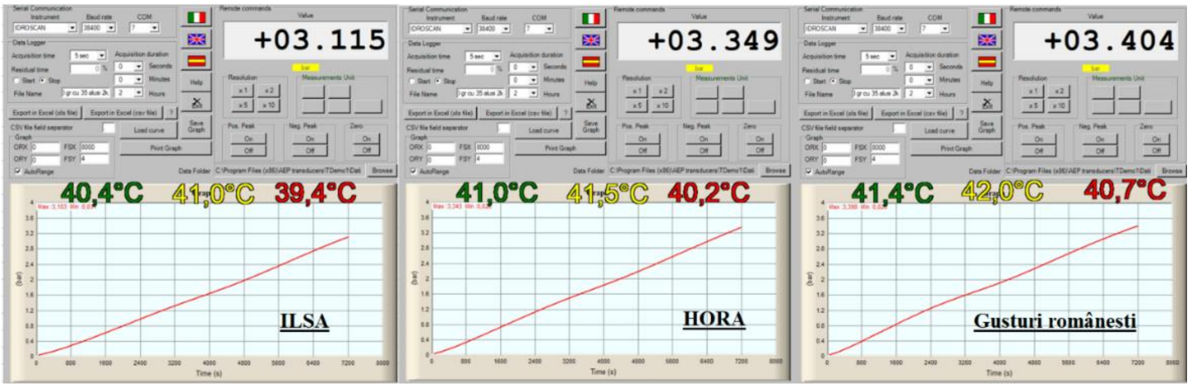


Fig. 5.36. Pressure in the experimental chamber for different amounts of dough

Another set of tests performed was to determine the pressure in the enclosure for several batches of flour type FA-650, from different mills (Fig. 5.37). The doughs were made under the same conditions and were used: flour type 650 (FA_1 650) - mill ILSA, type 650 (FA_2 650) - mill Hora and flour type 650 (FA_3 650) - Gusturi Românești mill; the physico-chemical characteristics of these flours can be observed in table 5.1.



a) b) c)

Fig. 5.37. The pressure in the reactor for three types of flour type FA-650
a- ILSA flour; b- Hora flour; c- Gusturi Românești flour

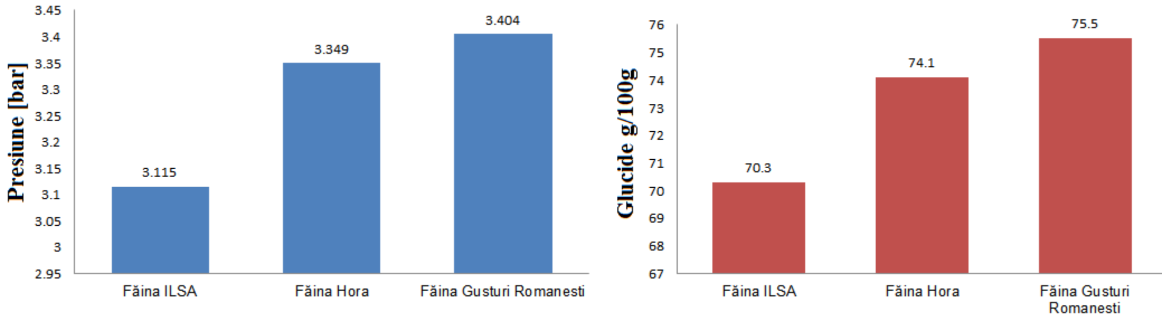


Fig. 5.38. The pressure in the reactor and varying the amount of sugar to flour FA-650 from different mills

The pressure variation due to the use of different extraction flours was also analyzed, respectively: flour type FA-650 from ILSA mill and type FI-1850, from 7Spice mill (fig. 5.39).

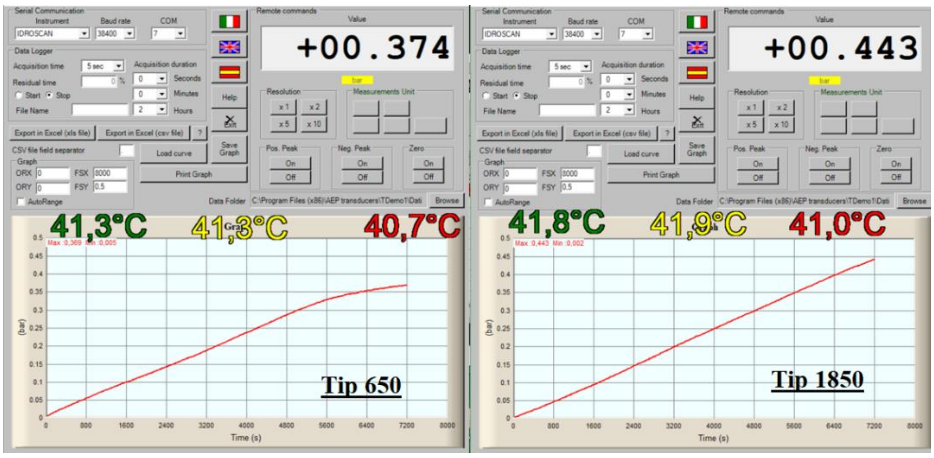


Fig. 5.39. Reactor pressure when using different extraction flours: left type 650; right-type 1850 (ash content)

5.5.2. Evaluation of carbon dioxide concentration released by bread dough during proving process at reduced scale

This subchapter presents the analysis of the leavening process of wheat flour dough, in order to establish a correlation between the concentration of carbon dioxide (ppm) released and the parameters of the working regime (time and temperature).

To determine the level of fermentation in correlation with the concentration of carbon dioxide released during the fermentation process and the working temperature, the bread dimensions (length, width, height) obtained after each experiment were measured and compared with those in STAS 91/1983 for white bread of 300 g (length - 28-30 cm, width - 10-11 cm, height - 7-8 cm).

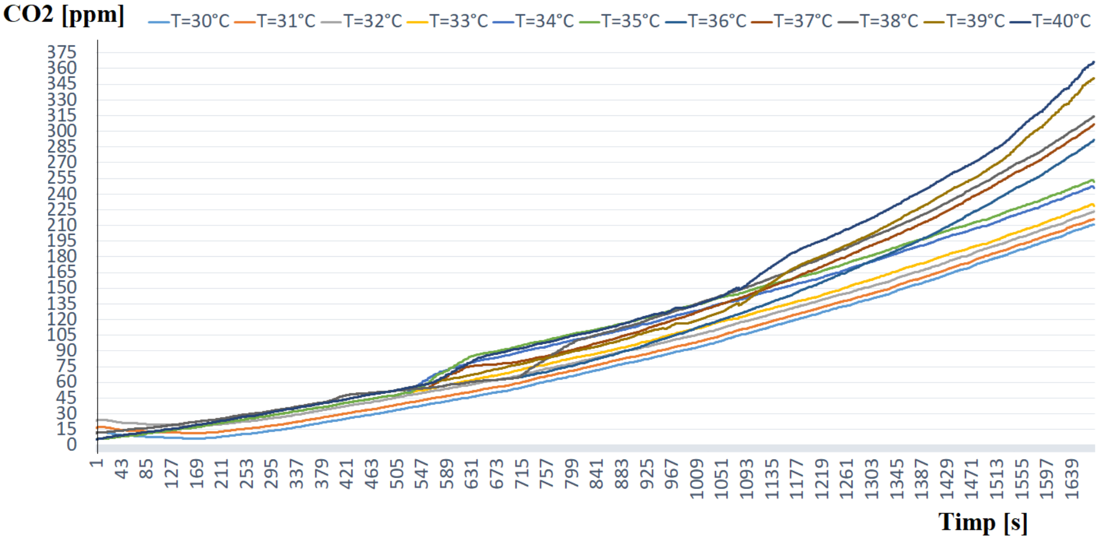


Fig. 5.41. CO_2 values recorded during the leavening process for a piece of dough at 11 different temperatures (from grade to grade), [72]

Analyzing the graphs in fig. 5.41, it can be observed that for the interval of 30 -33 °C, the development curves of carbon dioxide are exponential and the difference for intervals of 1 °C does not exceed 6 ppm at the end of the fermentation process.

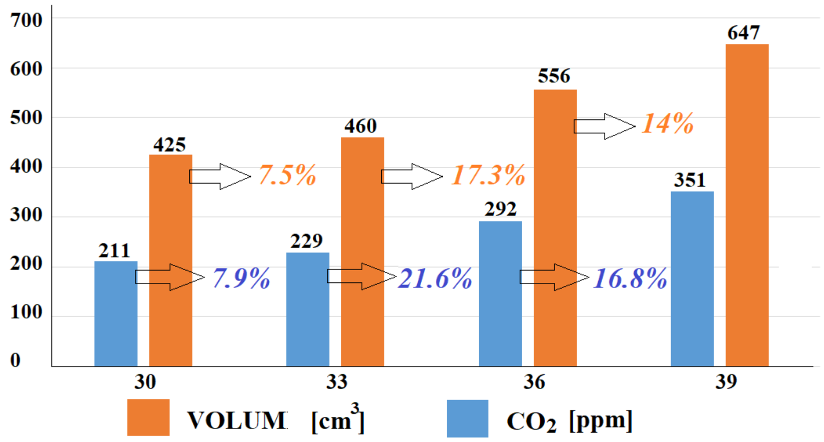


Fig. 5.43. Comparative values of bread volume and CO_2 concentration recorded for 4 leavening processes

Figure 5.42 shows the differences between the final values of carbon dioxide concentration recorded during the determinations at the end of the fermentation process (3600 s).

