DRYING PROCESS SIMULATION IN FOOD INDUSTRY USING LATTICE BOLTZMANN METHOD

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ABSTRACT

Drying Process thermodynamics has recently earned a significant interest in the research of food industry. Moisture release from the pasta-dough due to the external diffusive-convective heat transfer is investigated. From a process engineering point of view, such phase transition analysis can be used for process optimization. The objective of this study is the development of a lattice Boltzmann model in the particle scale, to solve the simultaneously coupled mass and heat transfer between the pasta-dough sample and the surrounding environment, also, the evaporation process across the boundaries is considered. Numerical simulations are held to deliver an insight into the heat and mass transfer processes, offering visualization and yet more understanding of the field variables. Simulation parameters are to be selected using the experimental data.

Keywords: Lattice Boltzmann Method, Drying Process, Phase Transition, Mass and Heat Transfer.

1. INTRODUCTION

Pasta are considered as one of the most common food around the world, originating from Italy in 1700 (Tammerman et al. 2006). Production quality of pasta, and in contrast production defects like crumbling during packaging, in-homogeneousness, unevenness in size, cracks due to extra dehydration, all have always been a concern to producers (Mokhtar et al. 2011). So, Drying process is an interesting topic for the industry of pasta and noodles. The drying parameters; Drying Air speed, its temperature, and relative humidity all are questionable values for high production rate and quality. All those parameters are usually gained by experience, though, it's thought that if they are studied using the developed tool, it can enhance the efficiency and the time cost of this process. The work in this publication, is to develop this computational tool using single time relaxation Lattice Boltzmann Method (LBM) but for multiple physical parameters which are the flow field, temperature, and moisture concentration to simulate this complicated process. Noodles' Geometry was implemented into the code using the image processing of a binary stack of images from a high resolution µCT Scanner. Finally, models from literature was used for the estimation of the thermo-physical properties of pasta-dough and drying air which are essential for the estimation of the relaxation time for each physical distribution function in LBM. The work is distributed as following; problem definition including process conditions, and image extraction process, then the mathematical equations, distribution functions, and non-dimensional parameters used in the LBM solver, then the implemented thermo-physical models from literature based on correlations of semi-empirical data for pasta-dough, and gas mixture of humid air, finally the available results from the simulation tool.

2. MATERIALS AND METHODS

2.1. Material Definition

Random sample of band noodle (Figure 1) of size 190x137x150 mm was investigated inside the computational domain shown in Figure 2. As sample's distribution and orientation are highly random, the geometry extraction was an issue for the computational domain. So, it was suggested to be done using a high-resolution GE/Phoenix µCT scanner. 3D model was built inside the solver by reading multiple binary Image scaffolds (Figure 3) extracted from the volume model (Figure 4), the final result is shown in Figure 5. Simple edge detection was also made to indicate the noodles' surface inside the simulation tool.

Initial conditions were set as 20 ^oC for the whole domain, and 0.3 moisture concentration for the noodles. Drying air inlet velocity, temperature and relative humidity were set to as 3m/s, 80 ^oC and 60% respectively.

Figure 1: Sample Band Noodles

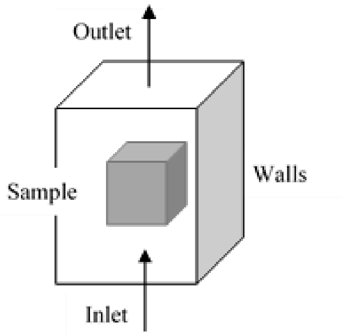

Figure 2: Computational Domain


Figure 3: Binary Image Scaffolds

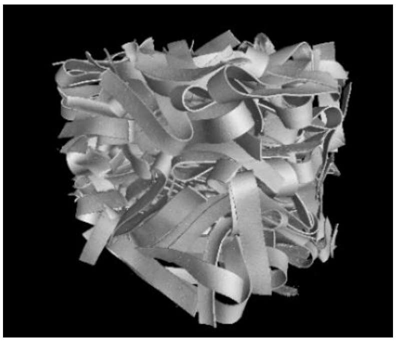
Figure 4: Volume File from the µCT scanner

