NUMERICAL ANALYSIS ON AN INDIRECT SOLAR DRYER

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Abstract.
Food production and preservation is one of the main big scale World's issues due to the increasingly world population over the decades. Considering that approximately 25% of the food production is lost from its production/harvest to the consumer, the preservation is one of the most important factors to be optimized in order to guarantee an increase in the productivity and reduction of costs. Moreover, it is the only feasible way to reduce considerably food losses, and among the most widely used preservation processes, drying must be highlighted as one of the oldest and most effective ways to detain deterioration by reducing the moisture of the product. The most used process of drying is the direct natural solar drying, due to the simplicity and to the low costs involving the process. However, it presents several disadvantages, such as the difficulty to control the process and the contamination by dust and microbial organisms. Some alternatives for this method are the indirect solar drying and artificial drying, being the artificial process not feasible for low investment and small scale producers. The main purpose of the present work is the design of a low cost indirect solar dryer with no artificial energy source. In this system, the mass is restrained inside a closed chamber, avoiding ambient contaminations. A flat plate with high absorptivity is insulated and the high temperatures induces an air flow inwards the system due to the reduction of pressure and to the buoyancy forces. The drying process is based on the natural convection between the heated air and the product positioned inside the drying chamber. A numerical analysis of the dryer is carried using the finite volume method in order to analyse the behaviour of the air flow inside the drying chamber and the positions for optimal mass drying.

***Keywords**: solar energy, solar dryer, indirect solar drying, finite volumes, OpenFOAM®*

1. INTRODUCTION

The increasingly dependency of humankind on the usage and development of energy prospection is as unarguable as the environmental and even social damage caused by energy extraction without ecological and renewable constraints. One well discussed way of overcoming this issue is the constant search and development of energy sources which cause none or negligible environmental impact.

Moreover, it is well known that the energy provided by solar radiation is enough to fulfill all worlds' energetic demands and among the renewable energy sources is one of the least aggressive regarding environmental impacts. The main reason which prevents the mass usage of solar energy sources is the small efficiency on absorbing, storing and distributing the energy, aligned with the high machinery prices, direct result of the development stage of these technologies.

One of the main applications of solar energy is on the drying process of products, mainly regarding the agricultural industry. Despite being one of the oldest processes adopted by society, recent development incorporated to the equipments increased considerably the performance and quality of products, increasing the economic return of the drying process.

According to V. Shrivastava el at. (2014), one of the main problem regarding food production and distribution is related to product wastage. Among the main problems faced by commodity producers is the biological degradation caused by water concentration *in natura*, which contributes to the proliferation of plagues and diminish the conservation time. Another detachable problem is the direct exposition of the products to solar radiation, generating color, texture or flavor changes which decrease the final product quality, reducing its economical return.

The usage of an adequate and efficient drying process using solar energy may diminish or eliminate the problems mentioned below. Therefore, detailed studies must be carried in the spec of the product to be dried, regarding aspects such as the nutritional value, texture, flavor and conservation time. Another spec of studies must be carried in order to analyze the physical phenomena within the drying equipment, such as energy absorption, the adequate air flow rate, temperature and moisture control and the seasonality of the solar radiation.

According to Chauhan et al. (2015), one of the available and widely-applied tools which contribute for these studies is the computational simulation tools, which predict the behavior of the thermal system through the resolution of the transport and thermodynamic differential equations governing the problem by numerical approaches, such as the finite volumes. An efficient usage of these tools provides a reduction on the prototyping necessity, resulting in the reduction of time and financial costs of the project. Moreover, data processing and transient softwares allow a long-term and more accurate analysis of system's behavior.

The main objective of this study is to develop a numerical model to study the drying process regarding the air stream behavior and temperatures within the system in a proposed indirect passive solar dryer with fixed dimensions and fixed operational conditions. Simplification hypothesis will be considered on the boundary conditions and the analysis will be focused on develop an algorithm to select the best location for the product to be positioned in order to obtain a maximum heat rate in permanent regime. The results are intended to be used as inputs in an experimental setup and experimental results used to improve the numerical model in a cyclic procedure.