Taking into account the results obtained in the first experimental stage, relevant proving temperatures for carrying out the experimental research in the second stage were determined: 30

°C, 33 °C, 36 °C and 39 °C. Figure 5.43 shows the comparative values of the concentration of carbon dioxide released during the fermentation process and the obtained breads volume, as well as the difference (in percentages) between the successive values of the volume of breads, and the CO_2 concentration respectively.

It can be seen that there is a correspondence between the CO_2 values and the volume of the breads. Thus, at 33 °C, compared to 30 °C, the concentration of CO_2 released and the volume of breads obtained increase by 7.9% and 7.5%, respectively. At 36 °C, the CO_2 concentration increases by 21.6%, and the bread volume by 17.3%. From 36 °C to 39 °C, the increase in volume is reduced to 14% and the CO_2 concentration to 16.8%.

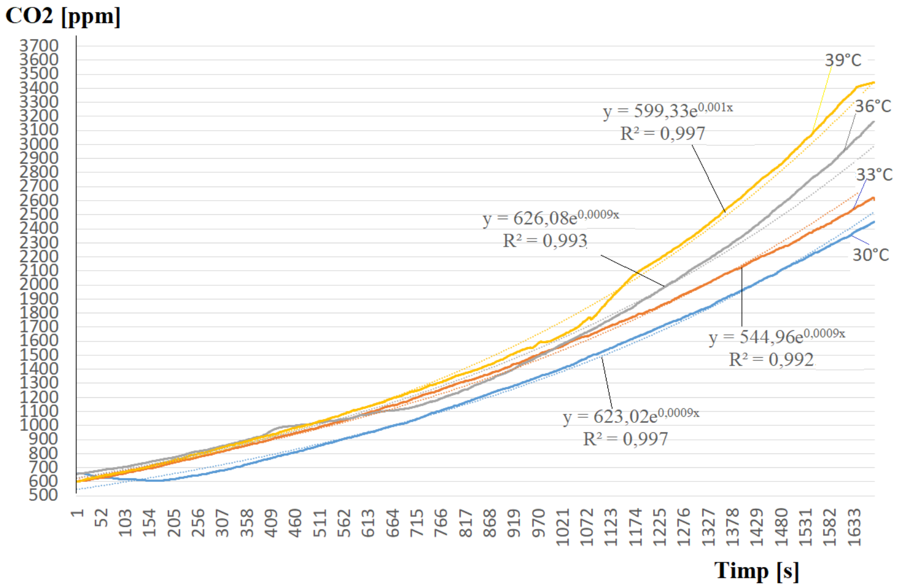


Fig. 5.44. The variation of CO_2 released for the nine pieces of dough proving at 4 different temperatures, [72]

Although the largest volume of the dough piece was obtained for the dough fermented at 39 °C, it can be seen in table 5.19 that the dimensions of the product do not correspond to the quality standard (length - 28-30 cm, width - 10-11 cm, height - 7-8 cm, according to STAS 91/1983). Taking this into account, the best dough development in correlation with the CO_2 concentration was recorded at the proving temperature of 36° C, [72].

5.5.3. Bread factory experimental research for proving control method development

The experimental determinations were performed at the Panifcom bread factory, Iași, between May 2018 and June 2019.

A) Experimental determinations using the Werner prover (with plates)

After installing the dynamic air conditioning systems of the prover and checking the functionality from a technical point of view, we proceeded to analyze the working regime of the Werner line prover, with a capacity of 3750 pcs / h. Figure 5.46 shows the variation of carbon dioxide in the prover from the beginning of the measurements, for a cycle of 90 minutes, the prover having a nominal load capacity of 2069 kg of dough (the graph corresponding to the articles in Annex 11).

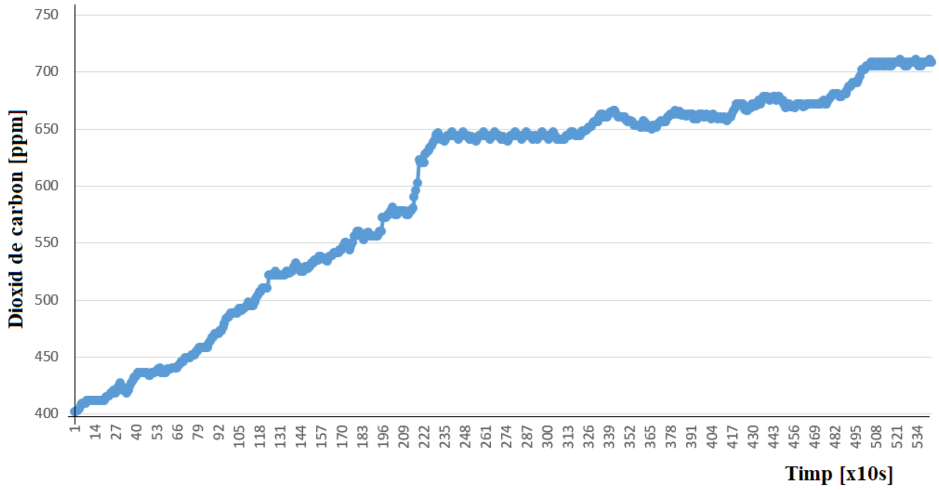


Fig. 5.46. Variation of carbon dioxide released for the first 90 minutes of Werner prover working with system set in manual mode

The temperature variations recorded in the center of the dough pieces have an average of 0.4 ° C, which can lead to differences of up to 6% in the volume of the finished products (Annex 11).

B) Experimental determinations using the Tibiletti prover (with plates)

The parameters of the working regime practiced by the manufacturer in the plates prover for the **the Tibiletti line** are: temperature - 35 °C, relative humidity - 75%, leavening time - 60 minutes.

Figure 5.48 shows the variation of the concentration of carbon dioxide released in the prover from the beginning of the measurements, for a cycle of 60 minutes, the prover being loaded with approximately 887 kg of dough.

Figure 5.48 shows the variation of the concentration of carbon dioxide released in the prover from the beginning of the measurements, for a cycle of 60 minutes, the prover being loaded with approximately 887 kg of dough.

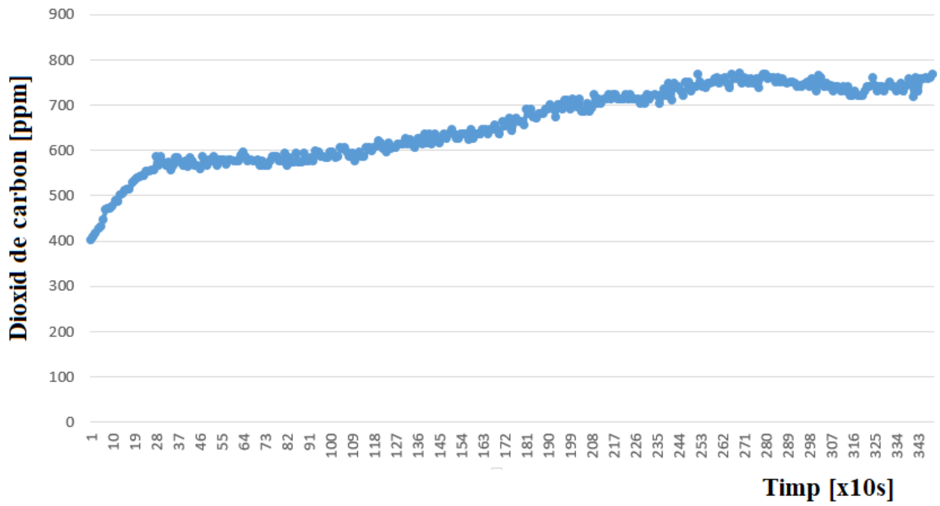


Fig. 5.48. The CO_2 variation for the first 60 minutes of working with the Tibiletti prover, in manual mode

Analyzing figure 5.48, it can be seen that the carbon dioxide concentration after loading the prover with dough, reaches values around 770 ppm.

A) Experimental determinations using the continuous prover Tecnopool

The parameters of the working regime practiced by the manufacturer in the continuous spiral type prover, Tecnopool, are: temperature - 33 °C, relative humidity - 74%, proving time - 60 minutes. The prover is brought to established working parameters before the dough pieces are loaded (about 30 minutes earlier).