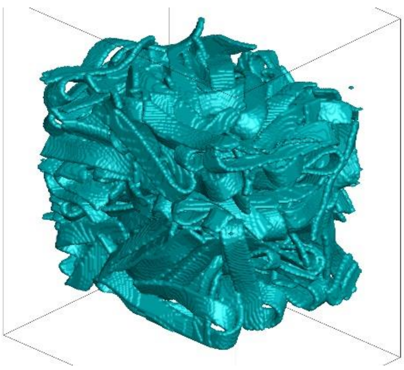
Figure 5: Exported Geometry from the code after processing and assembly of the images' stack

2.2. Lattice Boltzmann Method

Lattice Boltzmann Method has gained a lot of attention in the field of fluid mechanics, including Multi-phase flow, thermal flows, flow in complex and micro-scale media. This is due to the nature of the Boltzmann's equation, which describes the motion and interaction of fluid particles in a microscopic level.

The lattice Boltzmann's Equation relates the particle distribution f per unit time to the propagation motion and collision (Hussein 2010).

$$\frac{\partial f}{\partial t} + u.\nabla f = Q \tag{1}$$

Where u the particle velocity and Q is the collision operator.
The collision operator was approximated by (Koelman 1991), using the Bhatnagar-Gross-Krook (BGK) model as follows:

$$Q_i = -\frac{1}{\tau}\left[f_i - f_i^{(equ)} \right] \tag{2}$$

Where τ is the relaxation time toward the local equilibrium, and $f_i^{(equ)}$ is the Equilibrium distribution function (Equation 3) which is evaluated from the Maxwell-Boltzmann distribution (Succi 2001).

$$f_i^{equ} = w_i \rho \left[1 + 3\frac{\hat{e}_i \cdot u}{c^2} + \frac{9}{2}\frac{(\hat{e}_i \cdot u)^2}{c^4} - \frac{3}{2}\frac{u^2}{c^2} \right] \tag{3}$$

Where $\hat{e}_i$, w_i, c, and u are the discrete unit vectors, the weighting factor, the lattice speed $c = \frac{\Delta x}{\Delta t}$, and the macroscopic velocity respectively. The used lattice in this work would be the D3Q19 (Figure 6) & (Table 1).

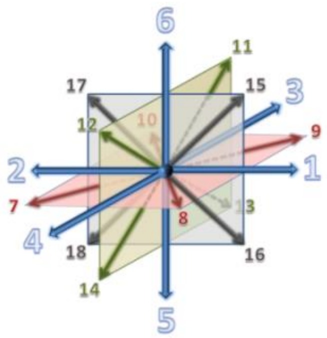

Figure 6: D3Q19 lattice model representing 19 velocity direction in 3D lattice (Hussein 2010)

Table 1: Weighting factors for each unit direction of the D3Q19 lattice

$\hat{e}_i$	w_i
0	1/3
1, 2, 3, 4, 5, 6	1/18
7, 8, .., 18	1/36

The advection-diffusion equation for Concentration and Temperature can be written as follows:

ISBN 978-88-97999-86-7; Bruzzone, Longo and Vignali Eds.

$$\frac{\partial C}{\partial t} + u \cdot \nabla C = D\nabla^2 C \qquad (4)$$

$$\frac{\partial T}{\partial t} + u \cdot \nabla T = \alpha\nabla^2 T \qquad (5)$$

Where C, u, D, T, and α are the moisture concentration, macroscopic velocity updated from the flow field equation, mass diffusivity, temperature, and thermal diffusivity respectively.

The Advection-Diffusion mass and heat transfer were then modelled in LBM using the following three distribution functions: Moisture concentration, Temperature, and Density. So, the flow field has been solved across the noodles and coupled with the Moisture and Temperature fields.