2. LITERATURE REVIEW

Several studies have been performed regarding the solar drying process. In Mustayen et al. (2014), studies were focused on reviewing and comparing different types of solar dryers, which are the direct, indirect and mixed mode dryers which have shown potential of application in tropical and subtropical countries. Moreover, a comparison is carried between active and passive mode solar dryers.

The direct solar drying is the most common method, which is based on the product exposure to solar radiation and an air stream covered by a transparent cover to reduce heat loss and avoid wind and rain contamination. In the indirect solar dryer, the radiation is absorbed by an auxiliary gadget positioned before the product drying region. The air stream is induced actively or passively through the heated surface and posteriorly the drying process occurs through convection between the air stream and the product to be dried. The mixed mode dryers are based both on radiation and convection heat transfer modes.

Regarding the active and passive modes of operation, the last is based on the natural convection, in which the air stream is induced by the heat surface inwards the system. The dryer is basically composed by three components, which are the absorber surface, the transparent cover and the drying chamber, connected in series. This system can achieve reasonable drying rates and low costs for manufacturing and temperature control. Besides, no external energy source is necessary to induce the air stream. The active drying operation is based on a similar structure, but the air stream is induced by an external source of energy, such as a fan. Although, this system has the additional maintenance and costs related to the external energy source, it is more suitable for higher drying rates and high humidity.

Regarding specifically the indirect solar drying system, Shrivastava et al. (2014) studies covered the developments regarding the system during the last three decades in various parts of the world. Effort have been carried in order to increase the system efficiency and reduce the drying time. In order to fulfill these goals, dryers were equipped with external fans, more efficient collectors, different energy storage materials and solar tracking systems. Passive dryers are usually applied for low humidity products and active dryers for high humidity ones.

Regarding the operation of the indirect solar dryers, Khawale and Thakare (2015) proposed a model to analyze the thermophysical process within the system for agricultural product drying. The main parameters analyzed were the stream velocity and the dimensions of the absorber surface and drying chamber. A high flow velocity results in smaller drying time, but the performance is reduced due to instauration of the mist air. Another relevant factors are the drying chamber length, collector area, but the mass flow rate is the most relevant factor and whose control can be performed by fan.

Phadke et al. (2015) performed a comparison between the mixed mode dryers and the indirect passive dryers. Although the mixed system has a bigger efficiency, it exposes the product to solar radiation. The natural convection based dryers are easy to build and have small manufacturing costs. Moreover, they are auto-sufficient regarding energy, once no external energy source is needed to induce the air flow. However, the control of drying rate in this system is more complex.

Regarding the numerical ambit, Tashtosh et al. (2012) proposed a mathematical model to study the indirect drying of a dairy industry product. The model was simulated through the software Engineering Equation Solver (EES) for a simple solar dryer. The permanent regime drying process is strongly dependent on the humidity layer above product`s surface, so the drying time can be estimated based on the initial and final humidity and on the initial product mass.

Drying systems can be optimized based on the dimensions of the collectors which influence on the temperature and air stream within the system. Both factors are increased for a longer absorber surface. Moreover, the collector width is inversely proportional to the outlet temperature e directly proportional to the air flow rate.

Another prototype model was proposed by Maia et al. (2012), in which a hybrid solar dryer was manufactured and tested in the city of Belo Horizonte, Brazil. A parallel numerical model was generated and experimental data regarding temperature and mass flow rates were used as inputs to validate the numerical model. The finite volumes method was applied to solve numerically the Reynolds Averaged Navier-Stokes (RANS) through the software ANSYS-CFX 11.

Another numerical analysis was carried by Vintilã et al. (2014), in which a 2D analysis was conducted in order to neglect the wall effects on the air flow. The finite volumes method was applied for the velocity and temperature fields of various situations. The study highlighted the development of experimental studies carried simultaneously to the numerical ones to validate the models, especially when simplifying hypothesis are incorporated in the numerical model. The increase in computational capabilities is essential on allowing complex CFD analysis which optimizes the equipment performance and reduce project costs.

