CFD ANALYSIS OF COFFEE PACKAGING IN CAPSULES USING GAS FLUSHING MODIFIED ATMOSPHERE PACKAGING

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ABSTRACT

The aim of this work is to analyze, by means of CFD, the gas flow in a packaging machine used to fill polymeric capsules with coffee. The final goal is to optimize the geometric shape of some of the mechanical components in the machine's sealing station in order to reduce inert gas consumption (N_2 in this case) and, at the same time, achieve an O_2 residual which is constantly equal or below 1% by mass in the center of the capsule.

The fluid domain has been obtained starting from the 3D CAD model of the sealing station of the packaging machine. The CAD software SolidWorks (version 2014) has been used to design the system, while Ansys CFX 14.5 software has been used for the CFD analysis.

The CFD model has been validated by comparing the simulation results with those obtained by experimental tests. The modified solution allows reducing the O2 residual from almost 3% to less than 1%.

Keywords: CFD, Food Packaging, Modified Atmosphere Packaging, Gas Flushing

1. INTRODUCTION

Modified Atmosphere Packaging (MAP) is a packaging technique which implies the addition (or removal) of gases from storage rooms, transportation containers or packages in order to manipulate the level of gases such as oxygen, carbon dioxide, nitrogen, ethylene etc., and achieve an atmospheric composition different to that of normal air around the food (Floros 1990). This technique is used generally to enhance the shelf-life of food products or to preserve their organoleptic features.

Nowadays MAP is an important part of food industry and it is used especially in the processing of fresh products such as fruits and vegetables, fish and fresh meat, or in the processing of products which have to maintain unaltered for a long period of time their aromatic features such as coffee, tea or spices.

MAP is nowadays frequently used in the packaging of coffee in capsules. Today, in fact, the demand of coffee packaged in capsules is constantly increasing, enhancing the attention in product quality. To fulfill the coffee quality requirements, producers started to ask for coffee packaging lines, which are able to minimize the O_2 residual inside the capsules. A low oxygen level in capsules help limiting the oxidation process of the final product, thus enhancing its shelf-life and reducing the organoleptic alteration of coffee. Some systems could be used to achieve this goal, such as: vacuum filling, vacuum filling with inert gas injection and many others. Among these techniques the most used is the gas flushing Modified Atmosphere Packaging. According to this method the capsule is fluxed with an inert gas before the filling phase until the sealing phase, to remove air from the inner side of the capsule itself and consequently reducing the O_2 residual in the closed package. The inert gases usually used for these purposes are N_2, CO_2, Argon or mixtures of them.

To make modified atmosphere packaging effective, three conditions must be satisfied:

1. the packaging phase must be preceded by a correct coffee degassing process, in order to minimize the quantity of air blocked in the coffee itself;
2. the packaging phase needs a very effective monitoring to be sure that air is completely removed by the capsules and Nitrogen is instead inside them;
3. the capsule and closing material must have a low permeability, in order to limit the permeation of the inert gas through the package wall (aluminium or multilayer polimeric films are usually used in this case).

The third point attends to technological aspects of the container manufacturers, while the first one attends to the food equipment manufacturer, whilst the second one is on the responsibility of food packaging manufacturer.

Considering its importance, MAP is now studied in a more methodical way, also by means of advanced techniques as CFD (Computational Fluid Dynamics). This tecnique was in particular adopted in the design of postharvest facilities or cooling facilities for the storage of fruits and vegetables (Delele et al., 2011 and Ferrua et al., 2008); recently it has also been used to investigate mass and heat transfer of bio-substrates in modified atmosphere packaging (De Bonis et al., 2013) or to evaluate the losses of CO_2 through a PET bottle containing a carbonated beverage (Carrieri et al., 2011). Nevertheless, CFD has never been used to evaluate the flow of gas in packaging machines and as a tool to optimize the packaging process.