The three LB Equations (LBE) used in this work are expressed as follows:

$$\frac{\partial\{f\}}{\partial t} + \upsilon \cdot \nabla\{f\} = \{Q\}$$

$$\{f\} = \begin{bmatrix} \rho \\ T \\ C \end{bmatrix}; \{Q\} = \begin{bmatrix} -\frac{1}{\tau_f}\left(f_i - f_i^{(equ)}\right) \\ -\frac{1}{\tau_T}\left(T_i - T_i^{(equ)}\right) \\ -\frac{1}{\tau_C}\left(C_i - C_i^{(equ)}\right) \end{bmatrix} \qquad (6)$$

$$f_i^{equ} = w_i\rho\left[1 + 3\frac{\hat{e}_i \cdot u}{c^2} + \frac{9}{2}\frac{(\hat{e}_i \cdot u)^2}{c^4} - \frac{3}{2}\frac{u^2}{c^2}\right] \qquad (7)$$

$$T_i^{equ} = w_i T\left[1 + 3\frac{\hat{e}_i \cdot u}{c^2} + \frac{9}{2}\frac{(\hat{e}_i \cdot u)^2}{c^4} - \frac{3}{2}\frac{u^2}{c^2}\right] \qquad (8)$$

$$C_i^{equ} = w_i C\left[1 + 3\frac{\hat{e}_i \cdot u}{c^2} + \frac{9}{2}\frac{(\hat{e}_i \cdot u)^2}{c^4} - \frac{3}{2}\frac{u^2}{c^2}\right] \qquad (9)$$

Where $\rho \,\&\, u$ are evaluated from the zeroth and first moments of the density distribution function (Equation 10), while the macroscopic T and C are calculated from the zeroth moment of Temperature and Concentration distribution function respectively (Equation 11 & 12).

$$\rho = \sum_i f_i \;; \rho\hat{u} = \sum_i f_i \,\hat{e}_i \qquad (10)$$

$$T = \sum_i T_i \qquad (11)$$

$$C = \sum_i C_i \qquad (12)$$

The relaxation time τ_f, τ_T, τ_C are related to the kinematic viscosity ν, thermal diffusivity α, mass diffusivity D respectively through the following relations (Wolf-Gladrow 2000):

$$\tau_f = 3\nu + \frac{1}{2} \qquad (13)$$

$$\tau_T = 3\alpha + \frac{1}{2} \qquad (14)$$

$$\tau_C = 3D + \frac{1}{2} \qquad (15)$$

The kinematic viscosity, thermal and mass diffusivities are evaluated in the lattice units according to the following non-dimensional groups respectively (Hussein 2010):

$$Re = \frac{u_\infty \cdot l}{\nu} \qquad (16)$$

$$Fo_T = \frac{\alpha \cdot t}{l^2}, Fo_C = \frac{D \cdot t}{l^2} \qquad (17)$$

$$Bo_T = \frac{u_\infty \cdot l}{\alpha}, Bo_C = \frac{u_\infty \cdot l}{D} \qquad (18)$$

Where the Reynold's, Fourier, and Bodenstein numbers are used to define the flow field across the noodles, both thermal and mass diffusivities inside the noodles' structure, and the ratio between momentum diffusivity to both thermal and mass diffusivities within the air domain between the noodles respectively. Given that u_∞, l, and t are the inlet flow velocity, the characteristic length, and process time.

2.3. Thermo-Physical Properties

2.3.1. Pasta-Dough

In order to get an estimation for the LBM relaxation time to each distribution function, pasta-dough thermo-physical properties should be implemented using semi-empirical relationships from literature. Though, uncertainty in these models was already stated due to the difference in raw materials for each case and experiment, these different models can be easily replaced if any is later appeared in literature, also can be tuned easily according to the dough properties.