3. METHODOLOGY

In the present work, a computational model is proposed based on selecting the best position for the product within an indirect passive solar dryer based on achieving the highest heat rate as possible, diminishing the drying time. The algorithm is based on the coupling of three softwares, which are the MATLAB®, for data analysis and sample generation, GMSH® for the mesh generation and OpenFOAM® to solve the transport and energy equations governing the problem. Initially, a computational model was created based on a conventional solar dryer with realistic arbitrary dimensions. The dryer can be divided in three distinct regions: The heating chamber, the drying chamber and the chimney. In this analysis, the dimensions of the dryer are fixed, but the focus of the algorithm is allowing the interchange of different collector geometries, tray dimensions and heat conditions. The regions of the collector and the dimensions of the system are highlighted in fig. (1) and fig. (2), respectively. The tray, in which the product is positioned, has dimensions of 100mm length and 10mm height.

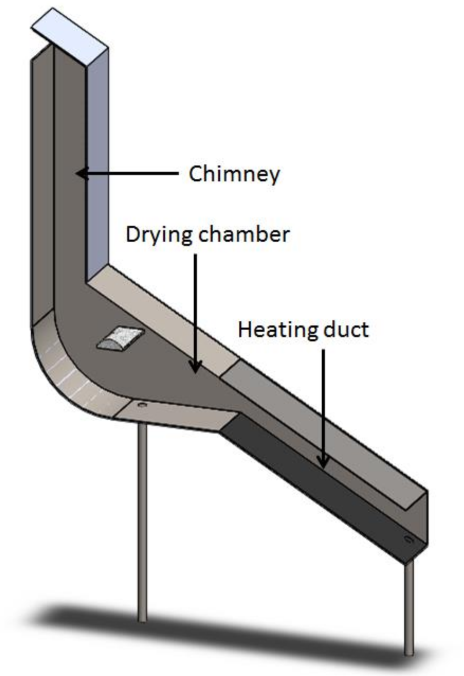

Figure 1: Regions of the dryer

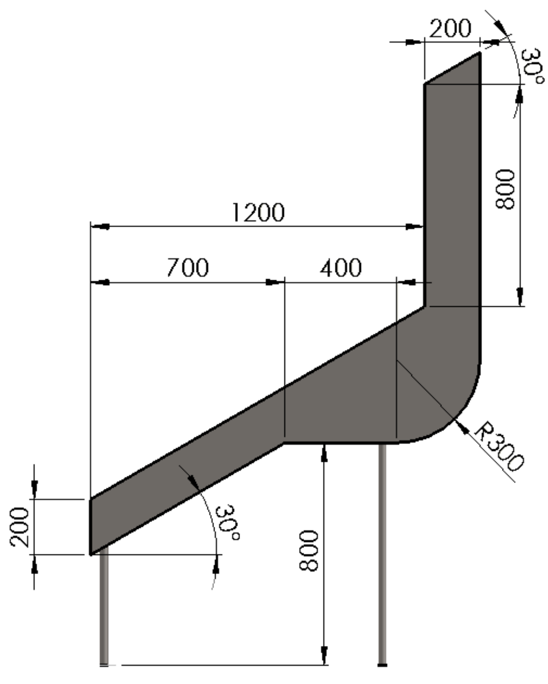

Figure 2: Dimensions of the dryer

3.1 Mathematical and numerical modeling

The analysis of the dryer is based on obtaining the velocity, pressure and temperature distribution in permanent regime based on initial and boundary conditions such as the heat input from solar radiation, the inclination angle of the absorber plate, the chimney height and the material properties of the dryer. This analysis allows determining the most suitable positions within the drying chamber for the products to be positioned.

