ADVANCED DESIGN OF A STATIC DRYER FOR PASTA WITH SIMULATION TOOLS

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ABSTRACT

In this work, a scientific approach was applied to the drying of pasta in order to obtain a simulative model for this particular industrial process.

At first, it was simulated the evolution of temperature and internal moisture inside a simple geometry product (spaghetti), using a Finite Difference Model (FDM) simulation, implemented in Microsoft Excel. In this way, it was possible to produce a spreadsheet that automatically calculates temporal progression of temperature and moisture in spaghetti of infinite length. Then, the results obtained were subsequently validated through the comparison with a real industrial case;

Later, it was analyzed a layout of static dryer for pasta, in this case various design parameter were determined through CFD.

Keywords: Static dryer, Pasta, FDM analysis, CFD analysis.

1. INTRODUCTION

Drying is one of the first technical operations of food preservation used, observed and studied by the industrial technology (Singh and Heldman, 2001).

In particular, the drying of pasta is one of the oldest operation developed in food processing. In fact, the fresh pasta cannot be stored for a long time, and drying has represented for many centuries the unique option to increase product shelf life (Milatovich and Mondelli, 1990).

Secondly, due to heterogeneity of the dough base, the successful implementation of the process is essential to obtain a homogeneous product by aesthetic, chemical, physical and organoleptic point of view (Rizzo et al., 2010). In order to obtain the best final product, dryer must ensure the thermodynamic equilibrium that can lead the dough to lose its moisture as homogeneously as possible.

2. THE DRYING OF PASTA

In the sector of pasta, the drying method most frequently adopted is drying the product through hot air flow (Migliori et al. 2004). In detail, this process is the union of two distinct thermodynamic processes: the heat flows from the drying media (the air) to the product and the moisture flows from the product to the drying media. The process is governed by transient thermal and mass transport phenomena, and the mechanism of moisture transfer depends on physical and chemical conditions of the product and of the drying media.

The initial different moisture content between product and heating media is the motor of the whole process, which looks for a thermodynamic equilibrium by the extraction of water from the food matrix to the drying media.

This extraction happens through two different mechanisms:

1. The internal water diffusion across the solid matrix of pasta. This movement brings the water at the product-air interface;
2. The evaporation of the moisture, in the form of vapor, from the interface to the external air (forced convection).

In this study it was reproduced an high temperature (HT) cycle of drying for long pasta (Milatovich and Mondelli, 1990).

This particular process is divided in two phases: pre-drying (air drying at 36 °C for 30 minutes) and drying (air drying at 76°C for 11-12 hours)

The work is divided in two different simulations of the drying process:

- At first, it was studied the product's internal flow of moisture, through the analysis of heat and mass transfer between the product and hot air;
- Secondly it was analyzed the layout of static dryer through external simulation of the thermal process.

3. INTERNAL SIMULATION

FDM was utilized in order to describe the phenomena that happens inside the product during a cycle of drying.

In order to implement this method, it was used the software MS Excel©, with the purpose to develop a predictive system that could become a future design tool. Thanks to this tool, generic users could recreate a drying's cycle, to verify the effect of this cycle on the product, in terms of internal evolution of temperature and moisture.

3.1. Geometry of product

A simply geometry of the product was adopted for this analysis. It was considered a cylindrical geometry of pasta (spaghetto, for example), with 10 mm diameter and infinite length, as in Figure 1.

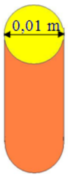


Figure 1 - Geometry of product

The FDM simulations based on the analysis of sequential points (also called nodes) taken from one of the diameters lying on a radial section of the product itself, as in Figure 2.

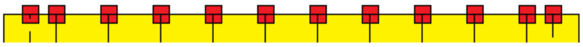


Figure 2 - Nodes of FDM analysis

In detail, the wall of the product is represented by the two external nodes, they are not at the interface product-air but at a distance of 0.5 mm inside the wall.
The nodes of the FDM method are described by their position, identified with radial coordinates.

Table 1 - Coordinate of node

Node	Coordinates on diameter [mm]	Radial Coordinates [mm]
Wall1	0	5
Wall's node1	0,5	4,5
Node1	1	4
Node2	2	3
Node3	3	2
Node4	4	1
Product's core	5	0
Node6	6	1
Node7	7	2
Node8	8	3
Node9	9	4
Wall's node2	9,5	4,5
Wall2	10	5

Now, it's possible to create through MS Excel the spreadsheet formed with the ten nodes described in Table 1.