Aim of this work is then to analyze, by means of CFD, the gas flushing of N_2 on a coffee in capsules packaging machine in order to optimize the geometric shape of some of the mechanical components in the sealing station of the machine itself. The new configuration should allow reducing inert gas consumption and, at the same time, achieving an O_2 residual in the center of the container which is constantly equal or below 1% by mass.

2. MATERIALS AND METHODS

Based on what stated in the introduction about the influence of the coffee degassing phase, both in the simulation and in the subsequent experimental phase the capsules were left empty in order to avoid the influence of the coffee degassing process on the results (since its accuracy could not be monitored).

2.1. Equipment

The coffee packaging machine is made by a conveyor belt which moves in a discontinuous way (one step every 0.4s). On all the elements composing the conveyor belt are present four holes and in every hole is housed a little basket which contains a capsule. The conveyor belt advances and stops at every station present on the packaging line. In particular, four station are present:

1. a filling station, where the capsules are filled with coffee;
2. an aspiration station, where coffee powder is aspirated from the edge of every capsule in order to facilitate the following sealing operation;
3. a station where a micro-perforated film is placed on the "free surface" of coffee;
4. a sealing station, where the capsules are closed with a polymeric or aluminium lid.

The second station is not always activated, depending on coffee granulometry.

From immediately before the filling station, to the sealing station, there is a tunnel where it is fluxed nitrogen gas in order to saturate the environment and remove air that may cause an excessive O_2 residual inside the closed package.

This packaging lines can produce more than 340 capsules per minute. The overall dimensions of the packaging machine are 4690 x 555 x 1340 mm.

Figure 1 shows a block diagram which resumes the functioning of the previously described packaging line.

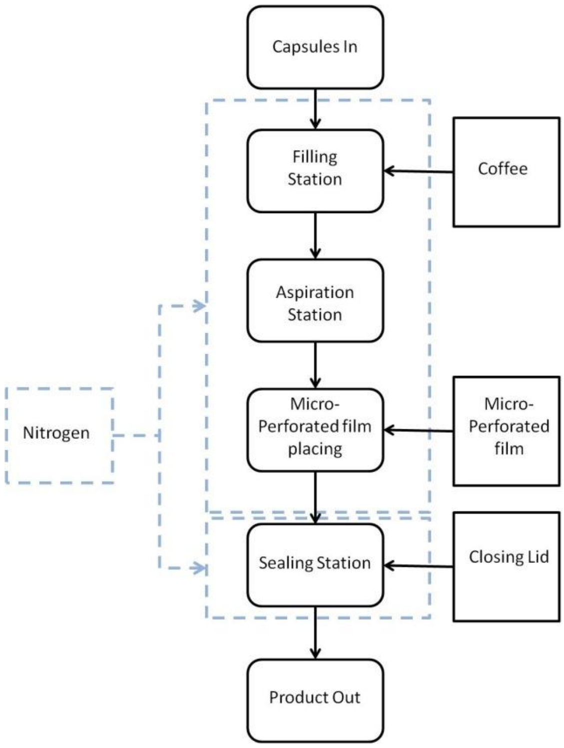

Figure 1:block diagram of the coffee packaging line considered in this study

As previously explained, the CFD analysis has been focused only on the sealing station of the packaging machine. The reason is that this is the area where the N_2 flow rate is higher. In Figure 2 is shown a 3D simplified geometry of the capsules' sealing station.

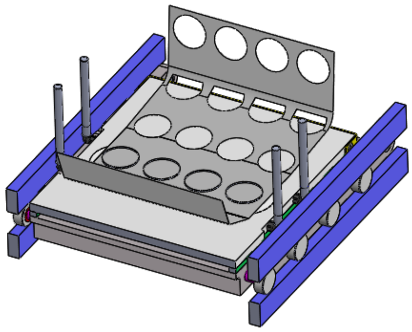

Figure 2: capsules' sealing station

The main components present in this station are: a stainless steel plate, within which a groove for the distribution of gaseous N_2 is formed by milling, four diffuser rings, which address N_2 inside the capsules, four small pipes (internal diameter equal to 8 mm) which direct N_2 flow inside the groove realized in the plate, the closing lid and, finally, four electric heaters welding the lid on the capsules' edge. Figure 3 shows a section of the stainless steel plate.