In order to solve the thermophysical problem regarding the system, the equations of continuity, the momentum conservation based on the Reynolds Averaged Navier-Stokes (RANS) equations due to the turbulence and energy balance equation must be solved simultaneously. Due to the geometric complexity of the system, some simplifications can be attributed based on the accuracy tolerance of the problem and which are fundamental due to the considerable reduction in computational time propitiated. Once the expected variation of temperature within the system is relatively slight (≈20°C), properties such as the specific heat, cinematic viscosity and Prandtl number can be assumed as constant evaluated at the average temperature of the system in permanent regime. Due to the simplifications considered for the system, the equations of continuity (1), momentum for a specific Cartesian direction (2) and energy for a (3) can be represented as follows:

$$\frac{\partial \bar{v}_x}{\partial x}+\frac{\partial \bar{v}_y}{\partial y}+\frac{\partial \bar{v}_z}{\partial z}=0 \tag{1}$$

$$\bar{v}_x\frac{\partial \bar{v}_x}{\partial x}+\bar{v}_y\frac{\partial \bar{v}_x}{\partial y}+=g_x-\frac{\partial \bar{p}_\infty}{\partial x}+\frac{1}{\rho}\frac{\partial}{\partial y}\left(\mu\frac{\partial \bar{u}}{\partial y}-\rho\overline{u'v'}\right) \tag{2}$$

$$\bar{u}\frac{\partial \bar{T}}{\partial x}+\bar{v}\frac{\partial T}{\partial y}=\frac{1}{\rho C_p}\frac{\partial}{\partial y}\left(K\frac{\partial^2 \bar{T}}{\partial y^2}-\rho C_p\overline{v'T'}\right) \tag{3}$$

In which $\bar{p}_\infty$ stands for the mean pressure, $\bar{T}$ is the mean temperature, $\bar{v}$ is the velocity, g is the gravity, ρ is the fluid density, μ is the fluid dynamic viscosity, C_p is the specific heat and k is the thermal conductivity. The viscous dissipation parcels were neglected due to the low velocity magnitudes expected in the system. The average terms are used in this approach due to the turbulent fluctuations in the momentum and energy equations. The second terms in equations (2) and (3) between brackets account for Reynolds Stress and the heat flux due to turbulent fluctuations, respectively. These terms are accounted by the usage of turbulence modeling. In this particular approach, the K-ε turbulence model was adopted. Turbulent variables were calculated based on the turbulence length scale of a fully developed pipe flow and the hydraulic diameter. Moreover, due to the impossibility of calculating a free stream velocity at the heating duct due to the lack of experimental setup and considering the low magnitude of velocities and turbulence, the stream velocity for turbulence variables calculation was based on a Reynolds number of 10000. Although the incompressibility of the fluid is an acceptable approximation due to velocity magnitudes of the air stream, there is necessity to account for the buoyancy forces generated by the heat transfer from the hot plate to the fluid. In order to do so, the variation of density is calculated from the boussinesq approximation, highlighted in equation (4),

$$(\rho_\infty-\rho)\approx\rho\beta(T-T_\infty) \tag{4}$$

in which β stands for the thermal volumetric expansion coefficient of the fluid, T_∞ is the ambient temperature and ρ_∞ is the fluid constant density. This simplification implies a much smaller computational time which is fundamental for complex domains. In order to improve the precision obtained with the boussinesq approximation, the fluid properties were evaluated at an estimated mean temperature for the system.

Due to the impossibility to solve the equations analytically, the computational numerical method of the finite volumes is applied, in which the differential equations are approximated to algebraic equations once the geometry is discretized in small elements in a meshing process.

The software choice for applying the finite volume methods was OpenFOAM®, which contains a vast spec of solvers for different thermal fluid dynamics problems. The chosen solver was buoyantBoussinesqSimpleFoam, which was found suitable due to the approximations made regarding fluid properties as being constant and buoyancy forces accounted based on the boussinesq approximation. Moreover, the solver applies the SIMPLE algorithm, which neglects the transient term in the transport equations, which in this case is irrelevant once the analysis is focused on the permanent regime. Moreover, once the width of the dryer is assumed as constant in the three sections of the dryer and that lateral viscous dissipation on the walls are small, especially due to the adiabatic condition assumed and to the small velocity magnitudes, the computational domain was reduced to a 2D model.