2.3.1.1. Thermal Conductivity

Pasta-dough thermal conductivity can be correlated with its temperature and moisture content through the following four parameter model (Saravacos and Maroulis 2001):

$$k_d = \frac{\lambda_0}{1+x}\exp\left[-\frac{E_o}{R}(\frac{1}{T}-\frac{1}{T_{ref}})\right] + \frac{\lambda_i x}{1+x}\exp\left[-\frac{E_i}{R}(\frac{1}{T}-\frac{1}{T_{ref}})\right] \quad (19)$$

Where λ_0, λ_i, E_0, E_i are dough material parameters given as 0.273 W/m K, 0.8 W/m K, 0.0 KJ/mol, 2.7 KJ/mol respectively, x is the water content on the dry basis, R is the universal gas constant $(8.314\cdot 10^{-3}\,\frac{KJ}{mol\cdot K})$, $T[^oC]$ is the dough temperature, $T_{ref} = 60^oC$.

2.3.1.2. Heat Capacity

Heat Capacity can be computed by the weighted average of the dough main components as follows:

$$C_{d,Total} = \frac{x}{1+x}C_{water} + \frac{1}{1+x}C_{Solid} \quad (20)$$

$$C_{Solid} = y_{Starch}C_{Starch} + y_{Proteins}C_{Proteins} + y_{Fats}C_{Fats} \quad (21)$$

Where the specific heat of each component is given by (De Cindio et al. 1992) in $[\frac{J}{Kg\cdot K}]$ as:

$$C_{Starch} = 5.737(T+273)+1328 \quad (22)$$

$$C_{Proteins} = 6.329(T+273)+1465 \quad (23)$$

$$C_{Fats} = 2000 \quad (24)$$

Considering that y is the mass fraction of each component with respect to the solid basis, given as 0.84, 0.146, 0.014 for each of starch, proteins, fats respectively as given by (Tammerman et al. 2006), and T is the dough temperature in $[^oC]$.

2.3.1.3. Density

The dough density can be evaluated as (De Cindio et al. 1992):

$$\rho_d = (3.02\cdot\frac{x}{1+x}+6.46)^{-1}\cdot 10^4\ [\frac{Kg}{m^3}] \quad (25)$$

2.3.1.4. Thermal Diffusivity

Thermal diffusivity is then calculated from its definition by:

$$\alpha_d = \frac{k_d}{\rho_d\cdot C_d}\ [\frac{m^2}{s}] \quad (26)$$

2.3.1.5. Mass Diffusivity

Water Mass diffusivity in dough can be evaluated using the semi-empirical model given by (Waananen and Okos 1996) as:

$$D_d = \left(1.2\times 10^{-7} + \varepsilon\cdot\frac{8\cdot 10^{-5}}{P}\right)\cdot\exp\left(-\frac{6.6e^{-20x}+E_a}{R(T+273)}\right)\left[\frac{m^2}{s}\right] \quad (27)$$

Where ε is the porosity of the dough which is assumed to be 0.26 (Xiong et al. 1991), $T[^oC]$ is the dough temperature, E_a is the activation energy for diffusion of a free water molecule which is used as 22.6 $\frac{KJ}{mol}$ (Waananen and Okos 1996), R is the universal gas constant ,$(8.314\cdot 10^{-3}\,\frac{KJ}{mol\cdot K})$, and P is the dough pressure [KPa].

2.3.2. Humid Air

As for Pasta-dough, humid air thermo-physical properties should also be evaluated based on its Temperature and Humidity using analytical procedure from literature for the gas mixture properties of dry air and saturated water vapour.

2.3.2.1. Dynamic Viscosity

Dynamic viscosity of humid air can be calculated using the fitted function by (Durst et al. 1996):

$$\mu = [(A_1 + A_2(T+273)) + (B_1 + B_2(T+273))x_v + (C_1 + C_2(T+273))x_v{}^2]\times 10^{-6}\ \left[\frac{N\cdot s}{m^2}\right] \quad (28)$$

Where T is the air temperature expressed in $[^oC]$, while, the numerical coefficients can be given in Table 2, x_v here is the molar fraction of water vapour in air which can be easily related to the specific humidity ω by:

$$x_v = \frac{\omega M_a}{\omega M_a + M_v} \tag{29}$$

Where $M_a \, and \, M_v$ are the molar mass of dry air and saturated water given by 28.97 and 18.01528 g/mole respectively.