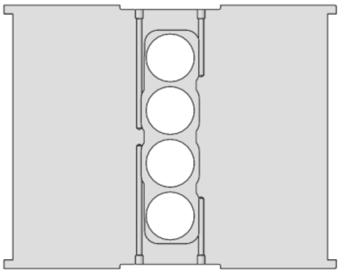

Figure 3: plate section

The one just outlined is the original configuration of the sealing station, which is currently installed on the packaging line. In addition to this, a modified station has been analyzed.

After the modeling phase, the simulations will be validated with an experimental phase. Both in the simulations and in the experimental phase. The considered capsule is the model "Blue", made by Lavazza, which has a truncated-cone shape, with a maximum diameter of 40 mm, a minimum diameter of 32 mm and an overall height of about 26 mm. It is important to specify the capsule's model because from it depends the kind of diffuser ring that has to be mounted.

After the validation of the CFD model some simulation with other two kind of capsule that the packaging line can process have been performed. The involved capsules model are "A Modo Mio", made by Lavazza and a Nespresso-Like capsule. The first one has a maximum diameter of 40 mm, a minimum diameter of 32 mm and an overall height of 17 mm, while the second one has a maximum diameter of 30 mm, a minimum diameter of 15.7 mm and an overall height of 28 mm.

Based on the obtained results some changes in the shape of the plate will be made and tested.

2.2. CFD Modelling

To set up the physics and solve the calculation, Ansys CFX version 14.5 has been used, because this software allows to simulate multi-component fluids. In fact, a 3D multi-component simulation has been set up, considering a gas mixture of Argon, N_2 and O_2.

In a mixture each component has its own equation for conservation of mass. After Reynolds-Averaging it can be expressed as:

$$\frac{\delta\tilde{\rho}_i}{\delta t}+\frac{\delta(\tilde{\rho}_i\tilde{U}_j)}{\delta x_j}=-\frac{\delta}{\delta x_j}\left[\rho_i\left(\tilde{U}_{ij}-\tilde{U}_j\right)-\overline{\rho_i''U_f''}\right]+S_i \quad (1)$$

where:

$\tilde{\rho}_i$ is the mass-average density of fluid component i in the mixture

$\tilde{U}_j=\sum\frac{(\tilde{\rho}_i\tilde{U}_{ij})}{\bar{\rho}}$ is the mass-average velocity field,

$\tilde{U}_{ij}$ is the mass-average velocity of fluid component i,

$\rho_i\left(\tilde{U}_{ij}-\tilde{U}_j\right)$ is the relative mass flux,

S_i is the source term for component i which includes the effects of chemical reactions.

The mixture, instead, is generally treated as an "Ideal Mixtures", meaning that its properties are calculated directly by means of a mass averaging of the component materials properties. Thus, for instance, the mixture density ρ can be calculated from the mass fraction Y_i and the thermodynamic density of each component ρ_i by means of equation 2.

$$\frac{1}{\rho}=\sum_{i=A,B\ldots}^{N_C}\frac{Y_i}{\langle\rho_i\rangle} \quad (2)$$

In the mixture, N_2 has been considered as constraint component, meaning that its mass fraction is calculated to ensure that all the component mass fraction sum to unity in every instant. This means that the mass fraction of nitrogen is set equal to the total mass fraction of the other components in the Ideal Mixture subtracted from unity.

The full buoyancy model has been implemented in the domain, to consider motion due to density differences and a heath exchange model has been considered, to take account of the heath generated by the electrical resistances used to fix the closing lid over the capsules. In particular, the "Total Energy" model has been adopted, which is usually recommended by Ansys CFX solver theory guide and Ansys CFX solver modeling guide when dealing with flow of compressible substances.