3.2. External conditions

For heat drying process, we will reproduce the effect of a hot air draught that laps against the product.

The data concerning the drying media to be included in the model are:

1. The flow velocity (v_∞);
2. The temperature of air (T_∞);
3. The humidity of air (φ);

This three parameters associated with the maintenance time of the particular condition of flow in the chamber, are able to describe the drying cycle selected by the user.

3.3. The conditions of the product

The dough base presents obvious and disparate heterogeneity, from both physical and chemical point of view, compared with the internal structure of the solid matrix.

This heterogeneity can be seen along the three dimensions and during the time of the process.

For this study, in approximate way, the heterogeneity of product internal structure has not been considered.

The user must enter the initial data about pasta:

- The Temperature of product at initial time t_0, (T_p);
- The initial internal moisture of product (UT_{pasta}), and the resulting water content of dough on dry basis (U_{pasta}), derived by Eq.1.

$$U_{pasta} = \frac{UT_{pasta}}{(1 - UT_{pasta})} \qquad (1)$$

In order to derive the product's internal temperature trend (the temperature trend in the nodes) we have divided the problem:

1. Study of thermal phenomena at the interface product-air;
2. Study of thermal phenomena inside the product.

3.4. Analysis of interface product-air thermal flow

3.4.1. External convection

The first thermal flow which was analyzed is the forced external convection, due to the hot air flow and its interaction with the product.

This process was summarized by the Eq. 2;

$$q_{conv} = h \cdot S \cdot (T_\infty - T_p) \quad (2)$$

h =: external heat exchange coefficient [J/m^{2}K];

S = contact surface [m^2];

q_{conv} = convection heat exchange [W].

The variables contained in the formula were obtained through a fluid dynamic approach, using the Hilbert's formula to calculate the Nusselt's number and the external heat exchange coefficient (Migliori et al. 2004).

3.4.2. The external conduction

The wall's node exchange heat through conduction mechanism with the nearest internal node of product.

This process was summarized by Eq. 3:

$$q_{cond} = \frac{\lambda_p}{s_p} \cdot S \cdot (T_{N-1} - T_p) \quad (3)$$

λ_p = thermal conductivity of dough [W/mK]

s_p = thickness of dough, the distance between the two nodes (called Δx) [m];

S = surface of thermal exchange [m^2];

T_{N-1} = temperature of nearest internal node [K];

q_{cond} = conduction heat exchange [W].

3.4.3. The evaporation

In this model, the water contained in the product at the beginning of the drying process (moisture content 30%) is partially "free moisture" and able to evaporate. In this time, the temperature of this water is the so called wet bulb temperature, and its pressure is equal to the saturation pressure.

During this period the evaporated water at the interface is continuously supplied by the internal mass flow and the heat power transferred from the air to the sample is fundamental in order to achieve the evaporation of water.

The heat flow that occurs from product to drying media is:

$$q_{evap} = h_m \cdot cl \cdot S \cdot (\rho_{v,T_\infty} - \rho_{v,T_{bb}}) \quad (4)$$

h_m = mass transport coefficient [m/s];

cl = water latent heat of vapourisation [J/Kg];

S = surface of thermal exchange [m^2];

$\rho_{v,Tbb}$ = vapor density at wet bulb temperature [kg/m^3];

$\rho_{v,T\infty}$ = vapor density at T_∞ [kg/m^3];

Eq. 4 is valid until the moisture of product remains in saturation conditions.

In this phase, the process proceeds at a constant rate of water evaporation. During this period the water that evaporates at the interface product-air is continuously supplied by the internal moisture flow. In this time, the heat power transferred from the air to the dough equates the thermal power required for water evaporation.

At the end of this part of drying process, when the internal moisture content has decreased due to the drying process, the water concentration inside the product arises and the internal water flow decreases. In this second part of process (descending rate of drying) the thermal power required for water evaporation is not sufficient to balance the external heat transfer, and as a consequence of this, the interface temperature increases.

