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Cfd Applied in the Optimization of A Dryer For Parchment Coffee Drying (Coffeaarabica L.)By Forced Ventilation

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ABSTRACT: *The present study analyzes the efficiency of parchment coffee drying process in a forced greenhouse type solar dryer. The environmental conditions in the solar dryer were measured during a day of operation, in which the air is introduced to the dryer by means of two driving fans and leaves the other side, with two extractor fans. A numerical model was established that allowed to replicate the internal environmental conditions of the dryer through software Fluent® de ANSYS Workbench. The air flow inside the dryer presents a laminar behavior, being little beneficial for coffee drying. It was proposed to introduce diffusers inside the dryer, which, through the simulation, proved to be effective in generating a more turbulent flow, which increases the effectiveness in the process of removing moisture from the coffee in the dryer.*

Keywords : *, Drying process, CFD.*

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I. INTRODUCTION

In Costa Rica, coffee production leads the greatest agricultural activity in the Canton of Mora, Acosta, Puriscal, Aserrí, Turrubares, Los Santos region; among others [1]. Among the varieties of coffee cultivated worldwide, the Arabica coffee of the species stands out *Coffeaarábica L*; which covers 70% of the international market [2]. Their demand is based on good agricultural practices of pre and post-harvest management added to the geographical area, climatic conditions, moisture content and type of soil; among other.Currently, Costa Rican coffee is sold as a gourmet type, which is a distinction given to the product due to its quality, aroma and flavor. The coffee produced in the area of Los Santos meets all these requirements, making it one of the highest quality coffees recognized worldwide [3]. Cooperativa de Caficultores de Dota R.L. (CoopeDota) is a small cooperative of coffee farmers established in 1960. It´s located in Santa María de Dota, district of the city of Dota, in the province of San José in Costa Rica [3]. Coffee production is divided in general into three phases, the agricultural, the beneficiary and roasted. The coffee production consists in the extraction of the pulp, washing and drying of the coffee fruit grain, obtaining the coffee parchment [3]. The objective of the drying process is to reduce the moisture content of coffee grains, so that it retains its organoleptic properties intact and reduce the risk of coffee contamination with mycotoxins or be affected by a fungus, implying that the grain loses quality and is rejected by the customers. It´s recommended that for the commercialization of the coffee this contains a humidity between 10% w.b and 12% w.b, never superior to 12% w.b [4]. In the installations of CoopeDota they dry the coffee in the sun and mechanically. There are drying yards and two greenhouse dryers to dry the coffee. The dryer in the studio has two air inlets by means of fans and two outlets with two other fans. This dryer currently has deficiencies in the coffee drying process, due to the low interaction between the air admitted and the coffee beans to dry, increasing the drying times and thus increasing production costs.

For this reason, the implementation of CFD models as a tool which allows to know the internal behavior of the dryer, and the implementation of solutions based on the results obtained according to the established numerical model.CFD have the potential to quantify efficiently and accurately the internal climate of a greenhouse under forced convection. Various design conditions can be evaluated within a virtual environment, reducing the number of experimental tsts, allowing to evaluate spatially and temporally parameters such as pressure, temperature and air velocity.The present study seeks to analyze the fluid-dynamic behavior in the interior of the dryer, in order to generate recommendations that increase the efficiency of the drying process, involving the reduction of drying times and therefore the economic and labor savings.

II. MATERIALS AND METHODS

The dryer in study is located in Santa María de Dota, at CoopeDota R.L. at 1535 m.a.s.l.. The dryer measures 40.00 m long by 17.50 m wide and 4.20 m high. Figure 1 shows an exterior view of the dryer.The floor of the dryer is totally make of concrete and the structure is made of metal tubes. All this can be seen in Figure 2. The plastic of the dryer is DURTAPLAST UV 8 MTx100MTx7 D-24 T/A with an approximate transmittance of 85%. The four fans that the dryer has come from the Monters brand, model EM50n of 0.75 hp.The trays with the coffee are located in two rows. These trays are made of a metal grid and have a dimension of 2.33 m long, 1.13 m wide and 0.05 m high. These trays are mounted on a metal tube structure and each row has 3 levels with 3 trays across and 16 along, their distribution is shown in figure 2.