Furthermore, the Shear Stress Transport turbulence model has been adopted. The SST model, proposed by Menter (1994), is an eddy-viscosity model, which is a combination of a k-ω model and k-ε model. The first is used in the inner boundary, while the second in the outer region and outside of the boundary layer (Bottani et al, 2008). The SST model has been used in order to overcome the problems of both the methods. These features make the SST model more accurate and reliable for a wider class of flows than the standard k-ω and k-ε models.

2.2.1. Mesh setting for the fluid domain

The fluid domain has been obtained starting from the 3D CAD model of the sealing station by means of the CAD software SolidWorks (version 2014), while the discretization of the fluid domain has been performed using the software Icem CFD version 14.5.

The mesh was initially set by creating a uniform subdivision, and then thickened in the critical areas of the fluid volume. In particular, a finer mesh was used near the capsules, in the groove realized inside the stainless steel plate and near the diffuser rings which address the N_2 flow inside the containers.

At the end of the operation, an unstructured grid with a total of 4,700,000 nodes and 27,600,000 tetrahedrons was obtained.

Figure 4 shows a section of the obtained volume mesh.

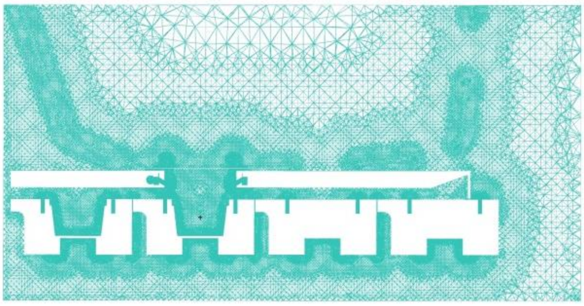

Figure 4: section of the fluid domain volume mesh

2.2.2. Simulation setting

A 3D multi-component simulation has been set up considering a gas mixture of Argon, N_2 and O_2. These three substances were considered as ideal gases, while the mixture has been set as "Ideal Mixture". N_2 has been used as constrain component, meaning that its mass fraction is set equal to the total mass fraction of the other components in the Ideal Mixture subtracted from unity.Since Argon Ideal Gas is not present in Ansys CFX material library it has been created using the settings showed in Table 1.

Table 1: Argon ideal gas settings

Argon Ideal Gas Settings	
Thermodynamic State	Gas
Equation of State	Ideal Gas
Molar Mass	$39.948\ \frac{g}{mol}$
Specific Heat Capacity	$520\ \frac{J}{kg\ K}$
Specific Heat Type	Constant Pressure
Reference Temperature	25 °C
Reference Pressure	1 atm
Dyamic Viscosity	2.217e-05 Pa·s
Thermal Conductivity	$0.016\ \frac{w}{m\ K}$

At the beginning of the simulation the fluid domain has been considered, in order to simulate air presence, as composed by 21% of O_2, 1% of Argon and 78% of N_2, while on the inlets only nitrogen was considered.

The boundary and initial condition for the original case are shown in Table 2.

Table 2: boundary and initial conditions for original case

Original Case Buondary Conditions	
Inlet_1; Inlet_2; Inlet_3; Inlet_4	Volumetric Flow-Rate = 20 l/min T = 25°C
Opening	Composition: 1% Ar, 78% N_2, 21% O_2 T = 25°C p = 1 bar
Resistenze	Free Slip Wall T = 90°C
Wall	Free Slip Wall Adiabatic
Original Case Initial Conditions	
Domain Composition	1% Ar, 78% N_2, 21% O_2
Velocity	0 m/s
T	25°C
p	1 bar

The simulations have been performed both in steady state and both in transient mode because the flow of N_2 is not time dependent but the capsules stay in the sealing station only for a fixed period of time (0.4s). In particular, in transient mode, 4s have been simulated with a time step of 0.02 s. The results have been checked at 0.4s.