3.2 Mesh generation

The first step regarding the numerical model is the setup of an appropriate mesh, which allies simultaneously accurate results and a reasonable computational time. Moreover, specifically for the present model there is interest on obtaining an easily parameterizable mesh generation in order to allow batch mode operation for the coupling algorithm. Taking into account all this factors, the mesh generator software chosen was GMSH®, which allows the generation of prismatic tetrahedral elements. Moreover, another advantage of the chosen software is the localized refinement of the mesh based on the element size on a specific surface, which improves accuracy of results next to the boundary layer without compromising significantly the number of elements and consequently the computational time of the simulation.

Although structured hexahedral mesh is more suitable for applications involving heat transfer through convection due to the influence of the boundary layer, the accuracy of the results is not deeply compromised due to the small velocity magnitudes of the air stream (≈0.5m/s), which implies in small pressure and velocity gradients within the boundary layers.

The product positioned inside the drying chamber is represented as a baffle within the mesh, in which no-slip wall boundary conditions are applied in each surface. As mentioned above, there is no necessity of a 3D meshing due to the small influence of the lateral walls of the dryer. A mesh example with coarse refinement is shown in fig. (3) to ease the visualization.

3.3 Boundary conditions

One of the main concerns regarding numerical simulations is related to adopting boundary conditions which fit the real operational conditions of the system analyzed. However, the tradeoff between results accuracy and computational time should also be considered.

In the system, no-slip condition was applied on all internal walls of the dryer. Once the air stream is based on passive principia, the velocity magnitudes at the inlet and outlet of the dryer were obtained based on the gradients of pressure created by the thermosiphon effect. Moreover, static pressure fixed values were applied both on the inlet and outlet of the system due to the open atmospheric condition.

Regarding the thermal boundary conditions, adiabatic conditions are applied in all internal walls of the dryer including the glass cover. In the absorber surface the heat provided by solar radiation was approximated by a constant heat flux of 800W/m², optimistic but suitable approach based on a peak radiation period in tropical regions and essential for the achievement of a permanent regime within the system. In order to analyze the heat flux transferred by convection from the air stream to the tray containing the product, the product was approached within the system as a baffle and a fixed temperature of 300K condition was applied to its surface. The inlet temperature condition was set to 300k and the outlet condition was set to zero gradient. An overview of the thermal boundary conditions of the system can be analyzed in fig. (4).

