CFD SIMULATION OF HEAT AND MASS TRANSFERS INSIDE AN INDIRECT SOLAR DRYER DESIGNED FOR MEDICINAL PLANTS (MINT LEAVES) DEHYDRATION

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Medicinal plants drying has a vital place in pharmaceutical production processes where the qualities and the quantities of extracted active components and other goodies are usually influenced by the drying phenomena. And consequently the optimization of drying procedure will prevent much loses and promote the productivity of the entire chain. In this work the mint leaves drying was simulated for an indirect solar dryer located at Constantine region in the north east of Algeria.

Drying analysis of mint leaves was done based on CFD simulation, where finite element is the used numerical method, and the mathematical assumptions of thin layer drying is employed to describe the air-product behaviors during dehydration, experimental data will serve in linking product to the air around, this data are sorption isotherms and drying kinetics and are picked up from the literature thus implemented in this work for giving a more realistic image of the transport phenomena.

The air circulation inside the unit operation was examined, and as a result the heat and mass profiles are obviously influenced by the fluid motion, the duration of drying was reported and its strongly influenced by the drying and the climatic conditions.

Keywords: Indirect Solar Dryer, Medicinal Plants, Drying, Mint Leaves, Finite Element Method, CFD, Thin layer.

1. Introduction

Drying is a key process in many industrial procedures where it has a significant contribution on final product qualities, and on its cost, this latter is highly influenced by the amount of used energy, so the assessment of the exact used energy for reaching all the qualities target will help in reducing its cost, and dipping the global warming effects of conventional energy thus promote the sustainability.

To preserve the quality and prevent it from degradation. Various materials with different chemical and physical composition are subjected to drying in order to get the longest possible shelf-life especially for food products.

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Many the industrial sectors use the drying in their production chains such as food industry, pharmaceutical and cosmetics plants, building materials and tissue manufacturing, paper production and many other fields, and as we know and reported in literature that the drying is an energy consumer process, hence it takes between 10-25% of national energy consumption [1][2]. R&D are always ongoing trying to encounter this problem, and aiming to reduce the energy loss within the dehydration processes.

The implementation of solar energy in drying processes help in reducing the carbon footprint and lead the ecological-friendly energy changeover, this traditional technique is the most used in past but still need an ongoing enhancement until achieve a high grades of performance as well as sustainability [3]. Different solar dryer configurations have been used for different product set, and are classified into direct or indirect, natural or forced etc.

The main objective of drying modelling is to predict and assess the evolution of water mass loss and water content distribution within the substrate during the dehydration [4] . Hence drying phenomena defined by [5] as, the process of coupled heat and mass transfer to generate the removal, through evaporation of part of the water contained in the product, and take place simultaneously with geometrical variation (shrinkage, dilatation, and deformation) and physical and micro-structural modifications (colour, flavour, appearance, nutrients, germination, depending on the product species).

Currently the thin layer approximation became a common practice [6], [7], [8], [9], [10], [11], due to its easiness and simplicity in modelling drying phenomena and for its accurate results, this approach assumes that the subjected sample to dehydration is formed as a monolayer [12], which permits to neglect the diffusion phenomena inside the sample because it is much faster and only adopts the cross boundary diffusion so it represents the lumped system analysis [13] .

Known that the medicinal plants are sensible to drying conditions, and any mistreatment of this latter can lead to signification lose in their active ingredients on high temperatures on the other hand, it could occur acceleration in the decomposition by promoting the enzymatic activity or microbial contamination if the temperature is lower [2].

Mint has a traditional history of use, with an important place in herbal and aromatic market with about 8000 $ by hectare in 1 year [14], the bioactive components contained in mints are usually used to treat health problems alike colds, flu, fever, jaundice, constipation and catarrh, motion sickness, food poisoning, rheumatism, flatulence and for throat and sinus ailments [15] [16], and due to big demand on mint derivatives, ensuring or amplifying the mass productivity with high product qualities it is an urge task, this challenge can be achievable based on proper dehydration process.