2.3. Experimental Method

To validate the CFD model some experimental tests have been performed on the packaging machine object of this study. In particular, the machine with the new plate has been tested.

As previously stated, the capsules considered during experimental phase were the "Blue" model and they were left empty, so the coffee dosing system has been excluded from the machine configuration. Furthermore also the tunnel has been excluded, in order to evaluate only the effects of gas flushing in the sealing station.

The sensor used in the tests was Dansensor CheckPoint, especially created to evaluate O_2 or CO_2 concentration in the headspace of containers processed in modified atmosphere. This sensor has a needle which must be inserted in the closed package. From the needle a small quantity of the internal gas mixture is aspired and then the probe evaluates the O_2 concentration in the mixture.

Before the test, few packaging cycles have been performed, in order to reach steady state condition in the flux of N_2.

The respected experimental procedure is the following:

1. execution of the packaging cycle;
2. taking of the capsules coming out from the packaging line;
3. placing on the capsules closing lid of a small piece of adhesive rubber, so to avoid the flow

of external air in the container during the perforation;
4. introduction of the sensor's needle;
5. test execution;
6. writing of the value of O_2 residual showed by sensor's monitor.

Before tests' execution is important to check the correct calibration of the sensor, measuring various time the O_2 concentration of the air around the sealing station and verifying that the showed value is always close to 21%.

3. RESULTS AND DISCUSSION

3.1. CFD simulation of the original case

With the "probe" tool in post process section of the used CFD code, that allows to measure the value of a given parameter in a specified point of the fluid domain, the O_2 residual in the geometrical center of each capsule.

The detected values are shown in Table 3.

Table 3: O_2 residual in capsules' center for current configuration

O_2 Residual in Capsules' Center		
Capsule	N_2 Concentration	O_2 Residual
Capsule 1	90.66 %	1.96 %
Capsule 2	83.51 %	3.46 %
Capsule 3	83.59 %	3.45 %
Capsule 4	90.88 %	1.92 %
Mean O_2 Residual		2.70 %

As can be noticed from the previous Table, in each capsule O_2 residual is higher than the target value of 1% and the mean O_2 residual is equal to 2.70%. It is interesting to note also that the two capsules located in the center position of the conveyor belt (indicated with Capsule 2 and Capsule 3) reach a lower N_2 concentration and consequently show a higher O_2 residual. Figure 5 shows the O_2 concentration inside Capsule 2.

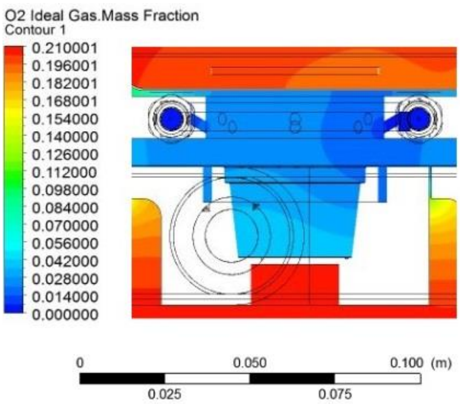

Figure 5: O_2 mass fraction inside one of central capsules

Streamlines have been analyzed too. In fact they represent the preferred trajectories of gas particles therefore their visualization could be useful to identify any N_2 leakage points. Figure 6 provides an illustration of the fluid streamlines within the domain.