Also, specific humidity can be related to the common Relative humidity ϕ through (Cengel and Boles 2002):

$$\omega = \frac{0.622 \phi P_g}{P - \phi P_g} \tag{30}$$

Where $P \, and \, P_g$ are the total mixture pressure and the water saturation pressure at a given temperature respectively, the later can be evaluated by (Tammerman et al. 2006):

$$P_g = 610.78 \exp\left[17.2694 \frac{T}{(T + 238.3)}\right] \; [Pa] \tag{31}$$

Where T is the expressed in $[^oC]$.

Table 2: Coefficients for the dynamic viscosity function

Coefficient	Value
A_1	6.0453459
A_2	0.042489943
B_1	−6.8323022
B_2	0.0059284286
C_1	−0.67799257
C_2	−0.011338714

2.3.2.2. Thermal Conductivity

Humid air thermal conductivity can be evaluated using the following expression for mixtures (Tsilingiris 2008; Reid et al. 1987):

$$k_{mixture} = \frac{(1 - x_v)\, k_a}{(1 - x_v) + x_v\, \Phi_{av}} + \frac{x_v\, k_v}{x_v + (1 - x_v)\, \Phi_{va}} \tag{32}$$

Where k_a and k_v are the thermal conductivities of air and water vapour respectively, which can be fitted by a polynomial (Durst et al. 1996):

$$\begin{aligned} k_i &= A_i + B_i\,(T + 273) + C_i\,(T + 273)^2 \\ &+ D_i\,(T + 273)^3 \end{aligned} \tag{33}$$

the coefficients $A, B, C,$ and D are given in Table 3.

Also, Φ_{av} and Φ_{va} are an interaction parameters given by:

$$\Phi_{av} = \frac{\left[1 + \left(\frac{\mu_a}{\mu_v}\right)^{0.5} \cdot \left(\frac{M_v}{M_a}\right)^{0.25}\right]^2}{\left[8\left(1 + \frac{M_a}{M_v}\right)\right]^{0.5}} \tag{34}$$

$$\Phi_{va} = \frac{\mu_v}{\mu_a} \frac{M_a}{M_v} \Phi_{av} \tag{35}$$

Table 3: Coefficients for the thermal conductivity polynomial equation

Coefficient	Value	
	Dry Air	Water Vapour
A	$-0.56827429 \times 10^{-3}$	31.997566×10^{-3}
B	$0.10805198 \times 10^{-3}$	$-0.13308958 \times 10^{-3}$
C	$-7.3956858 \times 10^{-8}$	3.8160429×10^{-7}
D	$3.7302922 \times 10^{-11}$	-2.0×10^{-10}

Where μ_a and μ_v are the dynamic viscosity of dry air and saturated water vapour respectively, which can be calculated using Equation 28, where the output at $x = 0$ is corresponding to the dry air, while $x = 1$ is for the saturated water vapour.

2.3.2.3. Heat Capacity

Specific heat can be evaluated using the correlated polynomial function (Durst et al. 1996) which assumes a linear mixture of the gas values:

$$\begin{aligned} C_{mixture} &= [A_a + B_a\,(T + 273) + C_a\,(T + 273)^2 \\ &+ D_a\,(T + 273)^3](1 - x_v) \\ &+ [A_v + B_v\,(T + 273) + C_v\,(T + 273)^2 \\ &+ D_v\,(T + 273)^3]\, x_v \end{aligned} \tag{36}$$

Where T is expressed in $[^oC]$, and the coefficients are given in Table 4.

Table 4: Coefficients for the heat capacity polynomial function

Coefficient	Value
A_a	1.0653697
B_a	-4.4730851×10^{-4}
C_a	9.8719042×10^{-7}
D_a	-4.6376809×10^{-10}
A_v	6.564117
B_v	-2.6905819×10^{-2}
C_v	5.1820718×10^{-5}
D_v	-3.2682964×10^{-8}

2.3.2.4. Density

Humid air density can be calculated from the gas equation of state (Durst et al. 1996):

$$\rho_{mixture} = \frac{1}{Z_F(T,x)}\frac{P_o}{RT}M_a\left[1 - x_v(1-\frac{M_v}{M_a})\right]$$

Where Z_F is the compressibility factor for the mixture i.e. The deviation correction of real gas from ideal gas behaviour, which can be expressed as:

$$Z_F = 1 + x_v\left[\frac{a+c(T+273)}{1+b(T+273)} - 1\right] \qquad (37)$$

Where $a, b, and\ c$ are given as 1.00784, -3.4299543×10^{-3}, and -3.4396097×10^{-3} respectively.