This work is envisioned having a clear sight on the comportment of the occurred phenomenon inside the unite operation, which lead to observe the inefficiencies spots thence adjust it, in order to obtain the proper drying conditions, which conduct to enhance the overall dehydration process.

2. Material and Methods

2D dryer geometry was devoted for modelling a coupled CFD, heat and mass transport phenomena, inside an indirect solar dryer. Configuration was chosen, where its dimensions are 0.8x0.4m for the drying chamber and 1x0.11m for solar collector.

A numerical modelling was done on CPU Intel Core i7-7500U Up to 3.5GHz, in an operating System 64 bits Windows 10, the calculus is based on finite element method, the Galerkin extension under the weighted residual methods is the chosen scheme, and basically it is integrated on the commercial package Comsol Multi-physics.

The experimental work was token from [18], and in their experience they used the classical standard gravimetric method, based on salty solution in humidity range of 10-90% for figuring out the sorption isotherms, the dry mass determined by putting the sample in an oven for 24 h at 105 C°, and they used a vertical shape dryer where the air flow was upward, the sample mass was weighted during the drying using semi analytical balance.

The physical properties are determined by [18] using the micro meter of 0.001 mm precision for determining the thickness, they use the pycnometer method for assigning the specific gravity, and weighting a given volume of packed particles for measuring the bulk density.

2.1 Experimental data

Multiple models are presented in the literature for characterizing the dewatering process of material in function of all drying conditions [12], these models are divided into three families which are theoretical, semi-theoretical, plus the empirical models [17].

2.1.1 Drying Kinetics

The drying kinetics are vital tools for studying the dehydration of any matter, while invoking thin layer approximation in the mathematical modelling, furthermore, it describes well the comportment of the substrate under specific drying conditions, and it's evaluated by weighting the moisture content of product through the time. Fig. 1.

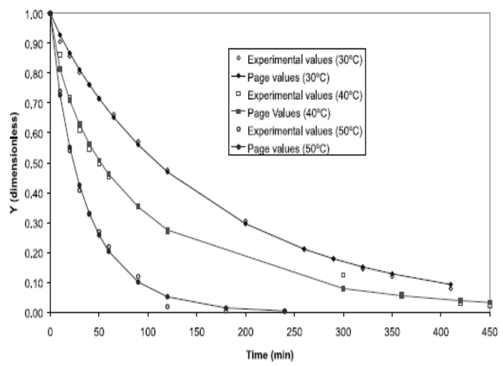

Fig. 1. Experimental values with Page model for 0.5 m/s

In this work the used drying kinetics and sorption isotherm are extracted from the paper of [18].

2.1.2 Sorption Isotherms

The sorption isotherms are essential tools for determining the adequate drying conditions and also helping in assigning the proper storage condition temperature, and humidity. Predict the water activity in function of water content which gives us bounding state of water inside the material [19].

This curve helps in predicting and preventing the degradation phenomena during the storage.

Generally, three methods are proposed and utilized in the experimental procedure, for determining the sorption isotherms and each of them has its specific reflections and limitations. These approaches are manometric, hygrometric and gravimetric. Fig. 2.

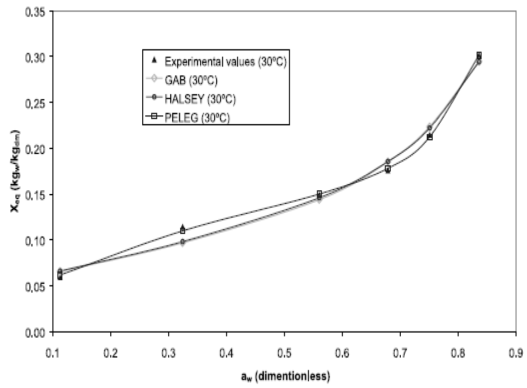

Fig. 2. Desorption isotherm for 30°C

Table 1: Mint leaves proprieties [18].