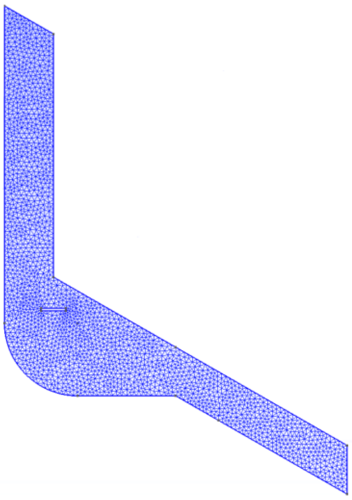

Figure 3: Tetrahedral unstructured mesh

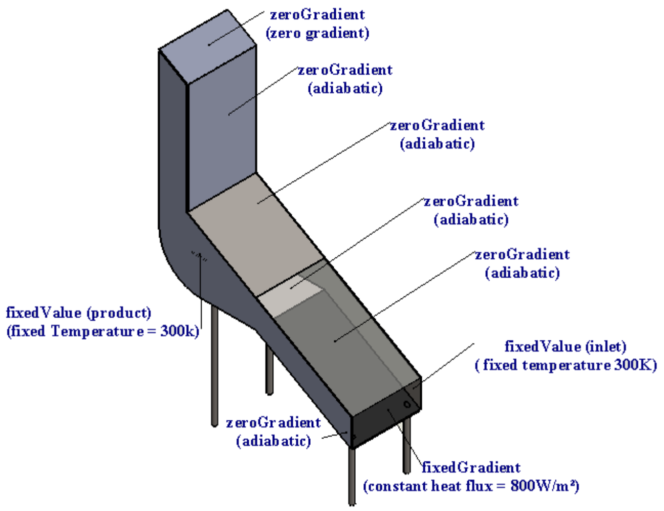

Figure 4: Temperature boundary conditions

3.3 Optimization algorithm

Once the constraints regarding the mesh generation and the physical setup of the system are fulfilled, the analysis of the best product position is based on generating a sample of possible positions and simulating each configuration individually. Moreover, post-processing is necessary once the analysis of the best position is based on the maximum heat rate within the baffle representing the product. In order to automatize the process, a MATLAB® routine was created which automatically generates a sample for tray positions, simulates each position individually and post-process the obtained data, allowing the analysis of the optimal regions for product positioning. The sampling method was the Latin hypercube, which guarantees better coverage of the domain. The sample set was defined as containing 30 samples within the drying chamber, defined by the center of the baffle. Afterwards, each individual mesh is adapted depending on the position and simulated until permanent regime is achieved. The heat rate of each possible position is obtained automatically from the wallHeatFlux function of openFOAM®.

Posteriorly, the individual results of heat rate are compared quantitatively and the best individuals chosen as optimal positions. In order to increase the resolution of the graphic results obtained by the algorithm, the half least efficient population was neglected in the performance analysis.

4. RESULTS

Despite the influence of the tray position in the behavior of the flow for the different configurations, results obtained numerically have shown reasonable agreement with the assumptions adopted for the boussinesq approximation, both regarding the mean temperature of the system and the free stream velocity at turbulent regions.

4.1 Thermophysical behavior

The post-processing allows the description of the flow within the system. The fluid closer to the absorber plate presented higher velocity magnitude, as a result of the buoyancy forces generated by the density gradients. Moreover, a negative velocity gradient occurred from the flat plate to the upper surface of the duct. In a more realistic approach, gradients would be reasonably higher due to the heat transfer through the transparent cover, which might lead to a recirculation zone. The mean velocity at the entrance of the system was 0.26m/s, leading to a mean mass flow within the system of 94 kg/h. The maximum value found for the velocity was 0.72m/s at the chimney entrance for this particular case, while the estimated value for the turbulence variables based on the fully developed turbulence for Reynolds equal to 10000 was 0.70m/s. regarding the temperature field, the overall increase in air flow temperature was dependent on the efficiency of the heat absorption by the product, but the mean outlet value varied between 330K and 340K. The overall behavior of the velocity and temperature fields for one of the simulations performed can be analyzed in fig. (5) and fig. (6). The temperature adopted to account for the fluid properties was 320K, which is in agreement with the results obtained numerically, once the overall temperature within the drying chamber varies from 310K to 335K.