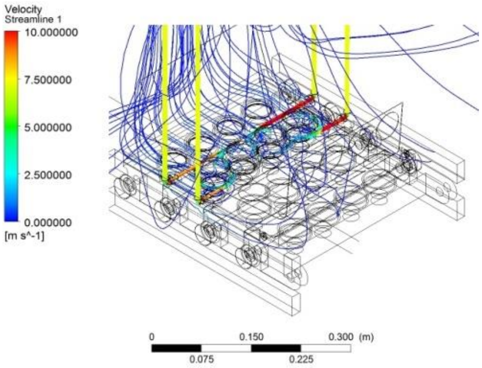

Figure 6: streamlines within the domain

It was not found any particular point of leakage, with the exception of the connecting zone between the sealing station and the tunnel, where there is the N_2 flushing with previously mentioned. This zone was however not considered like a real leakage point since the gas flowing out from here is not lost but goes inside the tunnel and thus contributes anyhow to the effectiveness of the packaging process.

Other analyzed results (respectively shown in Figure 7 and Figure 8) are the absolute pressure and the velocity distribution inside the groove for N_2 distribution, in order to observe the conditions which lead to the O_2 residuals indicated in Table 1.

In particular it has been noticed that the pressure distribution inside the groove is not perfectly homogeneous and that low velocities especially near the holes which address N_2 in the capsules. This may be the cause of the higher O_2 residual detected in the central capsules.

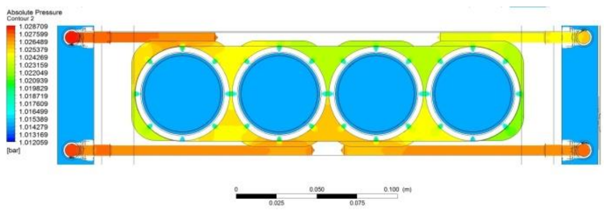

Figure 7: absolute pressure inside groove for N_2 distribution (original case)

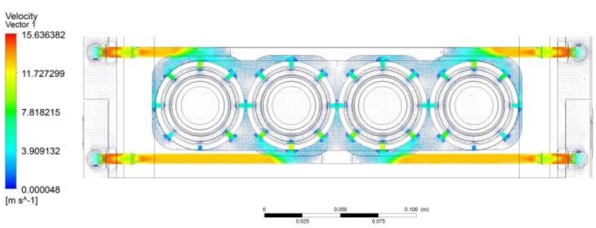

Figure 8: velocity vectors inside groove for N_2 distribution (original case)

3.2. Experimental phase validation

The CFD model has been validated with an experimental phase, which has been performed on the described packaging machine.

The followed experimental procedure is the one described in paragraph 2.3. Table 4 shows tests' results.

Table 4: experimental validation results

Experimental Tests Results				
Test no.	**Capsule**	**O_2 Residual [%]**	**N2 Flow-Rate [l/min]**	**Pressure [bar]**
1	1	2.1	80	2.5
	2	3.4		
	3	3.6		
	4	1.9		
2	1	1.8	80	2.5
	2	4.0		
	3	3.7		
	4	2.0		
3	1	2.1	80	2.5
	2	3.5		
	3	3.7		
	4	2.0		

The experimental validation phase showed good agreement between CFD model and the real case.

3.3. Design of a new N_2 distribution system

Considering the results obtained with the first CFD simulation and during the model validation phase a new N_2 distribution system has been developed. In particular, the main variation is in the shape of the groove realized within the plate. A section of the new plate is shown in Figure 9.

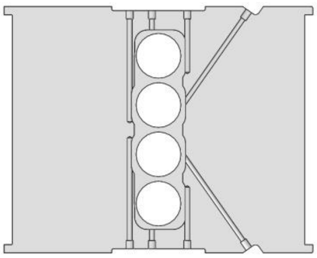

Figure 9: new plate section

As can be noticed from the previous picture the introduced changes have resulted in an increase in the number of N_2 inlet points (from 4 to 8).

After obtaining a new fluid domain a CFD simulation of the modified case has been set up. For the mesh generation the settings described in paragraph 2.2.1 have been adopted, while boundary and initial conditions are the same of the ones shown in Table 1, except for the Inlets. In fact, as previously explained, with the new plate eight Inlets are present thus on each one of them a Volumetric Flow-Rate of 10 l/min, and a Temperature of 25°C have been fixed, in order to keep the total flow rate constant.