Fig1. Exterior view of the greenhouse type solar dryer.

Fig 2. Distribution of trays for drying coffee inside the solar dryer

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a. Experimental measurements

The dimensions of the solar dryer and the location of the dataloggers were determined. In each row, ten dataloggers were placed, five of them in the upper trays and five in the lower trays, all located in the central tray of each level. Finally, two dataloggers were located in the center of the dryer. The exact location of them and their distribution is observed in figure 3. In addition, velocity measurements were made at different points of the dryer, as well as incident radiation.

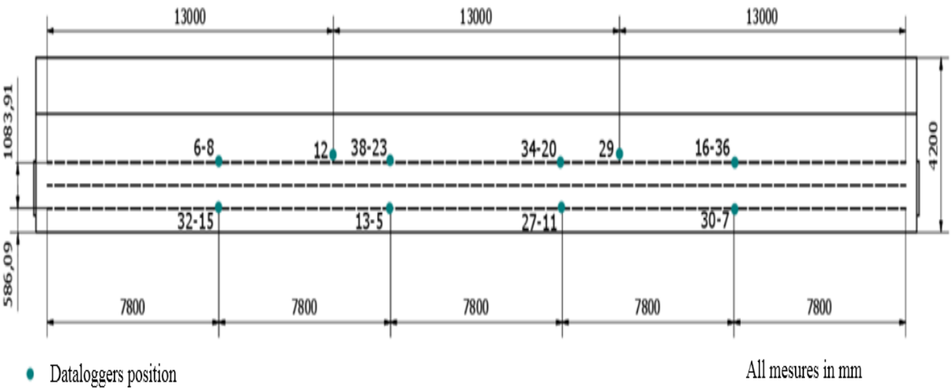

Fig2. Distribution of the dataloggers along the solar dryer.

2.2. Numerical model

2.2.1. Continuity equations

Every theoretical-numerical model and computational fluid dynamics is governed by laws of continuity of mass, momentum and energy. The conservation equation for a constant flow is [5]:

$$\frac{\partial(u^*\phi)}{\partial x}+\frac{\partial(v^*\phi)}{\partial y}+\frac{\partial(w^*\phi)}{\partial z}=\Gamma\cdot\nabla^2\phi+S_\phi \quad (1)$$

Where ϕ represents the concentration of the material transported in a dimensional form, that is, the 3-dimensional moment derived from the Navier-Stokes equations and the mass and energy conservation equations; u*, v* and w* are the reduced forms of the speed components; x, y, z they are spatial cartesian coordinates; Γ is the diffusion coefficient; S_ϕ is the term source and ∇ is the Laplace operator.

2.2.2. Turbulence model

Flows in ventilation systems are usually associated with turbulent movements, mainly due to the high flow rates and the heat transfer interactions involved in the flow field.The turbulence model κ-ε realizable is based on the transport model of turbulent kinetic energy (κ) and its dissipation speed (ε). The equations of κ and ε in the model κ-ε realizable can follows as [5]:

$$\frac{\partial}{\partial t}(\rho\kappa)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\partial\kappa}{x_j}\right)\frac{\partial\kappa}{\partial x_j}\right]+G_\kappa+G_b-\rho\varepsilon-Y_M \quad (2)$$

$$\frac{\partial}{\partial t}(\rho\varepsilon)=\frac{\partial}{\partial x_i}\left[\left(\mu+\frac{\mu_t}{\sigma}\right)\frac{\partial\varepsilon}{\partial x_i}\right]+\rho C_1 S_\varepsilon-\rho C_2\frac{\varepsilon^2}{\kappa+\sqrt{v\varepsilon}}+C_{1\varepsilon}\frac{\varepsilon}{\kappa}C_{3\varepsilon}G_b\kappa \quad (3)$$