2.3.2.5. Thermal Diffusivity

Thermal diffusivity is again calculated from its definition by:

$$\alpha_{mixture} = \frac{k_{mixture}}{\rho_{mixture}\cdot C_{mixture}}\ [\frac{m^2}{s}] \qquad (38)$$

Thermal diffusivity could also be directly read from the chart in the work by (Tsilingiris 2008) as a function of temperature and relative humidity.

2.3.2.6. Mass Diffusivity

The mass diffusion of water in air can be expressed using the correlation from (Perry and Green 1984; Migliori et al. 2004):

$$D_a = \frac{10^{-3}\cdot T_f^{1.75}\left(\frac{M_a+M_v}{M_a\cdot M_v}\right)^{0.5}}{P\left[(\sum\upsilon)_a^{1/3}+(\sum\upsilon)_b^{1/3}\right]^2}\left[\frac{m^2}{s}\right] \qquad (39)$$

Where P is the Pressure in atm, T_f is the film temperature which can be set as the average between the temperature of the humid air and noodles' surface temperature, $(\sum\upsilon)_a$ and $(\sum\upsilon)_a$ are material parameters which are given for air and water as 20.1 and 12.7 respectively.

3. RESULTS

Flow field streamlines can be shown, as well as temperature and moisture distribution around, inside, at the surface of the noodles in Figure 6, 7, 8, 9, and 10.

Heat transfer by convection is highly effective with higher time constant than diffusion in humid air, which truly appears in the temperature contours around the noodles. The thermal diffusion inside the noodles is also much slower, that's already appeared from the thermal diffusivity of the noodles', which is lower than that of air by order of magnitude of ($\mathcal{O}\sim10^{-2}$).

Average Temperature rise of the noodles during the process can be shown in Figure 11.

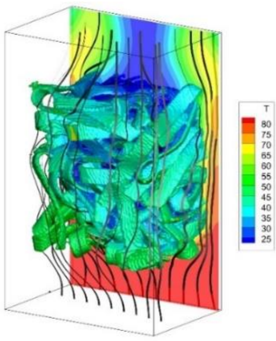

Figure 6: Flow streamlines with pasta's surface Temperature $[^oC]$

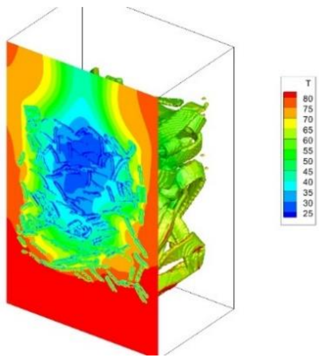

Figure 7: Temperature Distribution inside and around the pasta structure

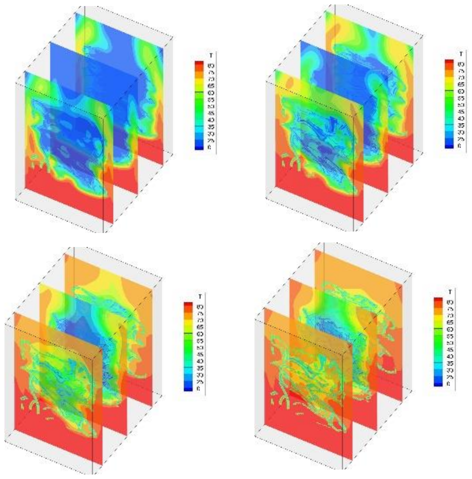

Figure 8: Sectional view for the Temperature Distribution with time inside and around the pasta structure