In this model, the mechanism is reproduced by changing the value of vapor density during the drying process. During the process constant rate, the vapor density at the interface equates the vapor density at wet bulb temperature. In the second phase the density decreases to the value of vapor density at the temperature of drying media ($\rho_{v,T\infty}$).

In this analysis it has been assumed a linear dependence between the internal humidity of product and the density of vapor:

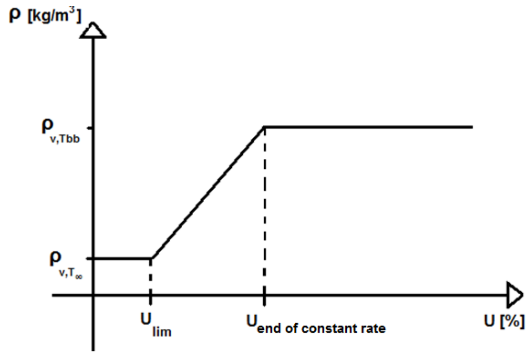


Figure 3 - vapor density at the interface

In this hypothesis, it has been researched the relation between the vapor density at the interface end the product internal moisture, explained by Eq. 5:

$$\rho_{v_i} = \rho_{v,T_\infty} + \frac{\rho_{v,T_{bb}} - \rho_{v,T_\infty}}{U_{end\ of\ constant\ rate} - U_{lim}} \cdot (U - U_{lim}) \quad (5)$$

$U_{end\ of\ constant\ rate}$ = internal moisture value corresponds with the end of the drying phase at constant rate of evaporation [%];

U_{lim} = internal moisture value corresponds with the end of the moisture evaporation [%].

The user, through his knowledge about the dough base, determines the value of this specific moisture values.

When, at the wall's nodes, the moisture U_{lim} is reached, the external skin of product is completely dried for the model, and the thermal contribution of evaporation is nullified.

3.4.4. Time dependence

During the time the heat flow that interests a particular node was described as follows:

$$\Delta q = \frac{\Delta x}{2} \cdot \rho_p \cdot C_p \cdot S \cdot \frac{[T_{t+1}^N - T_t^N]}{\Delta \tau} \qquad (6)$$

Δx (Δr) = the distance node-interface [m];

ρ_p = density of product [kg/m^3];

C_p = heat capacity of product [J/kg*K]

S = surface of thermal exchange [m^2];

T_{t+1}^N = temperature of the N-node at time t+1 [K];

T_t^N = temperature of the N-node at time t [K]

Eq. 6 must be equate with all the heat thermal flows related to the node:

$$\frac{\Delta r}{2} \cdot \rho_p \cdot C_p \cdot S \cdot \frac{[T_{t+1}^N - T_t^N]}{\Delta \tau} = \left(\frac{T_t^{N-1} - T_t^N}{\frac{\Delta r}{\lambda_p}} \right) + \left(\frac{T_\infty - T_t^N}{\frac{1}{h}} \right) + \left(h_m \cdot cl \cdot \left(\frac{P_{v,T_\infty}}{R \cdot T_\infty} - \frac{P_{v,Tbb}}{R \cdot T_{bb}} \right) \right) \qquad (7)$$

In the Eq.7, T_{t+1}^N is the unique unknown factor, thanks to recursive resolution process is possible to derive the trend of temperature along the time.

3.5. Analysis of internal thermal flow

3.5.1. Internal conduction

In the internal nodes the heat flow is determined through conduction mechanism, similarly to external conduction. Differently, the equation must be referred to the cylindrical geometry, by using the cylindrical coordinates:

$$\rho_p \cdot C_p \cdot \frac{\partial T}{\partial \tau} = \lambda_p \cdot \frac{\partial^2 T}{\partial^2 r^2} \qquad (8)$$

In Eq. 8, *r* is the distance that divides the observed node and the center of the product (the core).

Also in this case, the study ends with the research of the temperature trend during the time.

3.6. Analysis of interface product-air mass flow

3.6.1. The evaporation

The product loses his water content through the evaporation phenomena:

$$\dot{m} = h_m \cdot S \cdot (\rho_{v,T\infty} - \rho_{v,T_{bb}}) \qquad (9)$$

$\dot{m}$ = water mass transfer from product to drying media [kg/s];

h_m = external mass exchange coefficient [m/s];

S = surface of thermal exchange [m^2];

$\rho_{v,T\infty}$ = density of vapor at T_∞ [kg/m^3];

$\rho_{v,Tbb}$ = density of vapor at wet bulb temperature, on the surface of product until saturation conditions remains [kg/m^3].