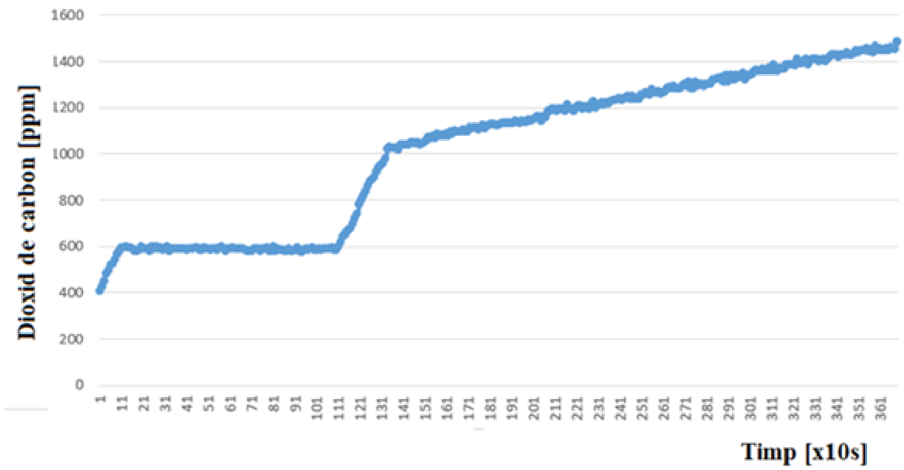


Fig. 5.50. Variation of carbon dioxide concentration for the first 60 minutes of operating with the Tecnopool prover in manual mode

5.5.4. Comparative analysis of two air conditioning systems mounted on Tibiletti prover

The analysis of the variation of the working parameters was performed on the Werner Pfleiderer prover, for the Tibiletti line, before and after its optimization by mounting the air conditioning system based on measuring the carbon dioxide concentration released during the fermentation process.

Figure 5.53 shows the variation of temperature and humidity inside the prover, at the level of dough pieces. It is found that the temperature varies between 28 - 36 °C, and humidity between 48 - 80%.

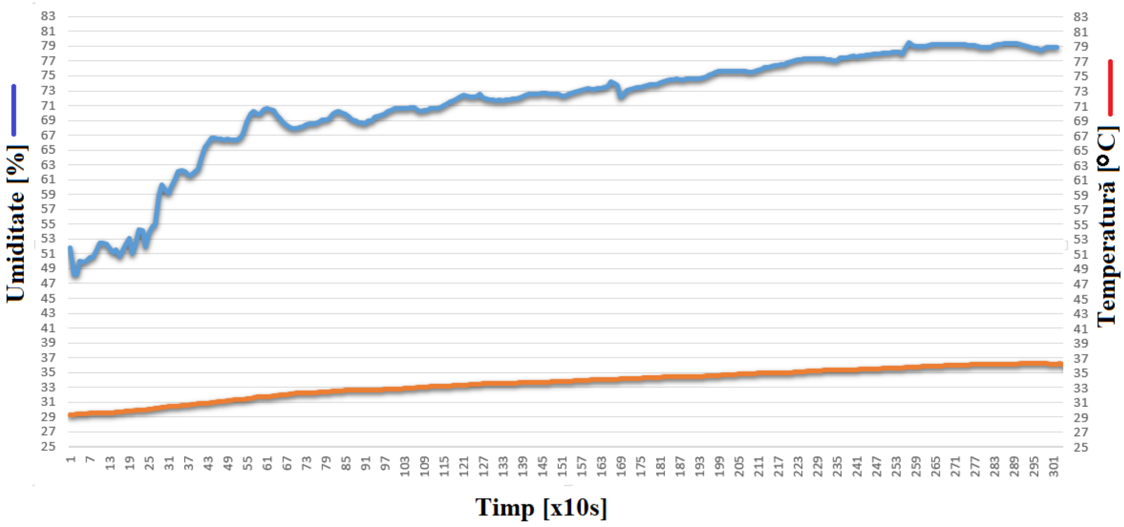


Fig. 5.53. Variation of temperature and humidity inside the prover during the fermentation process, when operating with conventional air conditioning, [74]

After mounting the new air conditioning system that uses the release of carbon dioxide for the control of the proving process, and the sensors of temperature (3 pcs), humidity (3 pcs) and carbon dioxide (1 pcs), as well as the connection of the control panel to hot and cold water pumps and steam solenoid valve and fan, respectively, in the work program was introduced the value of the desired carbon dioxide concentration for fermentation of the product "White bread 300 g" - 750 ppm, temperature - 35 °C, relative humidity - 75%).

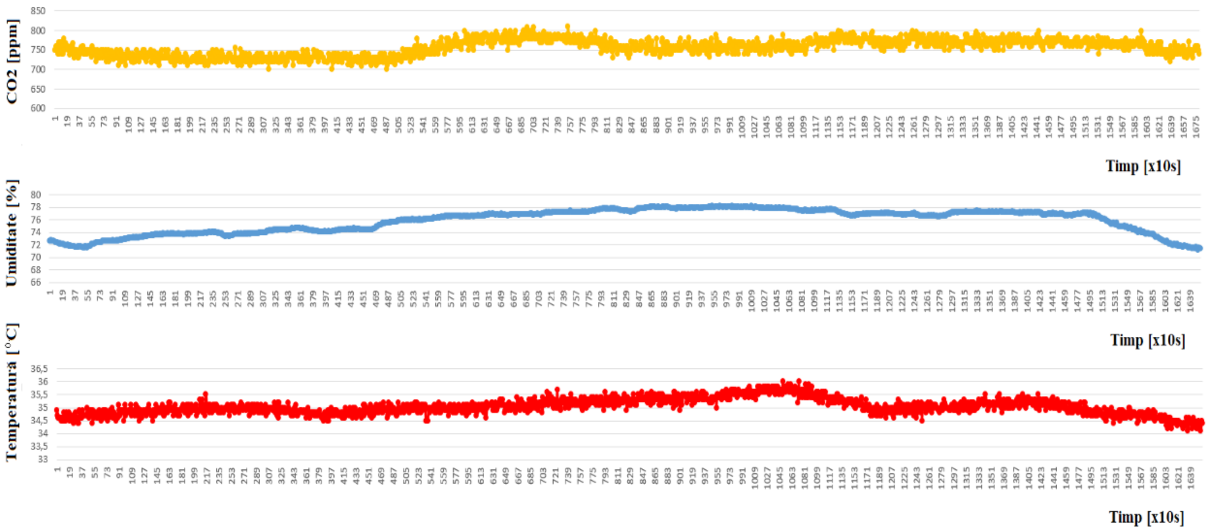


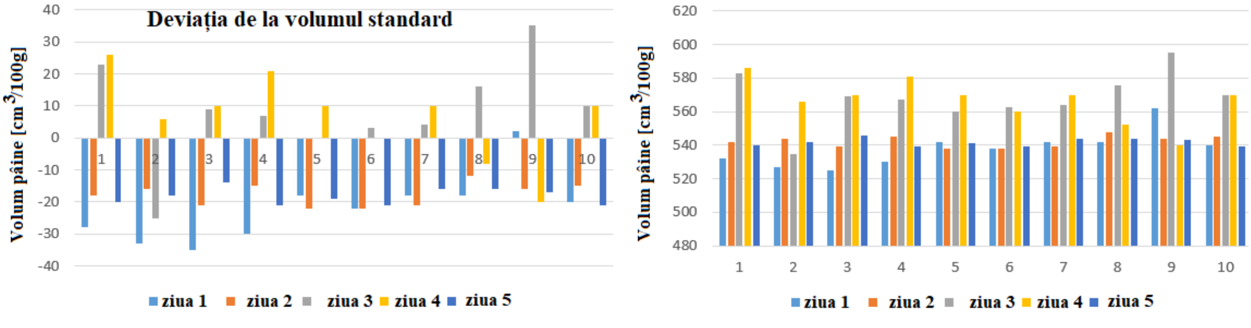
Fig. 5.55. Variation of temperature, humidity and concentration of carbon dioxide in the operation of the leavener with the dynamically controlled air conditioning system, [74]

Figure 5.55 shows a better uniformity of temperature and humidity values throughout the fermentation time, which ensures a constant fermentation process throughout its duration and thus a much smaller variation in the volume of finished products obtained after baking. The variation between the minimum and maximum temperature was below 1 ° C and the humidity of maximum 3%, and the variation of the amount of carbon dioxide does not exceed the value of 100 ppm, [74].

Figures 5.56 and 5.57 respectively show the variation of the volume of the finished products, both for the leavener with conventional air conditioning and for the one with the air conditioning system with automatic control of the leavening process.

Figure 5.56a shows the deviation from the volume standard for each average volume of products obtained at the conventional air conditioner. It can be seen that the largest deviation from the quality standard was +35 cm³ / 100g and the smallest was -35 cm³ / 100g. In Figure 5.56b, you can see the differences in the volume of products obtained at the same time, on different days, with differences of even 12%, with the same manufacturing recipe and the same adjustment parameters.

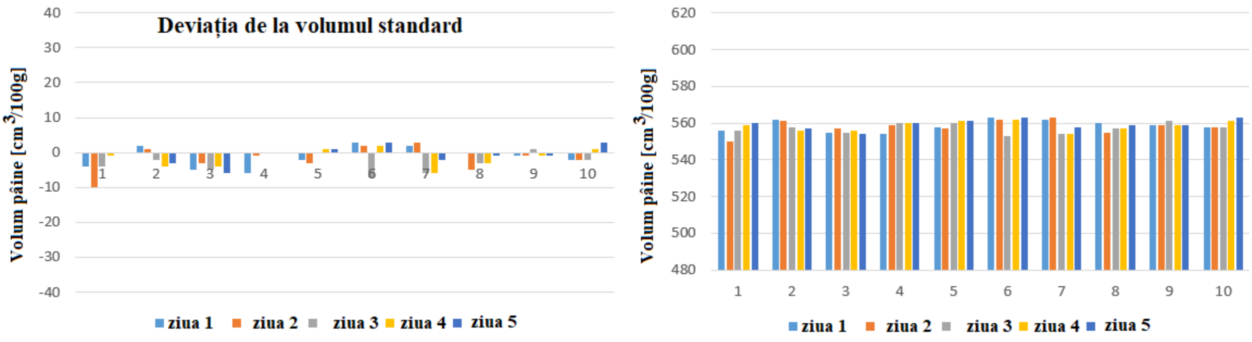
Figure 5.57a shows the deviation from the volume standard for each average volume of products obtained for the air conditioner with automatic control of the fermentation process. The largest volume deviation from the quality standard was +3 cm³ / 100g and the smallest was -10 cm³ / 100g. Figure 5.57b shows the volume differences of the products obtained at the same time, on different days.



a. b.