	Fresh Mint leaves	Dry Mint leaves
Thickness of leaves (m)	0.25e-3 ± 0.06e-3	
Specific Gravity (kg/m^3)	795.54 ±13.14	982.33 ± 96.72
Bulk Density (kg/m^3)	31.17 ±2.44	18.70 ± 1.34

3. Mathematical Modeling

Mathematical analysis became a common practice for investigating drying phenomena [20] and as a consequence the cost and time involved in experimental studies will be reduced [21], [22] but this analysis remains a key element for having a real phenomenon modelling.

Present model is based on trials and numerical approaches all at once

3.1 General Assumptions

a) The problem is treated as being two dimensional and unsteady.

b) The fluid considered as viscous.

c) The thermo-physical proprieties are pressure and temperature dependent.

d) The heat transfer influences the mass transport and not vice versa.

3.2 Governing equations:

Drying is a complex phenomenon where it needs to solve a conjugated problem, which is composed of three inter-connected physics: fluid motion, heat and mass transfer. The mathematical approximation of each physics is resumed in:

3.2.1 Fluid Flow (drying agent)

The fluid flow is treated as turbulent flow, so based on Computation Fluid Dynamics (CFD), there are five principal schemes which can lead to a solution of complex problems, these methods are the Direct numerical simulation (DNS), Large Eddy Simulation (LES), Detached Eddy Simulation (DES), Monotonically Integrated LES (MILES), and the Reynolds Average Navier-Stokes (RANS) approach, the latter is the least expensive and the most used in the industrial field. From the aforementioned methods, we have chosen RANS for modelling the fluid motion inside the solar dryer, which is valid only for incompressible and Newtonian fluid. From the RANS models the linear eddy viscosity K-ε variant was used, and is assisted with wall treatment technique; consequently, it gives us an accurate and stable solution that best describes the phenomenon, and it was chosen because it is the least expensive configuration, but it works only under the assumptions of:

The flow has a Reynolds number that is high enough.

Governing equations of the flow problem [23], are:

The general Navier-Stokes equation given by

$$\rho\frac{\partial u}{\partial t}+\rho(u\cdot\nabla)u=\nabla\cdot[-\rho I+K]+F \tag{1}$$

The conservation of mass equation is

$$\varphi\nabla\cdot(u)=0 \tag{2}$$

Turbulent kinetics energy as formulated below

$$K=(\mu+\mu_T)(\nabla u+(\nabla u)^T) \tag{3}$$

The transport equation for turbulent kinetic energy and the dissipation rate determined by

$$\rho\frac{\partial k}{\partial t}+\rho(u\cdot\nabla)k=\nabla\cdot\left[\left(\mu+\frac{\mu_T}{\sigma_k}\right)\nabla k\right]+P_k-\rho\epsilon \tag{4}$$

$$\rho\frac{\partial \epsilon}{\partial t}+\rho(u\cdot\nabla)\epsilon=\nabla\cdot\left[\left(\mu+\frac{\mu_T}{\sigma_\epsilon}\right)\nabla \epsilon\right]+C_{\epsilon1}\frac{\epsilon}{\mathrm{k}}P_k-C_{\epsilon2}\rho\frac{\epsilon^2}{\mathrm{k}} \tag{5}$$

$$\epsilon=ep \tag{6}$$

The turbulent eddy viscosity

$$\mu_T=\rho C_\mu\frac{k^2}{\epsilon} \tag{7}$$

Production term

$$P_k=\mu_T[\nabla u:(\nabla_u+(\nabla u)^T)] \tag{8}$$

Where the model constants are: $C\mu$, $C\varepsilon$ 1, $C\varepsilon$ 2, σk, σ, ϵ which their values are given respectively by 0.09, 1.44, 1.92, 1.3, 1.[24].