Also for the Eq.9, the simplification concerning the density of vapor remains valid.

3.6.2. The internal conduction

In order to completely study the phenomena related to the mass flow, the moisture diffusion between the wall's nodes and the nearest internal node of product must be analyzed:

$$\dot{m}_{cond} = D_{H_2O-pasta} \cdot S \cdot (U_t^N - U_t^{N+1}) \cdot \rho_p \qquad (10)$$

$\dot{m}_{cond}$ = water mass transfer between two nodes [kg/s];

$D_{H_2O-pasta}$ = water diffusivity in the dough [m^2/s]

S = surface of thermal exchange [m^2];

U_t^N = water content on dry basis of the N-node at time t $\left[\frac{kgH_2O}{kg\ dry\ product}\right]$

U_t^{N+1} = water content on dry basis of the N-node at time t $\left[\frac{kgH_2O}{kg\ dry\ product}\right]$

ρ_p = density of dough base [kg/m^3]

In particular, an important factor for the Eq. 10, equation is the water diffusivity inside the product. This variable, depending on internal moisture content, is determined for water concentration higher than 22% w/w through experimental step function, and for water content less than 22% w/w through experimental continuous chemical function, not reported.

3.6.3. Time dependence

The mass flow which has been analyzed in wall's node it has been obtained through the analysis of conduction and evaporation, in order to research the internal moisture trend during time.

3.7. Analysis of internal mass flow

3.7.1. Internal conduction

As seen for the conduction of wall's node, the Fick's law guides the diffusion of moisture between two contiguous internal nodes in its massive terms.

Also in this analysis, the model researches the trend of internal moisture during the time of the process.

3.8. Implementation in MS Excel

With the previously equation, it has been possible to implement the predictive model through MS Excel.

In the spreadsheet there is a preliminary part where the user can set the simulation of the process. The user must insert:

1. The drying cycle data. In this part, the data of the different phases of the process are required, in particular the property of the drying air, as shown in Figure 4:

Insert the drying data:				
Phase	Minutes	Air Temperature (°C)	Air Moisture content [%]	Velocity [m/s]
1	0	36	2%	0,5
2	30	76	95%	0,5

Figure 4 - drying data

2. The dough data. The user through his knowledge must insert the data visualized in Figure 5:

Dough data		
Initial temperature [°C]	30	[°C]
Initial temperature [K]	303	[K]
External diameter	10	[mm]
Thermal conductivity	0,41	[W/(m*K)]
% of starch	0,1171	[%]
% gluten	0,2423	[%]
Initial moisture	0,3	[%]
Heat Capacity (Initial)	1179945,278	[J/kg*K]
Density (Initial)	1289,609433	[kg/m^3]

Figure 5 - data of dough

3. Moisture limits. In this part the user can set the values of moisture limit for the external evaporation, this values is summarized by Figure 6:

	Total Moisture [%, w/w]	Moisture on dry basis [%]
Moisture limit of constant rate fase	19,00%	23,46%
Moisture limit	1,00%	1,01%

Figure 6 - values of moisture limit for the evaporation

4. The analysis data: in this part the user can set the temporal sequence of the calculation step. The value of $\Delta\tau$ cannot be higher than $\Delta\tau_{lim}$, which is the value of $\Delta\tau$ that makes unstable the model. This data are visualized in Figure 7:

Analysis Data		
Δt	10	[s]
Δtlim	1772,41238	[s]

Figure 7 - Analysis data

3.9. Results

3.9.1. The comparison with industrial case

Through the implementation of the model in MS Excel it was possible to recreate a real industrial cycle.

In particular, the data inserted through the preliminary part reproduce a classic HT drying cycle for long pasta:

- First ventilation phase (30 minutes) where the product is ventilated by dry cold air (moisture content 2%, temperature 36°C);
- Second phase of drying, where spaghetti are dried by hot air (air moisture content 95%, temperature of 76°C).

This cycle, visualized in Figure 8, dries the product slowly, in order to preserve its organoleptic properties.