Fig. 5.56. Variation of the volume of breads obtained for the leavener with conventional air conditioning

a. the variation of the bread volume over a period of 5 days obtained with a conventional air conditioning installation of a leavener; b. the volume of the related breads, monitored for a period of 5 days



a. b.

Fig. 5.57. Variation of the volume of the breads obtained for the leavener with automatically controlled air conditioning

a. the variation of the bread volume over a period of 5 days obtained with the dynamic air conditioning installation of the leavener; b. the volume of the related breads, monitored for a period of 5 days

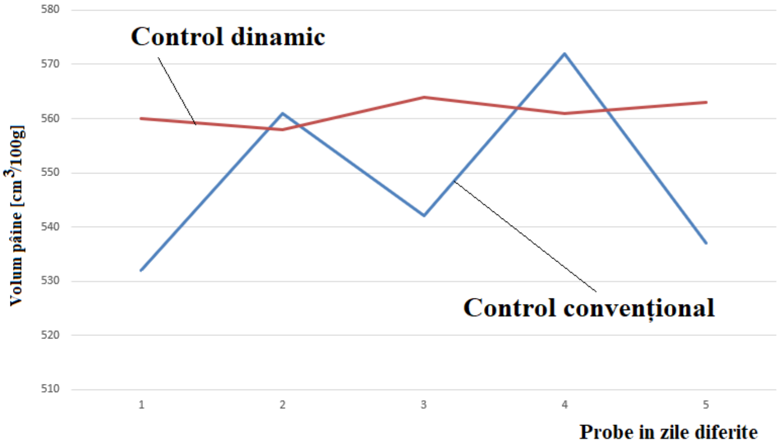


Fig. 5.60. Comparative analysis between the volume of breads obtained with dynamic air conditioning control versus conventional air conditioning control

Analyzing the graphs in fig. 5.60 a greater uniformity of the volume of finished products obtained after baking can be observed when dynamic air conditioning was used.

The data obtained from the measurement of bread volume (tables 5.8, 5.9) were analyzed using the two-factor ANOVA statistical method. The results obtained can be seen in tables 5.10, 5.11, 5.12.

Table 5.12. The ANOVA analysis itself

ANOVA						
Source of variation	*The sum of the squares*	*Degrees of freedom*	*The average of the squares*	*F*	*P-value*	*F crit*
Interaction between samples	4651,86	4	1162,965	19,364	1,6E-11	2,473
Inside the evidence	5405,3	90	60,058			
Total	15362,75	99				

Since F> F_{crit}, and its value $p < 0.001$, hypothesis H_0 is rejected, with a degree of significance of 99.9% and hypothesis H1 is chosen, according to which there are differences with a high degree of significance between at least two averages of the analyzed bread volumes.

5.5.5. Comparative analysis of the working regime for three dough provers

In order to verify the optimal operation of the dynamic air conditioning system, it was monitored on 3 different types of leaveners, from a constructive point of view. The analyzed standard was the CO_2 value (in ppm), respectively, how close to the value set in the program was the average of the CO_2 values measured in the leavener over a period of operation of 4 hours.

It should be noted that, until the operating mode values (temperature, relative humidity, CO_2) set in the program are reached, the air conditioning operates in manual mode, and when the set values are reached, the air conditioning switches automatically to automatic mode.

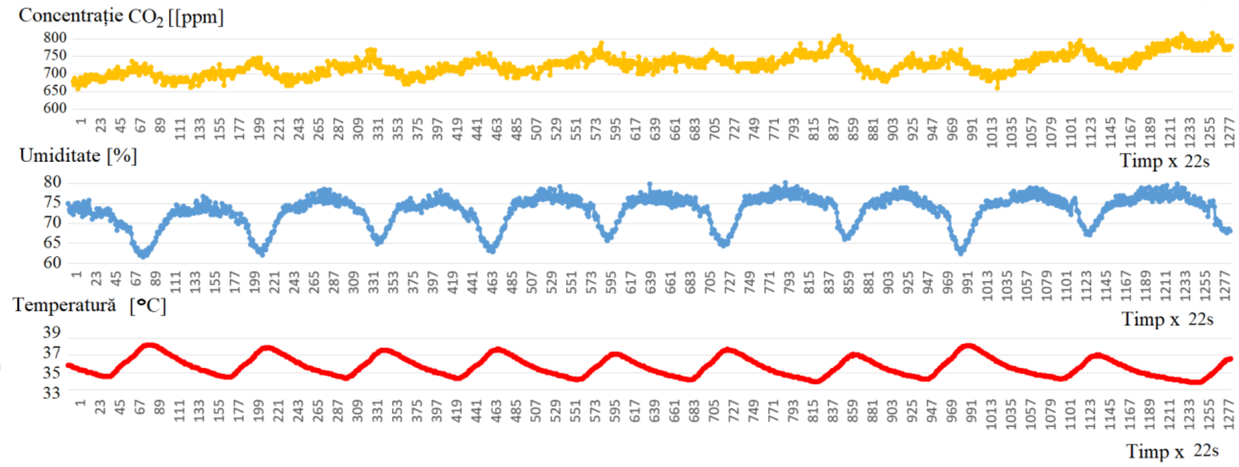


Fig. 5.60. Control of temperature and humidity, depending on the CO_2 concentration for Tibiletti prover

❖ The second plate prover, for the Werner line, has the same construction as the prover for the Tibiletti line, but the fermentation time of the dough is 90 minutes.

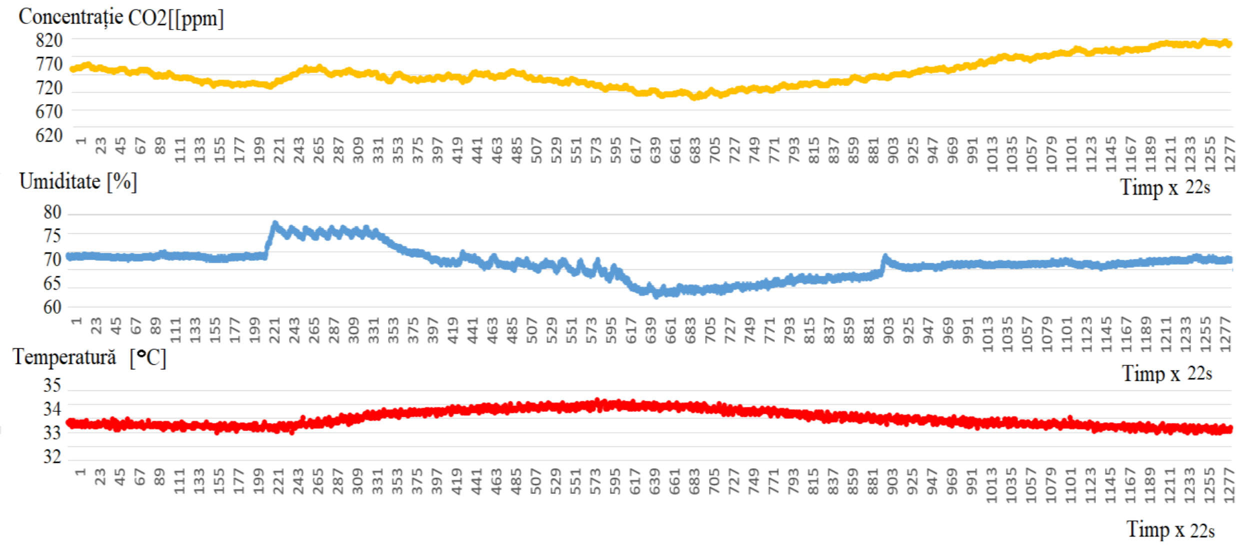


Fig. 5.61. Automatic control of temperature and humidity according to the value of CO_2 released by the prover of the Werner line

Analyzing the variations of temperature, relative humidity and CO_2 concentration in figure 5.61, for a proving operation of about 8 hours, it can be seen that longer proving time allows the establishment of shorter intervals of variation for the working parameters.

❖ The third prover, produced by Tecnopool, Italy, is spiral and has a proving time of 60 minutes.