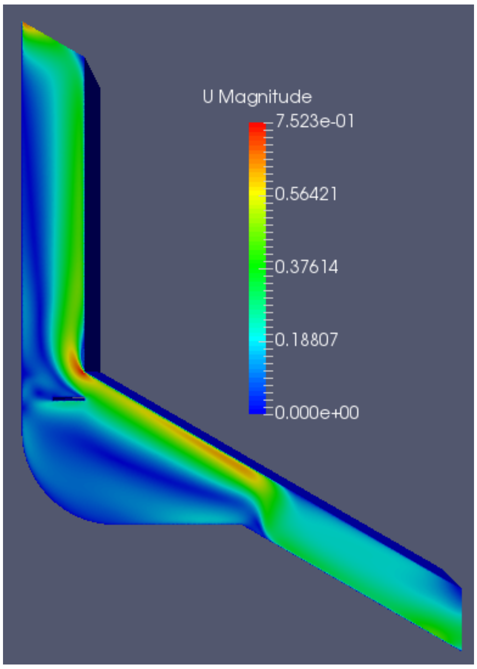

Figure 5: Velocity profile in permanent regime

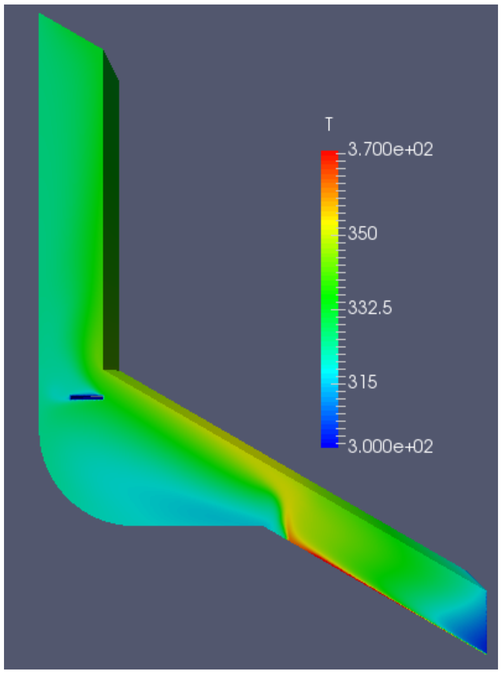

Figure 6: Temperature profile in permanent regime

The air stream can be split in two main flows based on their overall behavior: The primary stream zone and the secondary stream zone, whose contour lines are highlighted respectively in fig. (7) and fig. (8). The primary stream zone is characterized by a buoyancy-driven flow due to the thermosiphon effect generated by the gradients of temperature. Moreover, a necking effect can be observed at the entrance of the drying chamber. The constriction occurs due to the mixing of the fluid from the entrance duct and due to the interface effect between the primary and secondary stream zones. The secondary zone is mainly a recirculation zone which occupies approximately 80% of the drying chamber. The recirculation occurs due to interface between the stream zones, in which part of the cold fluid is transferred to the primary stream zone and part of the hot fluid form the primary zone is transferred to the secondary zone. This recirculation guarantees constant renewal of the air mass within the drying chamber. The circulation zone is also propitiated by the round edge at the corner of the dryer. A sharp edge would lead to a stagnation zone, decreasing significantly the performance of the dryer.

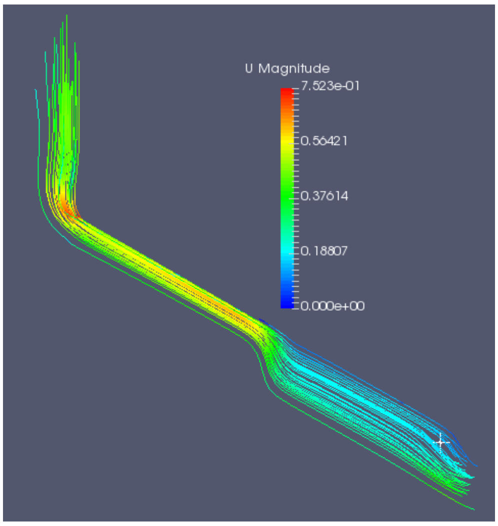

Figure 7: Primary stream zone

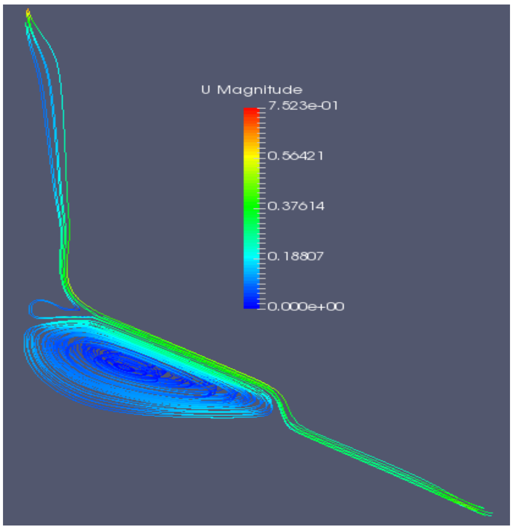

Figure 8: Secondary stream zone

4.2 Drying Performance

In order to analyze the drying performance of the system, the criteria adopted is that the performance is defined as a ration between the heat rate of the baffle in permanent regime and the total heat rate provided by the absorber plate. Results have shown that the performance of the system depends deeply on the position of the product. Results are shown in fig. (9). The maximum heat rate obtained was 54.4W, equivalent to a performance of 23.1%. The minimum heat rate obtained between the 15 best positions was 17.2W, equivalent to a performance of 7.4%. Results obtained show that the performance of the drying process is higher the closer the product is to the primary stream zone. Moreover, the heat rate was higher close to the chimney entrance, as a consequence of air acceleration due to the primary stream zone constriction. This relation can be clearly analyzed in the contour lines highlighted in fig. (10).