3.2.2 Heat Transfer

For evaluating the heat transfer in moist air during the drying process, a general heat equation was used, and it's written below [25]:

$$d_z\rho Cp\frac{\partial T}{\partial t}+d_z\rho C_p u\cdot\nabla T+\nabla\cdot q=d_zQ+q_0+d_zQ_p+d_zQ_{Vd} \tag{9}$$

Conduction heat flux.

$$q=-d_z\lambda\nabla T \tag{10}$$

We neglect the heat generated from the viscous dissipation and the work done by pressure change

3.2.3 Moisture Transport

In general, the equations which model the moisture transport in the air are derived from Second Fick's Law, and are set to be [25]:

$$d_z M_v \frac{\partial C_v}{\partial t} + d_z M_v u \cdot \nabla c_v + \nabla g = d_z G \quad (11)$$

Diffusive flux. $g = -d_z M_V D \nabla c_V$ (12)

Convective Flux. $d_z M_v u \cdot \nabla c_v$ (13)

Vapor Concentration. $c_V = \varphi c_{sat}$ (14)

3.3 Initial and Boundary Conditions

- For conditions used in this drying process, we can assume the air as an ideal gas. [19][26]
- The initial conditions are 0 m/s for the velocity and 0 Pa for pressure, a temperature of 20 °C and 50% of relative humidity.
- The Air enters the collector with velocity equal to 0.5 m/s and atmospheric pressure.
- Outlet air pressure equal to 10^5Pa
- Non-slip condition is applied at the other boundaries.
- Taking account the local climatic conditions, an average value of the heat flux of 700 W/m² is received by the upper boundary of solar collector.
- The drying chamber and the lower surface of the solar collector are well insulated using the polypropylene as an insulator.
- The surface of the product receives heat from the surrounding air, which equal to the needed evaporation heat of the wet surface.

$$-n \cdot q = d_z Q_b \quad (15)$$

Where Qb is the total latent heat on product surface.

In this study, we need to introduce experimental data; this information allows the adaptation of the transport phenomena occurring from each environment to the other, in order to create the best dryer design.

The entering air properties evaluated in the heat transfer is ambient pressure and temperature Tamb, Pamb, which are extracted from meteorological data which belongs to ASHREA and it is included in Comsol multiphysics.

Outflow

$$-n \cdot D\nabla(\varphi C_{sat}) = 0 \quad (16)$$

Where the Moisture flux on the boundary of product presented as

$$-n \cdot g = d_z g_0 \quad (17)$$

And

$$g_{evap} = -g_0 \quad (18)$$

Moisture flux is deduced from the drying kinetics curve and is estimated at the beginning to be equal to 2.5e-6 Kg/(m²*s) and this value will reduce as the product is getting dryer over time until reaching the equilibrium of moisture content and its expression will follow the drying kinetics phases.

For 0.5 m/s the drying kinetics of mint at a temperature of 40C° are used from the work of [18], these kinetics profile has a good agreement with page model and given by

$$X = \frac{X(t) - X_{eq}}{X_0 - X_{eq}} = e^{(-k_1 * t^c)} \quad (19)$$

So the moisture flux during the dehydration of mint set to be

$$g_0 = -2.5e\text{-}6 * e^{(-k_1 * t^c)} \ [\text{Kg/(m}^2\text{*s)}] \quad (20)$$

Where k_1=0.021, c=0.917

The boundary of products domains is saturated or partially saturated, and its statue depends on the drying stage, so with the evaporation of water from the surfaces it will become dry, and once the dehydration agent reaches the equilibrium with the wet product we can assume that the air in the vicinity of the product and the product itself have the same water content. The water activity of the product (a_w) is extracted from the water sorption isotherms, hence it designates the relationship between a material and the equilibrium relative humidity of the surrounding air [27].