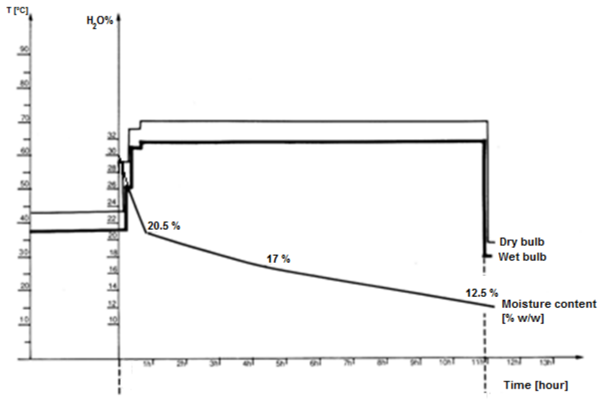


Figure 8 - internal moisture during HT drying cycle

In particular, one of the goals was to verify, through this model, the trend of internal moisture obtained by HT cycle.

The internal water content during the process, beginning from an internal value of 30%, reaches the value of 20,5% after 1 hour. This initial time of drying is due to the first process phase, that proceeds at a constant rate until the humidity of wall's node equates the value U_{lim}.

Later, the internal moisture reaches the value of 17% after 4-5 hours of process, in this period the most important phenomenon that interests the product is the internal mass flow, since the evaporation has entered in its descendent rate phase.

Finally, the product reaches the value of internal humidity of 12,5% (the maximum value of internal humidity is 12,5% for the Italian legislation) after 11-12 hours of drying process.

In the first instance, it was observed the temperature trend of the wall's node:

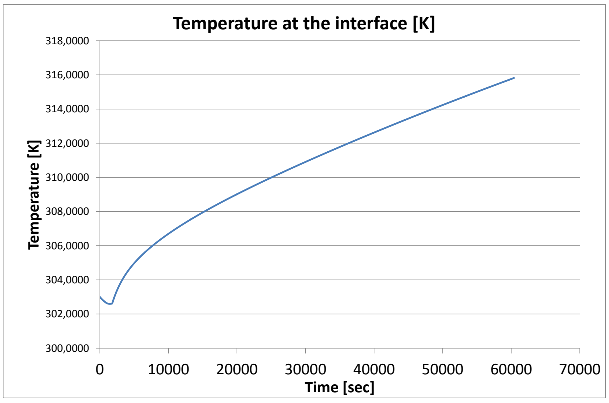
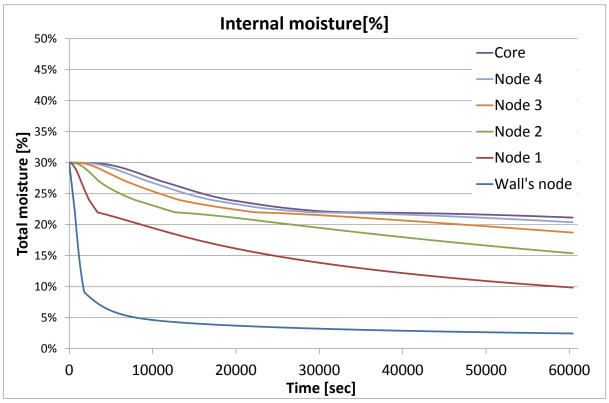


Figure 9 - temperature trend at the interface

From figure 9 it can be observed the two phases of the trend temperature at the interface product-air:

1. a first phase so-called "evaporative cooling" due to the contribute of the mechanism of evaporation, that impact on the temperature more than the conductive and convective terms;
2. in the second phase the temperature increases due to the convective heat exchange.

Secondly, it was analyzed the trend of internal moisture of nodes and the relative run of average internal humidity. This analysis is summarized by Figure 10:



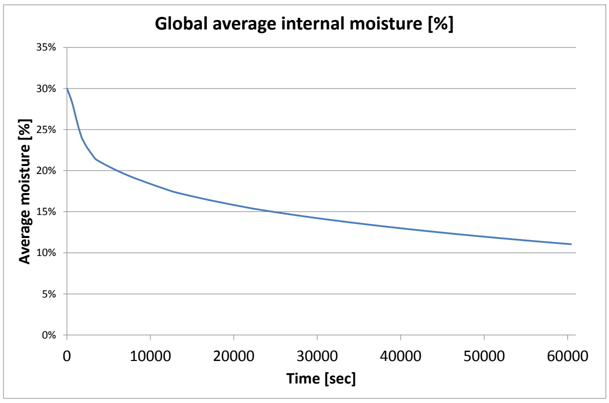


Figure 10- internal moisture trend

Thanks to the values of moisture previously identified, it has been possible to compare the results of the FDM simulation and the real industrial case. The results of the simulation are summarized in Figure 11:

	Time		
Value	**Hours**	**Minutes**	**Seconds**
0,205	0	51	50
0,170	3	35	0
0,125	12	30	10

Figure 11- characteristics value of cycle drying

The last phase of the process result slightly longer than the value identified for the industrial case.
Since the proposed values are highly dependent on the diffusivity coefficient, this variable was increased of 10%, obtaining the characteristic times shown in Figure 12.

	Time		
Value	**Hours**	**Minutes**	**Seconds**
0,205	0	52	10
0,170	3	28	20
0,125	11	44	40

Figure 12 - value of cycle drying with incremented diffusivity coefficient

Thanks to this control, the results of the model were verified, compared with the industrial case, taking into account the approximations used to create the model. In fact, with an incremented diffusivity coefficient, also the third part of process was reproduced with a good approximation.

4. EXTERNAL SIMULATION

4.1. The static dryer

In order to analyze a drying cycle of pasta through the simulation software TDyn, a simply layout of static dryer was selected for this study.

In this drying chamber, the product was introduced on perforated trays that were disposed along special supports.

This plants are often utilized in small and medium companies, thanks to its simplicity, its versatility and the low volume required.

The principal problem of this system is represented by the difficulties in obtaining the uniformity of the drying media inside the chamber.

This parameter is fundamental in order to achieve homogeneity of the process and therefore a better quality of product.

The CFD simulation was used to select the layout of static dryer of pasta capable of guaranteeing the best process uniformity.

The software TDyn, is able to predict with good approximation the evolution of product's temperature.

Thanks to this tools, the internal product's temperature was evaluated , through the analysis of the nodes that represent the pasta inserted in the room.

4.2. Initial conditions

It was selected a particular static dryer provided with singular inlet and singular outlet.

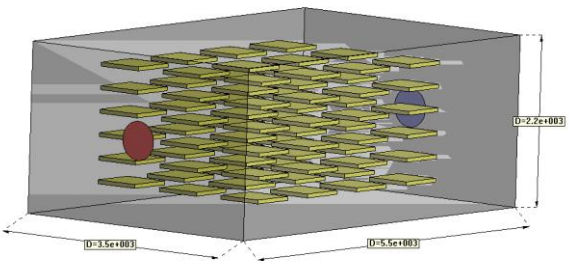


Figure 13 - static dryer

The design proposal in Figure 13 is one of the most used static dryer in small-sized company context.

The internal conditions of the drying chamber are settled through this parameter:

- The temperature of drying media: 353 K;
- The temperature of hot air: 293 K;
- Velocity of hot air at the inlet: 1 m/s;
- Surfaces of inlet and outlet: this parameters are settled to ensure a hot air flow of 1 m^3/s;
- The geometry of drier: the geometry of drier is the same for all the simulation, it is a chamber 5500x3500x2200 mm;
- The disposition of product.

The simulation was programmed to proceeds to 5200 seconds, at the end of this period the temperatures of internal product's nodes were analyzed.

4.3. Conclusions

In order to determine the quality of the drying process developed in the chamber, the statistical distribution of product's temperature was analyzed after 5200 seconds of process:

1. In order to evaluate the effectiveness of the process, the average temperature of product's nodes was analyzed. In fact, the biggest the average , the more drying process is effective,. Secondly, it was studied the value of median: the biggest the median, the further the drying stage is;
2. The efficiency of the process represents its homogeneity of product's drying. In order to evaluate this property, it was analyzed the value of standard deviation of product temperature . This parameter provides an indication of the distance between the maximum value of temperature and its average. In fact, the more the process dries homogeneously, the lower the standard deviation is.

	Singular inlet and singular outlet
Median	293,008
Average	293,1950103
Standard Deviation	1,275179069
Maximum	349,183

Figure 14- parameters of analysis

In addition, it was analyzed the statistical distribution of temperature of product after 5200 seconds, in order to appreciate graphically the evaluation of layout.