Where $C_1 = Max\left[0.43, {}^{\eta}/_{(\eta+5)}\right]$, $\eta = S({}^{\kappa}/_{\epsilon})$, $S=\sqrt{2S_{ij}S_{ij}}$, C_2 is a constant, μ it´s the viscosity, μ_t (turbulent viscosity) $=\rho C_\mu(\frac{\kappa^2}{\varepsilon})$, σ_κ y σ_ε are the numbers of Prandtl in turbulent regime for κ and ε, G_κ it´s turbulent energy generation due to buoyancy, Y_M is the contribution of fluctuating dilation in compressible turbulence to the rate of global dissipation and v is the coefficient of kinematic viscosity. The constants of the model $C_{1\varepsilon}$, $C_{2\varepsilon}$, C_μ, σ_κ and σ_ε present the following values: $C_{1\varepsilon}=1.44$, $C_{2\varepsilon}=1.92$, $C_\mu=0.09$, $\sigma_\kappa=1.0$ and $\sigma_\varepsilon=1.3$. The turbulence model κ-ε realizable provides better predictions in the distribution of speed, this is the turbulence model most used and validated for CFD research in greenhouses [6, 7, 8, 9].

2.2.3. Buoyancy model

For many flows in forced convection, a faster convergence with the Boussinesq model occurs than establishing a model in which the density of a fluid varies as a function of temperature. The Boussinesq model treats density as a constant value in all the equations to be solved. This model has been used successfully in multiple numerical modeling of greenhouses [5].

$$\rho = \rho_{ref}\left[1 - \beta\left(T - T_{ref}\right)\right] \quad (4)$$

Where ρ is the density (kg m^{-3}); β is the coefficient of thermal expansion (K^{-1}); and T is the temperature (K).

2.2.4. Radiation model

The radiation model of discrete ordinates (DO) solves the radioactive transfer equation for a finite number of discrete angles, each associated with a vector with a fixed address in a global cartesian system.This model covers the entire range of optical thicknesses, and allows solving problems ranging from surface radiation to the participation of radiation in combustion problems, while also resolving radiation conditions in semi-transparent walls.The OD model describes the radioactive transfer equation (RTE) in the direction $\vec{s}$ with a field equation. The RTE for the intensity spectrum $I_\lambda(\vec{r},\vec{s})$ as a field equation is [5]:

$$\nabla \cdot (I_\lambda(\vec{r},\vec{s})\vec{s}) + (a_\lambda + \sigma_s) I_\lambda(\vec{r},\vec{s}) = a_\lambda n^2 I_{b\lambda} + \frac{\sigma_s}{4\pi}\int_0^{4\pi} I_\lambda(\vec{r},\vec{s})\Phi(\vec{s}\cdot\vec{s}^{\,\prime})d\Omega^{\prime} \quad (5)$$

Where $\vec{r}$ is the position vector, $\vec{s}$ is the direction vector, $\vec{s}^{\,\prime}$ is the dispersion direction vector, σ is the constant Stefan-Boltzmann, I_λ is the radiation intensity of the wavelength, a_λ is the spectral absorption coefficient, $I_{b\lambda}$ is the intensity of the black body given by the function of Planck, σ_s is the dispersion coefficient, n is the refractive index, Φ is the phase function and $\Omega^{\prime}$ is the angle of the solid (radians).

2.3. Environmentmodeling

The geometric model was designed using the software Inventor® and imported to ANSYS Workbench 18.0, the mesh was made and exported to FLUENT, where, physical models, boundary conditions and material properties were established.

2.4 Preparation of CAD model

Figure 4 shows the detail of the geometric model with which the numerical modeling of the dryer was developed.