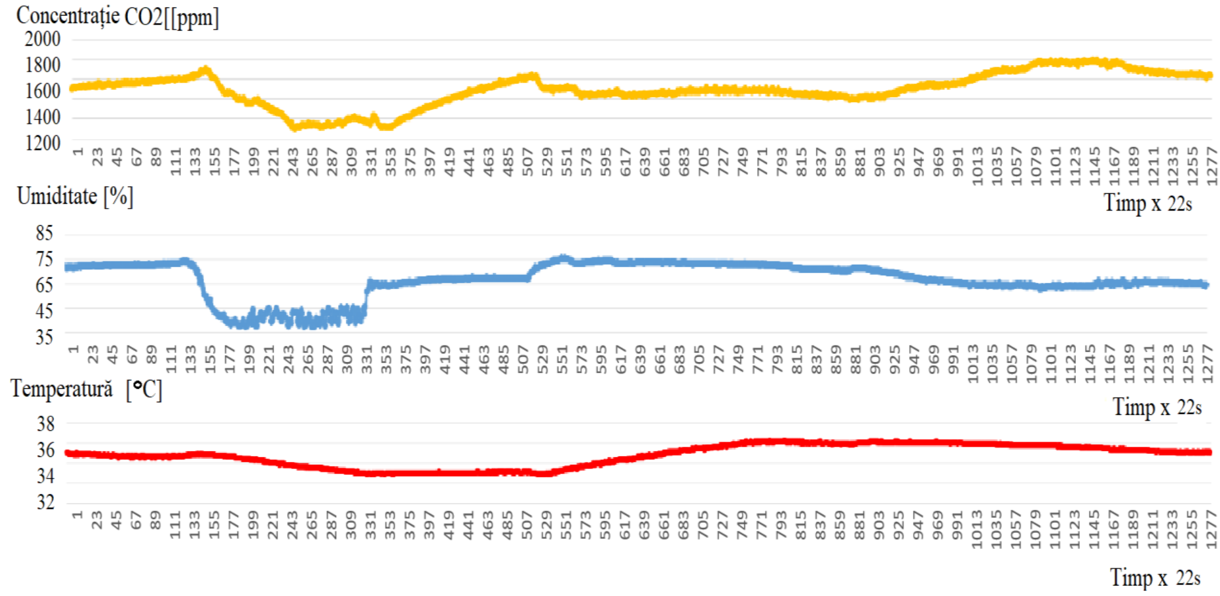


Fig. 5.63. Automatic control of temperature and humidity according to the CO_2 value released in the spiral prover, Tecnopool

The analysis of the control charts for the Tecnopool prover shows a malfunction in the automatic control of the operating mode parameters, because the temperature and humidity parameters do not respond in correlation with the variation of the CO_2 concentration.

It was found that the positioning of the sensor in the proving chamber and not in the piping as in the other two provers, as well as the presence of very small air currents in the prover, lead to the stratification on height of temperature and humidity parameters within very wide limits.

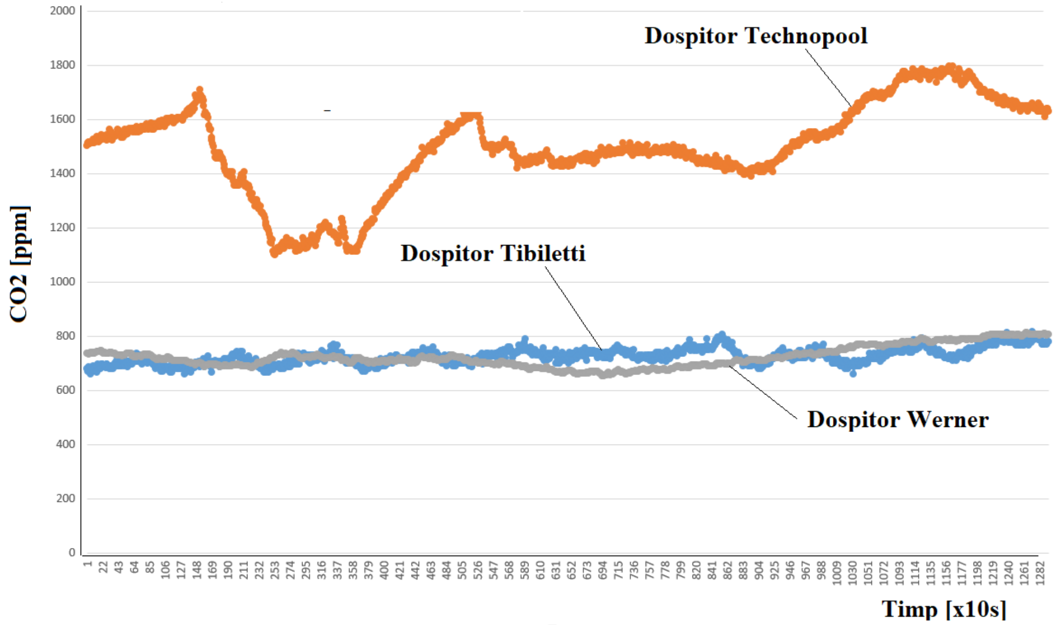


Fig. 5.64. Carbon dioxide concentrations recorded in the 3 provers for 4 hours

- **Analysis of experimental data using the ANOVA statistical method with a single factor**

Table 5.14. The ANOVA analysis itself

ANOVA						
Source of variation	*The sum of squares*	*Degrees of freedom*	*The average of the squares*	*F*	*P-value*	*F crit*
Interaction between samples	512665294	2	256332647	25745,099	0	2,998
Inside the evidence	38621499	3879	9956,5607			
Total	551286793	3881				

Since F> F_{crit}, and the value of p = 0, hypothesis H_0 is rejected, with a degree of significance of 99.9% and hypothesis H1 is chosen, according to which there are differences with a high degree of significance between the averages of carbon dioxide values measured in during the fermentation process in the three analyzed provers, the main cause being the positioning of the carbon dioxide sensor to perform the measurements.

Figure 5.66 comparatively shows the carbon dioxide values set in the work programs compared to the averages of 1294 measured values, under the conditions of automatic air conditioning operation, at the working parameters set out in subchapter 5.4.3.

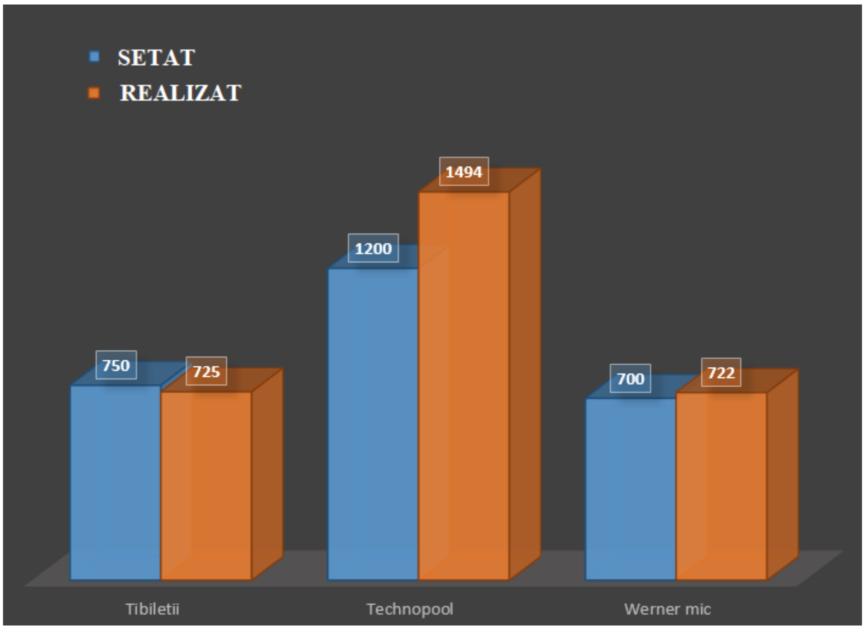


Fig. 5.66. The set CO_2 values and the average of the measured ones, for the 3 dough provers

The Tibiletti prover had a deviation from the set value in the woking program, of 3.7%, the Werner prover had a deviation from the set value of 3.5% and the Tecnopool prover had a deviation from the set value, of 25%, during the 4 hours of operation analyzed.

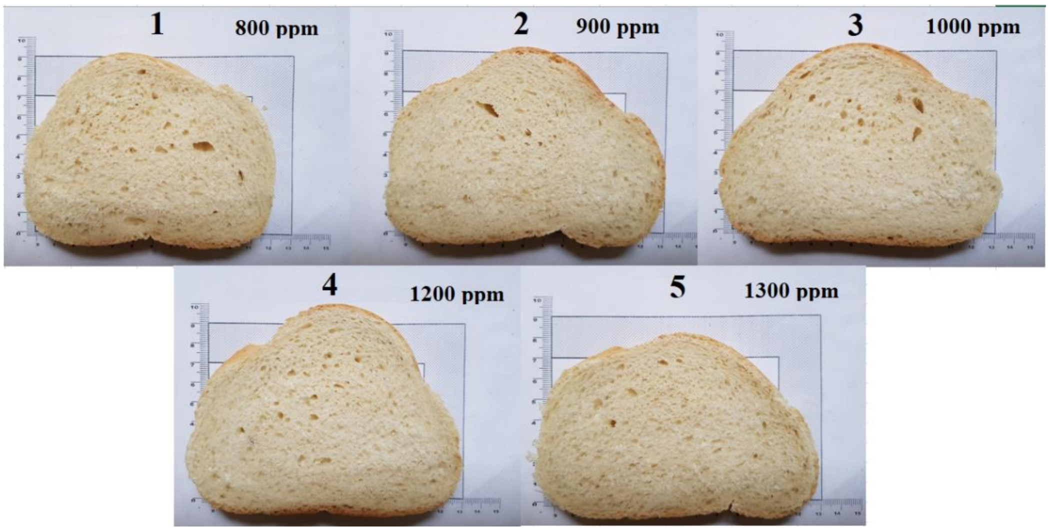


Fig. 5.67. Dimensions of the finished products at different concentrations of carbon dioxide released in the proving chamber

5.5.6. Proving parameters influence on finished product

Figure 5.69 shows the diagrams of variation of the bread volume in the two analyzed cases.