Initially, it was proposed the global distribution of temperature. Secondly, it was visualized the initial part of distribution ("the head") in order to appreciate the median value. Finally, it was showed the last part of distribution ("the tail"), in order to visualize the homogeneity of the process, represented by shorter tails of distribution.

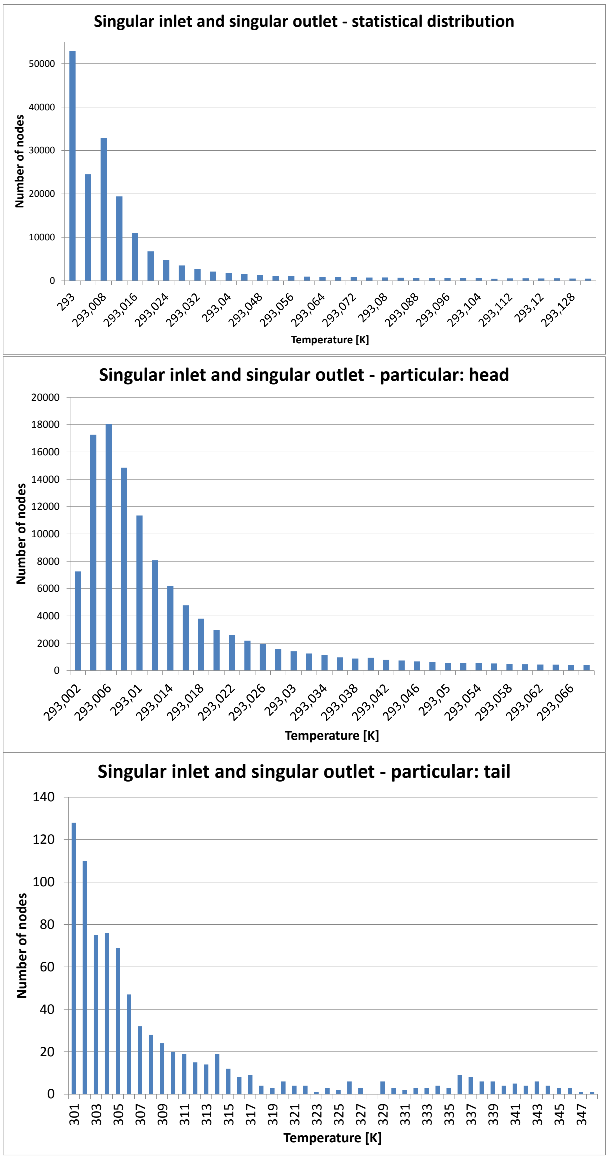


Figure 15 - statistical distribution of temperature

Thanks to parameters visualized in Figure 14 and the graphical analysis showed in Figure15, it could be possible to study the layout proposed.

This configuration layout, the most utilized actually to implement the modern process, has reported poor performance regarding the homogeneity of drying: the value of median is low and the standard deviation is high, and the distribution of temperature emphasizes a long tail.

This conclusion is further verified through the visualization of internal flow of drying media, which, thanks to this layout, is able to reach principally the product placed near the inlet, as shown in Figure 16.

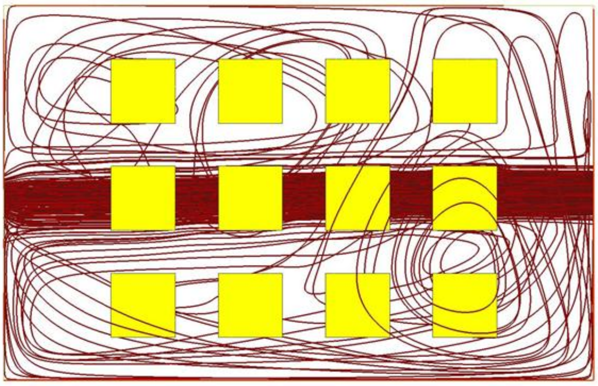


Figure 16 - internal flows

The tool developed can be used to compare the performances of different layouts of drying chambers in order to determine which one ensures the best drying treatment, in terms of homogeneity and effectiveness of the process. This improvement in the dryer design results in a better quality of the product and in a more efficient use of energy resource.

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