3.4 Numerical Solution

Simulation work was carried out with Comsol multiphysics, intended to solve a system of highly nonlinear partial differential equations, based on finite element Analysis, through the weighted residual method, this procedure includes different schemes which are summarized in the Least Squares method, Galerkin approach and colocation plus subdomain pattern, so the used method in Comsol multiphysics is the Galerkin extension.

The problem was split into two study steps, the first step for calculating the coupling heat and fluid flow, because the applied heat flux is constant during the air flow motion inside the dryer, then invoke this results calculate the second study step where the heat and moisture transfer are intra-conjugated. Consequently, each study has its specifications, from mesh size to the required resources and solution time, therefore the mesh sizes are gradual, where inside the domain the employed mesh are fine and at the boundary the extra fine mesh as the Fig. 3 displayed , the total degree of freedom which were solved are 612384 in addition to 720463 internal degree of freedom and used 4.6GB virtual memory (storage memory) and 3.55GB physical memory (RAM) to calculate the first step over a computation time of 1 h 30 min 36 s, the second step took 2.1 GB virtual memory and 2.43 GB physical memory but computation time of 3h 18min 13s all these studies performed by CPU Intel Core i7-7500U Up to 3.5GHz, in an operating System 64 bits Windows 10, Knowing that COMSOL multiphysics time-dependent solver used the Backward Differential Formula (BDF) in addition to the direct solver (PARDISO).

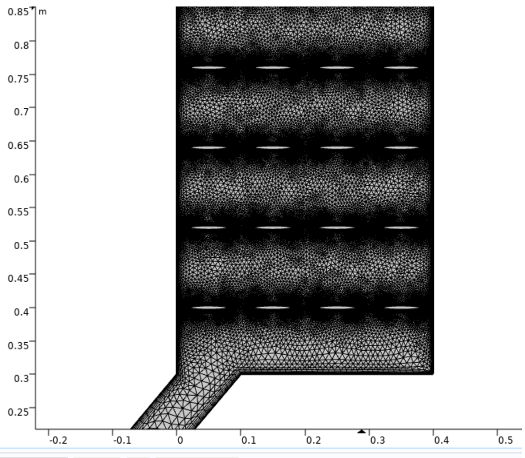

Fig. 3. Different mesh sizes inside an indirect dryer

4. Results Interpretation

The Figures 5, 6 display a non-uniform heat distribution inside the drying box, which follows the fluid motion presented in Figure 4 and as a result the product situated at the left upper part of the box will dehydrate first.

From the Figs. 7, 8, 9 show a decrease in the relative humidity over time, which follows the used drying kinetics stages.

After around 4 hours, the exiting air flow had approximately the same relative humidity as the entering air flow, which means that the equilibrium stage was reached, because the rate of exchange at this time is insignificant, and as result the product-air reaches the equilibrium.