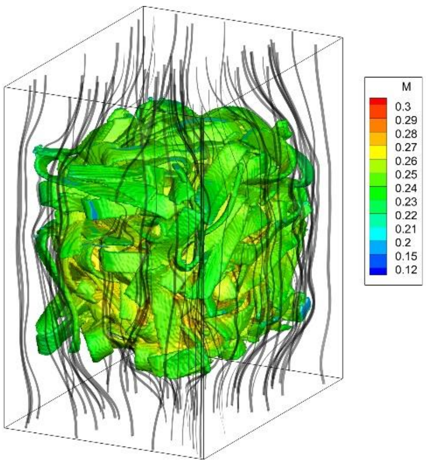

Figure 9: Flow streamlines with pasta's surface moisture concentration on dry basis

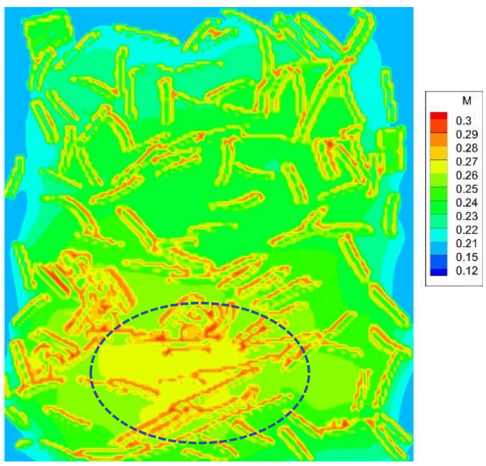

Figure 10: Sectional view for the Moisture Distribution inside and around the pasta structure

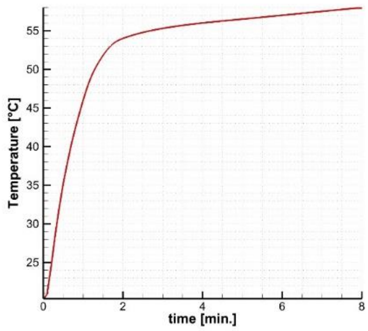

Figure 11: Average temperature of the Noodles with time

Temperature profile seems to be higher at the regions of high velocity profiles which is between the walls and noodles' assembly. Although velocity within noodles are much lower than the inlet, this's due to the noodles network which obstructs the flow field, delaying heat and mass transfer by convection, that explains why both the temperature and the moisture at the core of the noodles' network are lower and higher respectively.

Noodles surface temperature are always higher than its core, which is logical as the heat flux through the noodles surface are faster than the heat diffusion inside its structure (Figure 7 & 8), the inverse happens with the moisture, water evaporates from the surface, then diffuses inside the noodles from the core to the surface (Figure 10). Worth to mention, that the areas of higher noodle intensity reflect lower evaporation due to the limited air voids blocking the hot flux to propagate, thus inhibited drying region (see Figure 10 dotted region).

4. CONCLUSION AND FUTURE WORK

Drying process physics seems to be much complicated, also the estimation of the thermal and mass diffusive properties are not very straight forward. Though, the developed three distribution LBE appears to be a powerful way to analyse this complex phenomena. Results seems to be reasonable, flow field is dominating the transport phenomena of moisture and temperature. Although, further developments need to be done with the noodles' surface treatment, also a deeper insight is required for the parameters of the semi-empirical models used to exactly match the drying product.

ACKNOWLEDGMENTS

This work has been supported by the FEI (Forschungskreis der Ernährungsindustrie), AiF (Arbeitsgemeinschaft industrieller Forschungsvereinigungen), and Ministry of Economics and Technology. AIF project number: 19018 N.

It's notable to mention that the µCT scan wouldn't be done without the cooperation and help of the GeoZentrum Nordbayern, Faculty of Natural Sciences, Friedrich-Alexander University Erlangen-Nürnberg, we specially would like to thank Dipl.-Geol. Christian Schulbert for his valuable and professional support with the µCT imaging session. Special thanks to M. Sc. Julian

Thünnesen [(a)] for his valuable help with data collection and cooperation with the µCT scan.

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