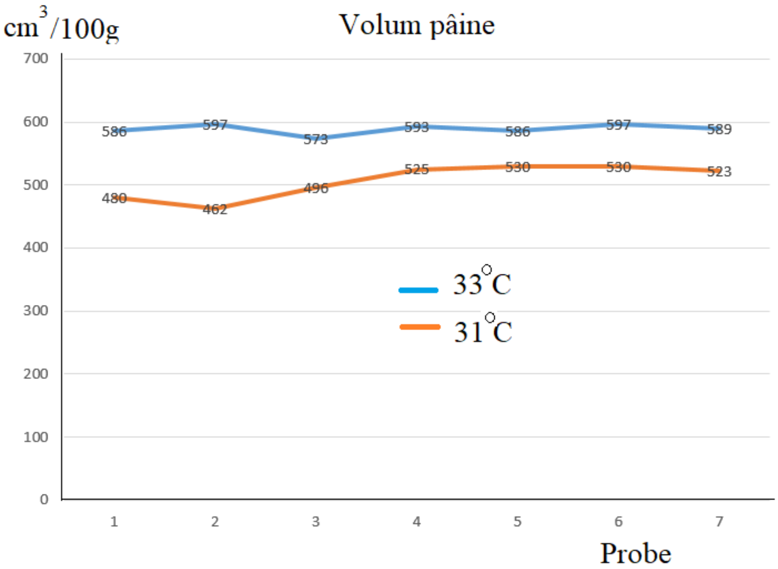


Fig. 5.69. Variation of the volume of the finished product using different fermentation parameters

5.6. VALIDATION OF PROPOSED MATHEMATICAL MODELS FOR BREAD DOUGH PROVING PROCESS EVALUATION

5.6.1. Validation of mathematical model for determination of optimal air current speed in the prover

In order to verify the accuracy of the three-dimensional simulation (from subchapter 4.2.) On the distribution of air currents and temperature in a 4-storey industrial bread maker (presented in subchapter 4.1.), Real air velocity measurements were performed. in three different points of each floor of the leavener: at the discharge mouth, in the middle of the floor - at the level of the bread and at the exit from the floor.

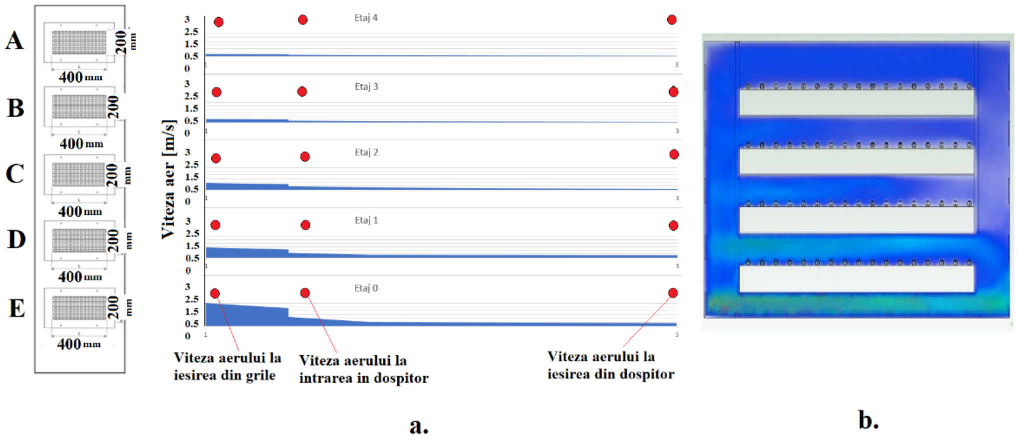


Fig. 5.71. Graphical representation of air velocity values measured on each floor of the leavener, using air distribution through equal grids

a. the variation of the air speed values on each floor of the prover and the marking of the air speed measurement points; b. the model generated in the Ansys program

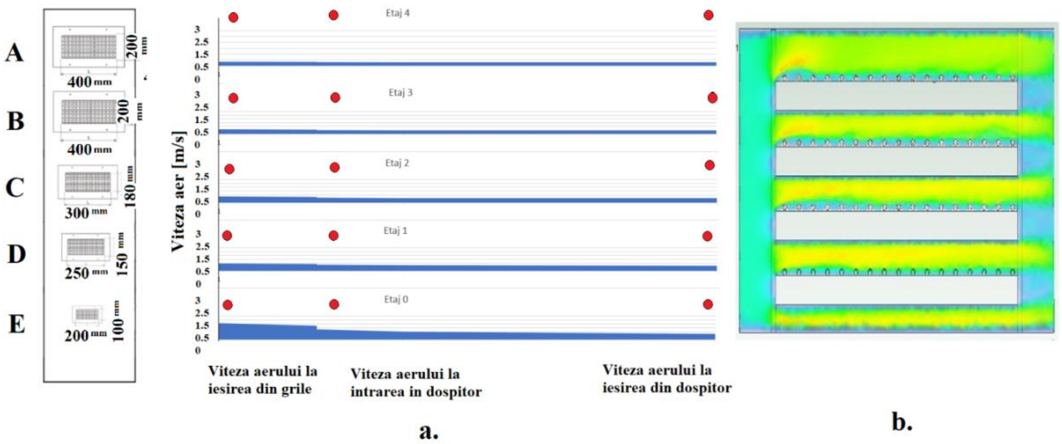


Fig. 5.72. Graphical representation of air velocity values measured on each floor of the leavener, using the distribution of recirculated air through grids of different sizes

a. the variation of the air speed values on each floor of the prover and the marking of the air speed measurement points; b. the model generated in the Ansys program

Comparing the 2 images in the section of the leavener, we can see the difference in density of the points where the air speed has a speed of 0.6 m / s. Where the surface area of the grilles has been changed, the distribution of air velocity at height has been improved by reducing the values of air velocities at the bottom and increasing at the top.

5.6.2. Validation of mathematical model for energy efficiency during proving

Figure 5.73 shows the comparative energy consumption calculated and measured to obtain the necessary parameters in the leavener in the 3 stages of operation of the leavener. Annexes 8, 9 and 10, respectively, present the measured values of energy consumption in all 3 analyzed modes.

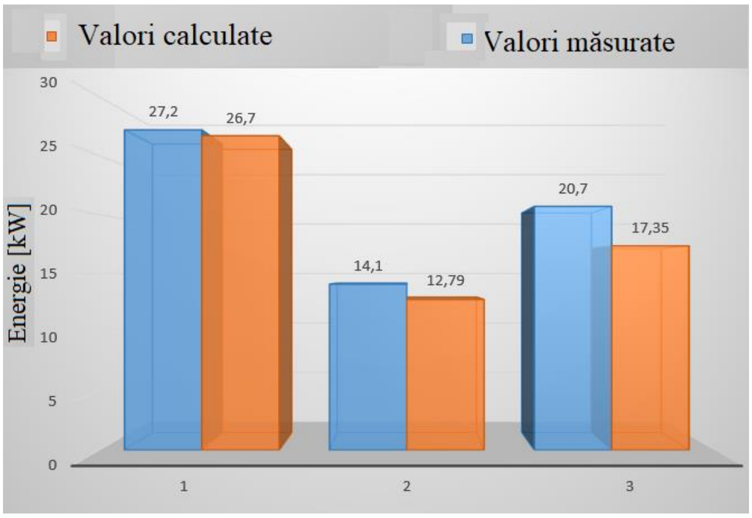


Fig. 5.73. Energy consumption measured, respectively calculated for the air conditioner of the leavener, in the 3 operating modes, [71]

As can be seen, in the case of the first mode of operation, the smallest differences between the calculated and the measured values are recorded, because in this calculation the smallest number of variables is introduced, compared to the other two modes.

5.6.3. Validation of mathematical model for estimation of carbon dioxide specific volume during fermentation process in laboratory

To validate the mathematical model by which the entire volume of carbon dioxide released in the fermentation process can be estimated, based on the pressure recorded inside the reactor where the process takes place, the results obtained by calculation were compared with the measurements directly performed during the same experiment. a device for measuring the concentration of carbon dioxide, produced by Extech.