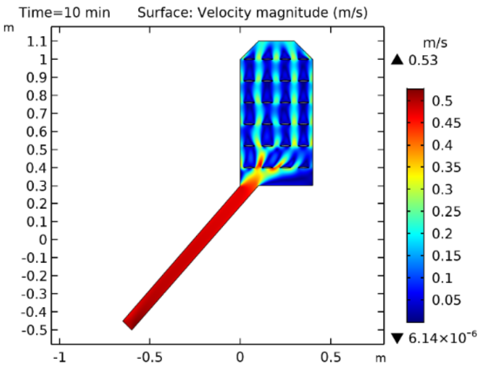

Fig. 4. Drying air velocity distribution after 10 min

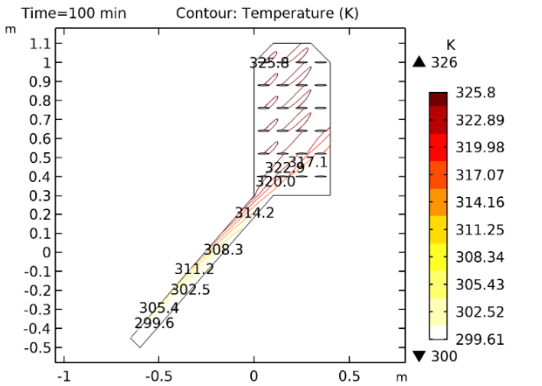

Fig. 5. Drying air temperature isocontours after 100 min

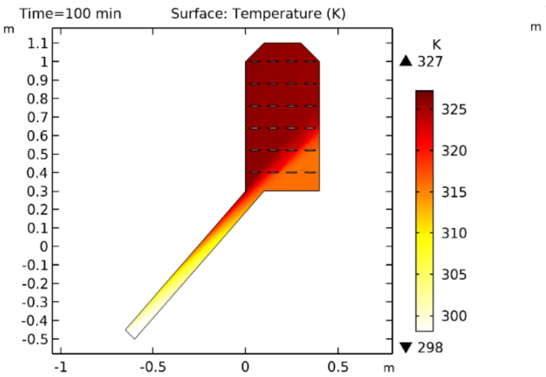

Fig. 6. Drying air temperature distribution after 100 min

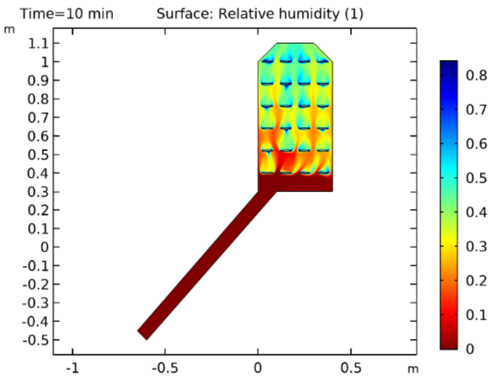

Fig. 7. Drying air relative humidity profile after 10 min

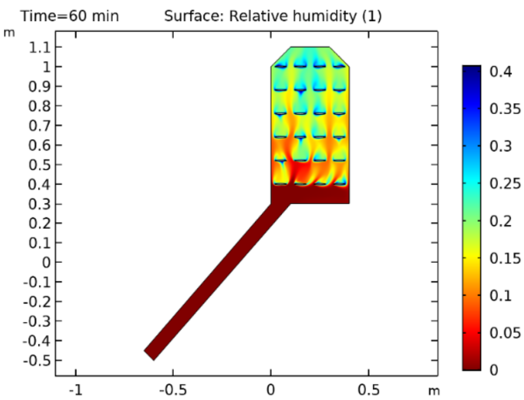

Fig. 8. Drying air relative humidity profile after 60 min.

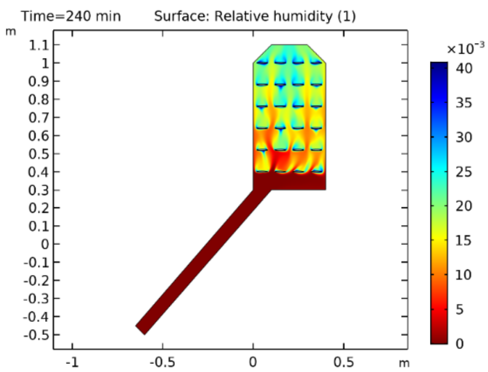

Fig. 9. Drying air relative humidity profile after 4 hours

5. Conclusions

The distribution of drying agent inside the unit operation has an extreme influence on the occurred phenomena hence a non-uniform air distribution inside the dryer may leads to a significant difference in final product quality which is undesirable, and as result an increasing on microbial contamination, therefore a CFD simulation can enhance the air circulation.

The drying front inside the drying chamber can be observed and describes the evolution of the hygro-thermal state of the product with time.

Using a multiphysics analysis to simulate the drying process inside the unit operation and by appealing to experimental work can lead to the assessment of the approximate needed time for dehydration, thus determine the required energy for a complete drying process.

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