3.4. CFD simulation of the new case

The results obtained for O_2 residual with the new plate are shown in Table 5.

Table 5: O_2 residual in capsules' center for new configuration

O_2 Residual in Capsules' Center				
Capsule	**N_2 Concentration**	**O_2 Residual**	**Increase in N_2 Conc.**	**Decrease in O_2 Residual**
Capsule 1	96.44 %	0.75 %	6.4 %	- 61.7 %
Capsule 2	97.34 %	0.56 %	16.6 %	- 83.8 %
Capsule 3	97.42 %	0.55 %	16.5 %	- 84.1 %
Capsule 4	96.25 %	0.78 %	5.6 %	- 59.4 %
Mean O_2 Residual		0.66 %		
Mean Increase in N_2 Conc.			11.28 %	
Mean Decrease in O_2 Residual				- 72.25 %

As can be noticed from previous Table, the introduced changes allow to reach the target goal of an O_2 residual lower than 1% by mass. In particular the new configuration shows a mean decrease in O_2 residual of - 72.25 %, allowing to reach a mean O2 residual of 0.66% (max residual 0.78 %). Furthermore, with this configuration the most disadvantaged capsules are no longer the ones in central position but are Capsule 1 and Capsule 4.

Also in this case, absolute pressure and velocity distribution inside the groove realized within the plate have been analyzed (respectively Figure 10 and Figure 11).

In particular it has been noticed a more homogeneous pressure distribution, with values closer to atmospheric pressure and higher velocity values in correspondence of some of the injection holes (maximum velocity of about 16 m/s).

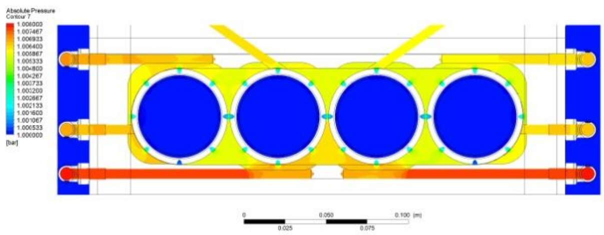

Figure 10: absolute pressure distribution inside groove for N_2 distribution (modified case)

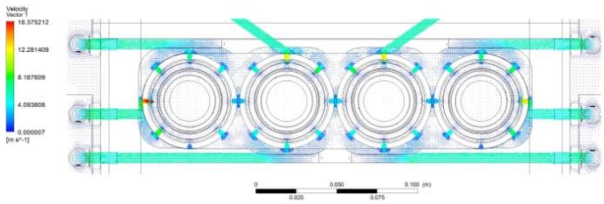

Figure 11: velocity vectors inside groove for N_2 distribution (modified case)

Clearly, maintaining the total flow-rate constant but increasing the number of inlets, N_2 velocity inside the distribution pipes is lower than in the original case, and also this fact can be noticed comparing Figure 9 and Figure 11.

3.5. Experimental phase results

As previously stated, experimental tests have been executed also on the new configuration of the packaging machine, in order to validate the CFD model.

The followed experimental procedure has been described in paragraph 2.3. Table 6 shows tests' results.

Table 6: experimental phase results

Experimental Tests Results				
Test no.	Capsule	O_2 Residual [%]	N2 Flow-Rate [l/min]	Pressure [bar]
1	1	0.5	80	1.8
	2	0.4		
	3	0.4		
	4	0.4		
2	1	1.80	80	2.1
	2	0.7		
	3	0.7		
	4	1.0		
3	1	0.6	80	2.5
	2	0.6		
	3	0.6		
	4	0.7		

The experimental tests, especially test no. 3, show a good correspondence between CFD modeling and experimental phase.

3.6. Other CFD simulations

The CFD simulations with the other type of capsules have been performed only in steady state mode.