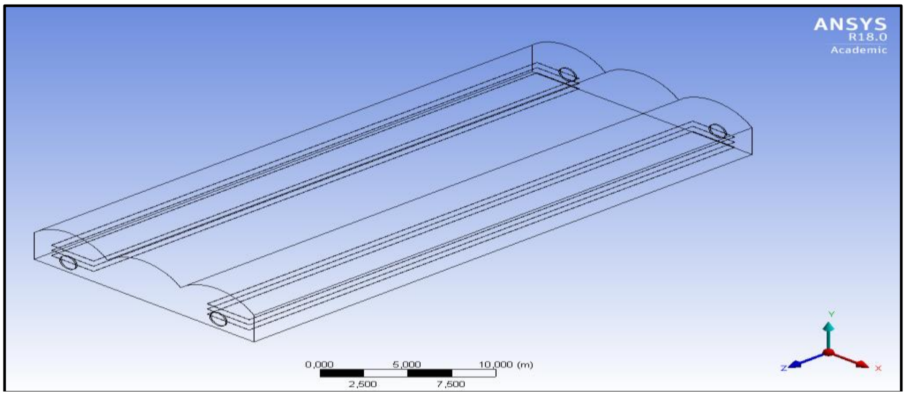

Fig3.3D model of the solar dryer for drying coffee.

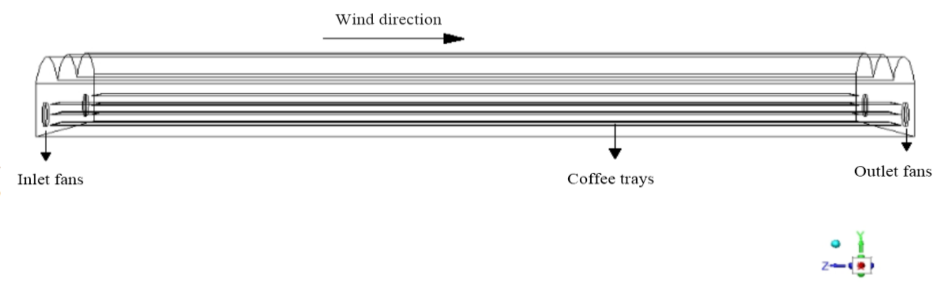

Fig4. View in a YZ plane of the solar dryer specifying inlet and outlet fans, bed of coffee beans and direction of flow.

Figure 5 shows in greater detail the elements that make up the geometry of the dryer, which includes two fans of air inlet and two extraction, as well as six sheets of 39.00x3.40x0.02 cm, which represent the porous medium generated by the coffee layers.

Discretization of the domain

Meshing is a key part of the quality and convergence of the solutions. The discretization of the domain was based on the finite volume method, by means of the decomposition of the domain into small control volumes, generating a three-dimensional mesh of nodes. The finite volume method considers the principles of conservation of mass, momentum and energy, which are the basis of fluid-dynamic mathematical modeling.For this case, a mixed mesh between tetrahedral and hexahedral elements was used, generating a mesh with a total number of nodes of 152090 and 405077 elements, presenting an orthogonal quality of 0.793±0.228 and an obliquity value of 0.212±0.145.

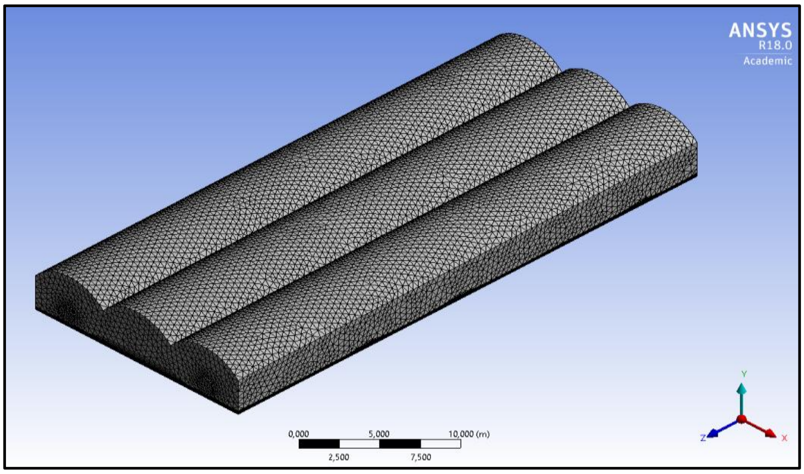

Fig5. Mesh domain of the solar dryer.