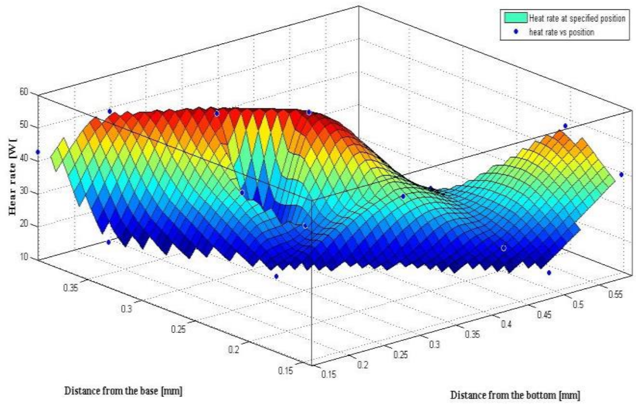

Figure 9: Heat rate absorbed by the product as a function on the position.

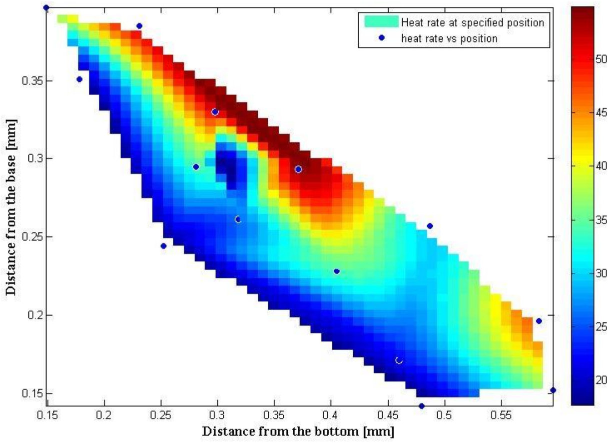

Figure 10: Contour lines of the absorbed heat rate by the product.

Results obtained also detach that secondary stream zones should be avoided in order to obtain higher efficiencies. Which means geometrically that a thinner and longer drying chamber may result in higher performance for the drying product. However, the recirculation zone is preferred rather than a stagnated zone at the bottom of the drying chamber.

5. CONCLUSION

The studies developed in this paper focused on developing a method to analyze the performance of a passive indirect solar dryer based on automatically obtaining the best position for the product. A model of indirect solar dryer was proposed in which simplified boundary conditions were applied. The overall stream behavior of the system was analyzed both quantitatively and qualitatively to obtain the performance of the drying process based on the ratio of heat rates between the absorber plate and the product.

The developed system is suitable for initial approaches regarding the project of an indirect solar dryer. However, the simplification of boundary conditions, such as the isolated walls and the constant heat rate, compromise the accuracy of the results. In order to obtain a valid computational model which represents precisely the behavior of the system, a feeding forward procedure is necessary, in which experimental results are used as inputs for the system and a cyclic process leads to a more accurate model.

Results obtained regarding the performance of the collector allow a qualitative analysis of the system and the stream behavior, especially the primary and secondary stream zones within the drying chamber. Post-processing analysis have shown that the performance of the system was higher for samples closer to the primary stream zone due to the higher temperatures and velocity of this region. Moreover, the constriction of the primary stream zone propitiated an increase in the air velocity, leading to higher convective coefficients and consequently higher heat rates. The performance obtained with the algorithm was reasonable high, once in the best position the total heat rate was 54.4W, representing an efficiency of 23.1%.

Further research will be focused on manufacturing an initial prototype of the collector and compare the results obtained numerically. Results obtained numerically and experimentally would be compared focused on the applying the feeding forward process to improve the computational model.

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