The O_2 residual results are presented in Table 7 for the model "A Modo Mio" and in Table 8 for the Nespresso-Like capsule.

Table 7: O_2 residual in "A Modo Mio" capsules' center

O_2 Residual in Capsules' Center		
Capsule	N_2 Concentration	O_2 Residual
Capsule 1	96.55 %	0.73 %
Capsule 2	97.63 %	0.49 %
Capsule 3	96.94 %	0.64 %
Capsule 4	96.65 %	0.71 %
Mean O_2 Residual		0.643 %

Table 8: O2 residual in capsules' center for Nespresso-Like capsules

O_2 Residual in Capsules' Center		
Capsule	N_2 Concentration	O_2 Residual
Capsule 1	94.15 %	1.22 %
Capsule 2	95.08 %	1.03 %
Capsule 3	95.27 %	0.98 %
Capsule 4	95.06 %	1.04 %
Mean O_2 Residual		1.068 %

In Figure 12 is compared the O_2 mass fraction inside the container for this two kind of capsules.

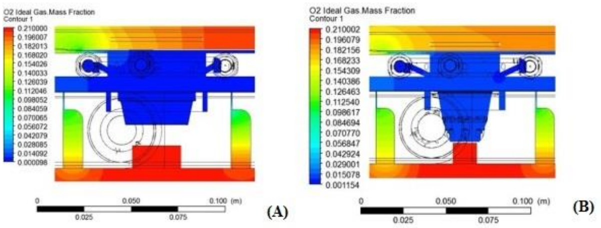

Figure 12: O_2 mass fraction inside one of central capsules for the model "A Modo Mio" (A) and the Nespresso-Like capsule (B)

4. CONCLUSIONS

Modified atmosphere packaging of coffee in capsule is increasingly used because producers need to preserve as long as possible final product quality. In particular it is increasingly felt the need to obtain a O_2 residual in the head space of containers equal to or less than 1% by mass. Thus, the aim of this work was to optimize, by means of CFD analysis, the geometrical shape of some components in the sealing station of a coffee packaging machine, in order to achieve the desired O_2 residual with an equal or lower inert gas (N_2 in this case) consumption. In particular, it has been modified a groove realized within a stainless steel plate which composes the sealing station of the machine and that is used for N_2 distribution. To avoid the need to consider the effectiveness of the coffee degassing process capsules were considered empty. The model of the capsule used in the simulation is "Blue", produced by Lavazza.

The original configuration of the packaging machine was first simulated, using the plate currently installed, showing how this design could not allow to reach an O_2 residual lower than 1% for each capsule. In particular a mean residual of 2.70 % was detected for the simulation.

The CFD model has been validated with an experimental phase, executed on the packaging machine with the old plate installed on it. The tests showed a good correspondence between simulations and experimental data.

Subsequently, it has been simulated the new configuration of the packaging line, with the modified plate installed. This analysis showed how the new plate can allow to reach the prefixed goal: in fact, a mean O_2 residual of 0.66 % has been detected for the simulation, which means that the introduced changes have led to a mean decrease in unwanted gas residuals of - 72.25 %. Thus it is confirmed that the new sealing station is more effective in reaching a low level of O_2 residual than the previous one.

Other two simulations have been performed in order to analyze if the introduced changes were effective also with other capsules models which can be processed by the machine object of this study. The analyzed capsules in this case were the model "A Modo Mio", made by Lavazza, and a Nespresso-Like capsule. In the first case a mean O_2 residual of 0.643% has been obtained, while in the second case the mean O_2 residual was equal to 1.068%.

These new simulations also have highlighted a correlation between the capsule shape and the level of O_2 residual that can be reached. In particular it has been noticed that higher is the capsule height, harder is to reach a low level of O_2 residual and that smaller is the capsule diameter, harder is to reach a low residual.

Future researches could be addressed to improve the CFD simulation process and make the analysis more accurate, adding a moving mesh, in order to take account of the motion of the conveyor belt.

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