Material properties

Table 1 shows the characterization of the materials included in the numerical modeling to represent the physical boundaries formed by the walls, roof and floor of the dryer.

Table 1. Physical and thermal properties of the materials used in the solar dryer [10].

Physicalproperty	**Plastic**	**Concrete**
Density, (kg·m^{-3})	920	2100
Specific heat (J·kg^{-1} °C^{-1})	1900	880
Thermal conductivity (W·m^{-2} °C^{-1})	0.30	1.4
Absorptioncoefficient	0.10	0.60
Scatteringcoefficient	0.00	1.00
Refractiveindex	1.00	1.00
Emissivity	0.90	0.71

For the study, the physical properties of the Geisha variety (*C. arábica var. Geisha*) were used. The determination of the physical properties was carried out in the laboratory of the Forestry Resources Unit of the Institute of Engineering Research (INII). The physical parameters used are shown in Table 2. These parameters were used to characterize the bed of the coffee sheets with the properties that allow to represent in a more detailed way the behavior of the air flow in the porous medium.

Table2. Physical and fluid-dynamic properties of parchment coffee after the fermentation process.

Property	**Value**
Moisturecontent$_{d.b.}$ (%)	116.36±2.05
Bulkdensity(kg·m^{-3})	741.33±9.33
Unitdensity (kg·m^{-3})	801.33±76.49
Porosity (%)	11.9±3.78

Sphericity (%)	64.4±0.020
Diameter (m)	0.009±0.001
Viscousresistance ($1\cdot m^{-2}$)	35.282
Inertialresistance ($1\cdot m^{-1}$)	0.333

Boundaryconditions

The domain of the dryer included in the numerical modeling by means of CFD was characterized with the properties of air. In the space of the simulation the surfaces indicated as fans were established as conditions of inlet velocity, the lateral limits were established as walls, indicating adequately the relevant thermal parameters. The boundary conditions included in the study are indicated in Table 3.

Table 3. Boundary conditions considered in the numerical model.

Parameter	Average
External temperature of the dryer (°C)	24.70±1.13
Internal temperature of the dryer (°C)	27.85±3.09
Intensity of solar radiation ($W\cdot m^{-2}$)	869.32±66.39
Interior temperature in the roof (°C)	29.41±2.75
Internal temperature on the east wall (°C)	27.56±3.08
Internal temperature in the west wall (°C)	27.51±3.44
Internal temperature in the northern wall (°C)	25.55±2.78
Internal temperature in the south wall (°C)	25.62±2.29
Fan velocity 1 (m/s)	5.23±1.66
Fan velocity 2 (m/s)	4.73±3.36
Fan velocity 3 (m/s)	5.90±1.31
Fan velocity (m/s)	5.73±1.23

III. RESULTS AND DISCUSSION

The modeling of internal conditions in solar dryers is a field of study of great interest to researchers who seek to increase the efficiency of these facilities.The behavior of the movement of the air inside the dryer is shown in figure 7. It is observed that the air moves in a practically linear manner from its entry to the exit, presenting a slight recirculation of the flow in the entrance area. There is a marked reduction in the velocity of the flow in a matter of a few meters, this implies that the installed fans do not have enough capacity to drive the air flow at a constant speed along the dryer. When a practically laminar flow occurs and such a marked reduction in the speed inside the dryer, an uneven drying of the coffee beans is promoted, mainly because the grains closest to the impulse fans reach the optimum moisture content in a shorter period of time, generating a possible overdrying of the same, when the necessary time passes for the other layers of grains to reach the optimum humidity, a condition that could generate cracks and cracks in the coffee beans, affecting their quality.

Product of the flow distribution that is presented for the conditions of the solar dryer, there is an increase of the temperature in the middle zone of the dryer, presenting an average temperature of 28 °C. The latter is a consequence of the low air circulation in this region, causing the grain to be dried practically by the incident radiation in the dryer. In the regions near the fans, the temperature fluctuates between 24 °C and 26 °C.