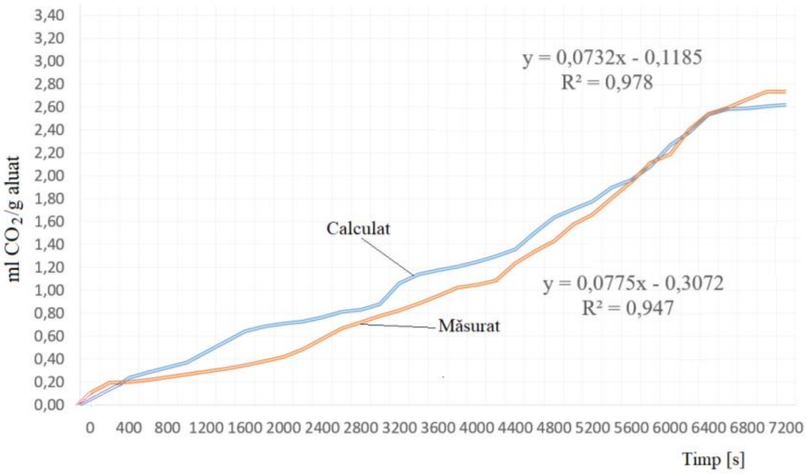


Fig. 5.74. Checking the mathematical model after the compressibility factor Z has been introduced to the FA_1-650 flour, [73]

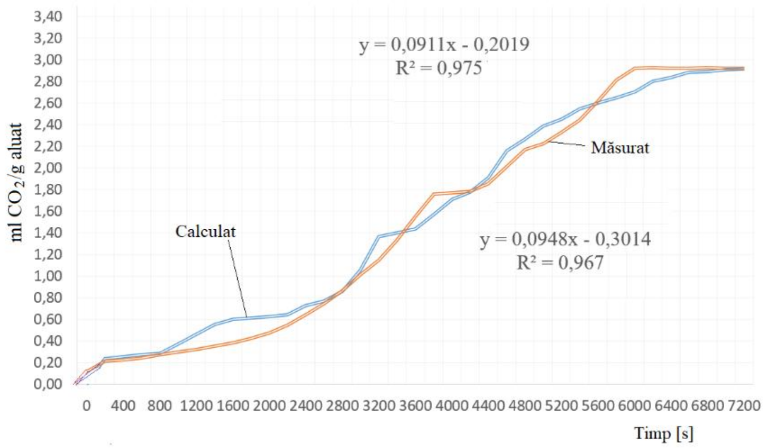


Fig. 5.75. Checking the mathematical model after the compressibility factor Z was introduced to the FI-1850 flour, [73]

A difference can be observed between the 2 diagrams, this resulting from the fact that the Extech device measures the volume of CO_2 released in the fermentation chamber, and in the mathematical model the total volume of CO_2 was considered.

The degree of similarity of the results obtained by applying the mathematical model with the values obtained from the measurements indicates the possibility of assessing the volume of carbon dioxide released during the fermentation process, using the pressure variation in a reactor (sealed container) that accompanies the phenomenon.

The final values of the specific volumes of carbon dioxide measured in the experiments gave the following results: 2.92 ml CO_2 / g dough for FI-1850 black flour, respectively 2.74 ml CO_2 / g dough for FA1-650 flour.

The final values of the specific volumes of carbon dioxide calculated in the experiments gave the following results: 2.92 ml CO_2 / g dough for FI-1850 flour, respectively 2.62 ml CO_2 / g dough for FA_1-650 flour.

5.6.4. Cost analysis for energy consumption during proving, with and without energy recovery system

Figure 5.77 shows the diagram of the inlet and outlet temperatures, respectively, in the recuperator, during the period of 3 days of operation of the recuperator, for a water flow recirculated by the pump of the gas-water energy recuperator of 1.2 m^3 / h. The temperatures were monitored with the help of 2 PT 500 probes mounted in the inlet and outlet pipes of the recirculated water in / from the recuperator.

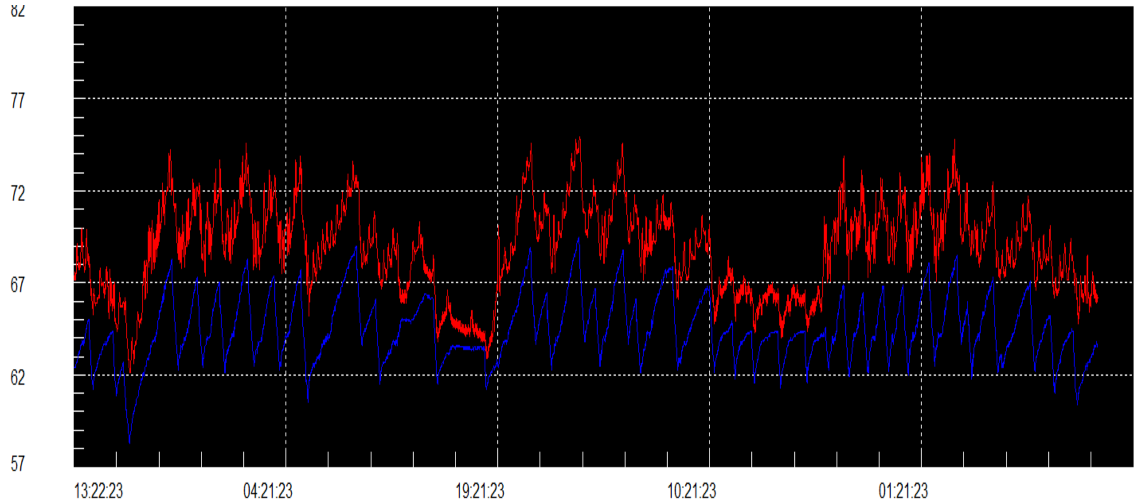


Fig. 5.78. Water temperature at the entrance to the recovery system (blue color), respectively at the exit of the recovery system (red color), measured for 3 days

A certain similarity can be observed in the variation of the two recorded temperatures. The lowest values are recorded at the start of the production line (when the oven is cold), and the highest after the leavener has reached the reference temperature. Measurements were also made with a heat meter to determine the amount of energy recovered, which is up to 9% of the energy produced by the burner. When the oven is closed, the recuperator produces energy for another approximately 2 hours, until the flue gas temperature drops below 50 °C.

By consuming the energy from the thermal power plant for 1 hour, the heating period of the furnace is taken into account, during which the flue gases do not have a temperature from which the excess energy can be extracted. After the furnace has warmed up, the temperature of the exhaust gases ensures the production of at least 25kWh of energy, which ensures the need for the heat exchanger in the CTA.

Table 5.16. The cost of monthly energy consumed for leavening, with and without heat recovery

Operation 20 h / day	Power consumption from the thermal power plant for 1 h [kWh]	Steam consumption 1h [kWh]	Energy consumption from the thermal power plant; 19 h [kWh]]	Steam consumption to increase humidity in 19 h [kWh]	Cooling consumption 1h [kWh]	Cooling consumption 19h [kWh]	TOTAL Consumption [kWh]	Total month [kWh]	Cost Ron / kWh	Total Cost [Ron] / month
CTA without recovery	27.2	12	393.3	152	4.5	85.5	718.2	21546	0.16	3447
CTA with recovery	27.2	12	0	152	4.5	85,5	324.9	9747	0,16	1559

5.7. CONCLUSIONS

Research on the volume of the finished product according to the leavening parameters showed that by increasing the temperature by 2 °C and humidity by 20%, the volume of the finished product for the white bread assortment of 300 g, increases by an average of 86 cm^3 / 100g, ie 17% more than the volume of bread obtained under the previous conditions.

The optimal operation of the dynamic control installation of the temperature and humidity parameters in the leavener was verified and validated by mounting it on the three leaveners and analyzing the operation for periods of 4 hours, each. The analyzed standard was the value of CO_2 (in ppm) set in the work program, more precisely, how close to the set value was the average of the CO_2 values measured in the leavener.

Also, following the ANOVA analysis performed on the experimental data, it was concluded that there are differences with a high degree of significance (99.9%) between the averages of carbon dioxide values measured during the fermentation process in the three fermenters analyzed, the main cause being the positioning. carbon dioxide sensor for measurements.

Currently, the MACDA method, which is the basis for the operation of the dynamic air conditioning installation of the temperature and relative humidity parameters in the leavener, holds **the patent no. 133450 dated 27.11.2020, the author of the thesis being one of the co-authors.**

Cost analysis for leavening energy consumption, with and without energy recovery for the 4-band tunnel leavener, Technobit Automatizări, Romania, with a production capacity of 4000 pcs x 360 g dough / h and a production time of 20 h / day highlighted a decrease in the monthly cost required to ensure the temperature parameter in the leavener by 55%, if the recovered energy is used.

CHAPTER 6
GENERAL CONCLUSIONS, PERSONAL CONTRIBUTIONS AND FUTURE REASEARCH DIRRECTIONS

6.1. GENERAL CONCLUSIONS

As an efficient bakery industrial process is optimized both in terms of quality of finished products and for economic reasons, a mathematical model has been developed to determine the energy consumption of leavening for a 4-floor tunnel type prover, air-conditioned, with a capacity of 4000 pieces of dough x 360 g / hour. The results obtained by calculation were compared with real measurements performed in working flow. Also, the energy consumption during proving was analyzed, by reusing a part of the energy recovered with the help of the heat recovery system mounted on the gas pipe outlet and which can recover up to 9% of the burner power.

The results obtained by calculation did not register major differences from those measured, these showing deviations between 2 - 16%, the largest deviations can be justified by the multitude of variables (different ambient temperatures, additional losses through the feeding / unloading areas dough) which were not taken into account when performing the calculation. However, the mathematical model is a very close estimate of the actual energy consumption to ensure the leavening parameters.