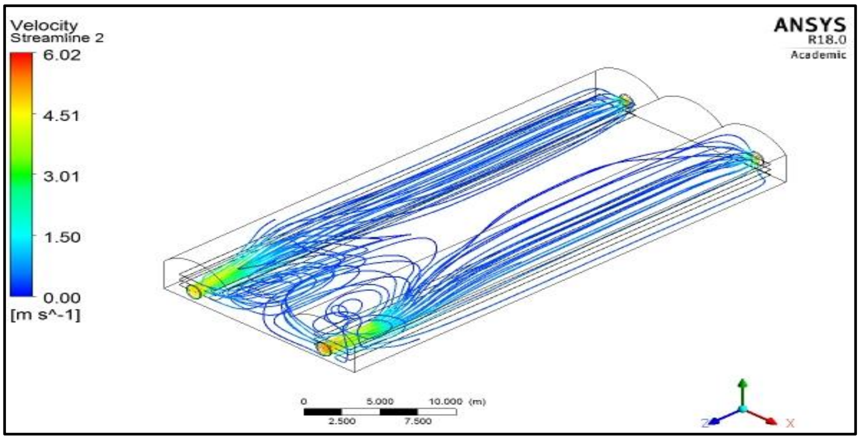

Fig6. Pattern of the air flow lines inside the solar dryer.

Figure 8 shows that the movement of air occurs parallel to the layer of coffee beans, this generates a low interaction between the porous medium of grains and the air flow, affecting the transfer of heat by convection between means, therefore, efficiency in the drying process is decreased.

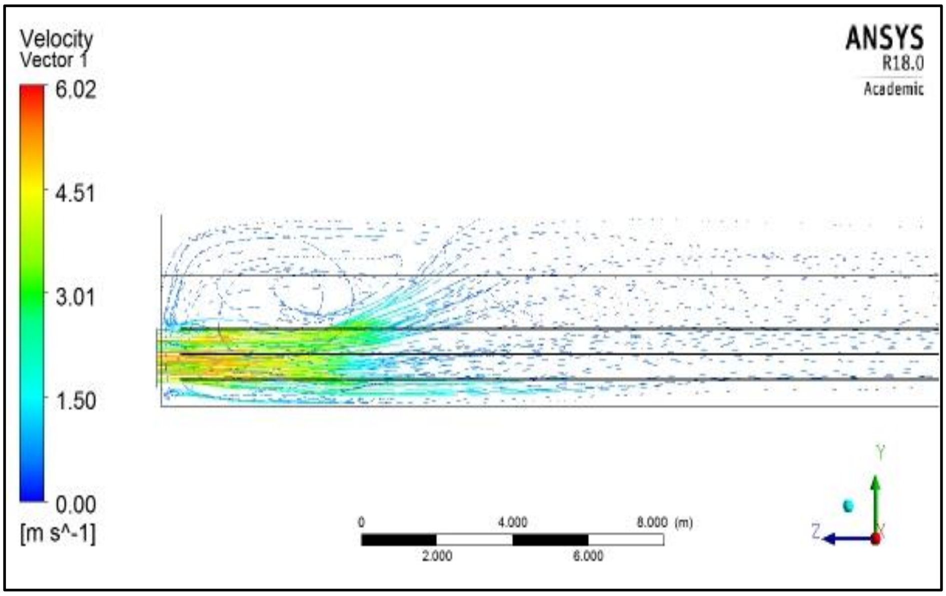

Fig7. Direction vectors of the air flow inside the solar dryer.

Osorio et al [11] analyzed the internal behavior of a greenhouse-type solar dryer for coffee drying by varying different ventilation configurations. Their results indicate that, the greater the airflow in the dryer, the temperature distribution was more uniform, improving the mass transfer between the grains and the medium.The results obtained by Osorio et al [11], represent a guide of the optimum conditions that must be reached in order that the drying process is carried out in an efficient way, therefore, obtaining uniform speeds and a high grain-air interaction product of a turbulent flow are recommended conditions for the dryer in the study.Based on the results presented above, a variation in geometry was proposed that would increase the turbulence of the air flow, this in order to increase the heat and mass transfer between the bed of coffee beans and the air. The proposed variation is based on a series of deflectors shown in Figure 9, evenly spaced and varying the elevation thereof.