The use of recovered energy can reduce the cost of providing leavening parameters by more than 55%.

Another important parameter in establishing a proper leavening process is the distribution of air currents in the prover and their speeds on the prover floors. The three-dimensional simulation highlighted the need to experimentally establish the dimensions of the air vents and the air velocity in the prover, in correlation with its influence on the characteristics of the dough and the need to ensure uniform temperature distribution on all floors of the prover. The best results were obtained at an air speed of 0.6 m / s and a discharge grid configuration as shown in fig. 4.13 and 5.72 of chapters 4 and 5.

The tests performed on 3 provers, 2 with plates of similar construction, but different capacity and one of spiral type, highlighted the following aspects:

- the standard value of carbon dioxide (ppm) is reached when the prover is loaded to the nominal capacity, and until then, the installation operates according to fixed parameters of temperature and humidity, like a conventional air conditioning installation;
- in the first fermentation cycle, the carbon dioxide concentration diagram shows an upward trend, always starting from the average value of the carbon dioxide concentration in the environment;
- the leavening parameters are established in correlation with the desired temperature in the dough piece.

Experimentally, it was determined that for a fermentation time of approx. 90 minutes, the temperature in the dough piece at the end of the fermentation cycle will be very close to the average value of the operating temperature, and for a fermentation time of 60 minutes, the average temperature in the dough piece at the end of fermentation will be approximately 2 °C lower than the value of the temperature parameter; therefore, when setting the parameters of the working regime, it is necessary to take into account the leavening time;

- the resulting diagrams for temperature, relative humidity and concentration of carbon dioxide, following the analysis of the air conditioning operation with the automatic control method show the way of adjusting the parameters, according to the PID (proportional-integrator-derivator) logic, and the registration of the parameters in the established values. in the work program validates the functionality of the system.

At the same time, following the ANOVA analysis performed on the experimental data, it was concluded that there are differences with a high degree of significance (99.9%) between the averages of carbon dioxide values measured during the fermentation process in the three fermenters analyzed, the main cause being sensor positioning. of carbon dioxide for measurements. Therefore, it has been established that the best positioning of the sensor for measuring the concentration of carbon dioxide is in the air intake manifold in the leavener.

The use of the dynamic air conditioning installation of temperature and relative humidity parameters in the leavener brings visible benefits in the bread making process, by controlling the working parameters and limiting the influence of external variables (consistency, dough temperature, etc.) on the quality of the finished product.

Currently, the MACDA method, which is the basis for the operation of the dynamic air conditioning installation of the temperature and relative humidity parameters in the leavener, holds **the patent no. 133450 dated 27.11.2020, the author of the thesis being one of the co-authors.**

6.2. PERSONAL CONTRIBUTIONS

I mention here some of the personal contributions made dough leavening process and control its parameters during leavening:

1) Demonstration of the usefulness of the doctoral thesis whose main objective was to control the final fermentation process of baking dough, by implementing a system to control the temperature and humidity parameters of any type of leavener, based on the concentration of carbon dioxide released in it , during the fermentation process.
2) Making a documentary study on the physico-chemical and rheological behavior influencing dough fermentation.

3) Making a documentary study on control methods and state of equipment and systems that facilitate control of the final fermentation of the dough.

4) Design and construction of an experimental stand consisting of a sealed reactor, temperature, pressure and carbon dioxide sensors and computer data acquisition software, to calculate the specific volume of carbon dioxide released during the fermentation process.

5) Development of a mathematical model, using the increase of pressure in the reactor, to identify a method of analysis of the fermentation process under controlled conditions.

6) Evaluation of the leavening process of bread dough, using the concentration of carbon dioxide released in the leavener, on a small scale.

7) Development of a mathematical model for calculating leavening energy consumption for a 4-band tunnel leavener with a production capacity of 4000 pcs x 360 g dough / h and a production time of 20 h / day.

8) Checking the accuracy of the mathematical model by measuring the energy consumption of the leavener during operation, by mounting a heat meter on the return of the air conditioning system.

9) Evaluation of the reduction of the energy consumption of the leavener, following the use for the heating of the enclosure, of the heat recovered from the flue gas chimney of the furnace, with the help of a gas-water type energy recuperator.

10) Development of a three-dimensional simulation model of air distribution in an industrial bread maker, tunnel type, with 4 conveyor belts. Determination of the optimal dimensions of the suction and discharge grilles and the optimal frequency of the fan to even out the air speed in the leavener.

11) Analysis of the variation of the volume of the finished product depending on the parameters of the fermentation process.

12) Design and implementation of a fermentation process control system, with the help of 3 temperature and humidity sensors, respectively a carbon dioxide sensor and an operating system equipped with a touch screen, with the help of which the temperature and humidity parameters from leaveners are dynamically controlled according to the concentration of carbon dioxide inside the leavener.

13) Testing the functionality of the system by controlling the fermentation process of the bread dough in two leaveners with panacoades of different capacities and in a spiral leavener.

14) Development of a serial product called dough fermentation control system.

15) The results of the research carried out during the doctoral training were capitalized by the elaboration and publication of 10 scientific papers in specialized journals (indexed BDI, of which 2 SCOPUS) or in the volumes of international conferences (2 indexed ISI, 2 SCOPUS, 3 other BDI) as author and co-author, according to the list attached at the end of the thesis. It was also granted by OSIM the patent with no. 133450 / 27.11.2020, of which I am co-author.

6.3. FUTURE RESEARCH RECOMMENDATIONS AND DIRECTIONS

1. In order to reduce the energy consumption during leavening, it is recommended to use the energy recovered from the flue gas baskets, which can provide the almost complete heat demand for the temperature parameter in the bread maker.

2. In order to ensure a better standardization of the temperature and humidity parameters in bread makers, in correlation with the speed of recirculated air, the manufacturers of such bakery equipment may place more emphasis on the redesign of air distribution systems.

3. Also, in order to prevent the obtaining of inappropriate batches of bread in the long term, it is recommended to integrate in the operation of the leavener and / or air conditioning, alarm systems in case the parameters of the working regime can no longer be ensured (technical defects in the thermal power plant, the integrity of the air piping, etc.).

Future research in this segment may include:

1. Continuation of research and real-time monitoring of the values of temperature, humidity and carbon dioxide in air conditioning systems with automatic control installed in bakeries, in order to integrate them into an alarm system in the form of a text message on the phone at exceeding the measuring range set in the work programs.
2. Continuation of research and real-time monitoring of the values of temperature, humidity and carbon dioxide, in order to observe the differences in the operation of the dynamic automation system, due to the different constructive types of dough leaveners.
3. Continuation of theoretical and practical research by analyzing the values recorded in the cloud, in the long term, in order to observe changes that occur in the fermentation process at the change of seasons.
4. Development of research in the field of automatic control of work process parameters for other categories of equipment on the bakery flow.

SELECTIVE REFERENCES

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CURRICULUM VITAE

PERSONAL INFORMATION

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PROFESSIONAL EXPERIENCE

22.06.2020 – prezent

Director General

SC DOARGRANE SRL, 15 Pucheni Street, sector 5 Bucharest;;

- Coordonarea întregului proces de fabricație la nivelul secției;
-Coordination of the entire manufacturing process at the department level;;
-Responsible for production issues regarding: Food safety, ISO procedures, HACCP.
Type or sector of activity: Bakery - Production

01.09.2016 – 01.06.2020

Process Improvement Specialist

SC BiotehnologicreativSRL, Road Dudeşti-Pantelimon, nr. 42, www.biotehnologicreativ.ro

-Evaluation of industrial baking processes from a technical and technological point of view and identification of complete solutions for their improvement;
Type or sector of activity: Bakery Consulting

04.06.2014 – 01.06.2016

Food industry engineer

SC Vel Pitar SA, P.L Bucharest Berceni, Str. Emil Racoviță, no.3-5, sector 4, www.velpitar.ro

-Coordination of the entire manufacturing process at the department level;
- Coordination, organization and training of directly productive staff;
-Preparation of documents specific to the production activity;

-Type or sector of activity: Bakery - Production

EDUCATION AND TRAINING

10.2016 -prezent **PhD**

Polytechnic University of Bucharest, Faculty of Biotechnical Systems Engineering, “Mechanical Engineering” Doctoral School

-Advanced technologies in the bakery industry

10.2012 -07.2014 **Master degree**

Polytechnic University of Bucharest, Faculty of Biotechnical Systems Engineering, Specialization Engineering and management of processing and storage of agri-food products

- Advanced technologies in the food industry, Technology of agricultural products processing, Modern methods of packaging agri-food products

10.2008 -07.2012 **Bachelors degree**

Polytechnic University of Bucharest, Faculty of Biotechnical Systems Engineering, Specialization Engineering of sustainable rural development

-Food processing and storage technologies, Technical thermodynamics, Fluid mechanics, Hydraulic and pneumatic drives, Technical drawing

LIST OF SCIENTIFIC WORKS IN THE FIELD OF THESIS
PhD student. Eng. Istudor Adriana

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Multidisciplinary Scientific GeoConference SGEM, 2018, pag.161-170, ISSN: 1314-2704, DOI: 10.5593/sgem2018V/6.4/S08.021, *Indexat SCOPUS*

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