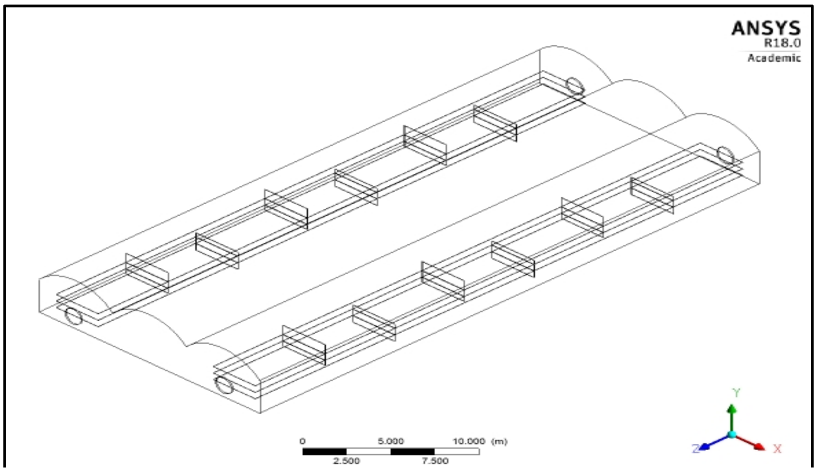

Fig8. Fins placed perpendicular to the movement of air flow.

The change in the behavior of the movement patterns of the air flow when performing the numerical modeling including the designed deflectors is observed in figure 10. A behavior of greater turbulence between the grain layers is observed, product of the air flow shock against the deflectors. The increase in the turbulence of the flow is accompanied by an increase in velocity along the air movement, affect shown in figure 11. It´s observed that the flow maintains an intermediate velocity upon reaching the second deflector, accompanied by the reduction of the speed as the air flow travels through the rest of the dryer.

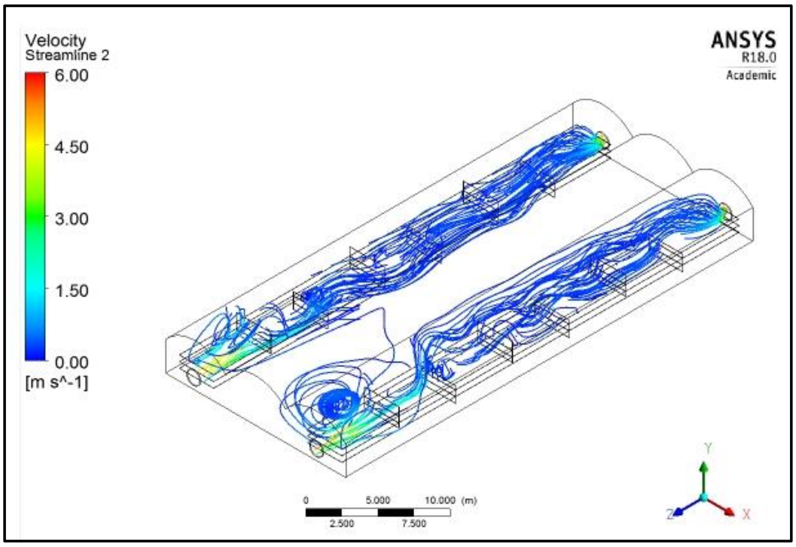

Fig 10. Pattern of the air flow lines inside the solar dryer when placing the designed deflectors.

When these changes appear in the behavior of the movement of the air flow inside the dryer, a marked uniformity is observed in the temperature of the solar dryer, where the average internal temperature is around 29 °C; said uniformity in the internal temperature is due to the fact that it improves the heat transfer in the dryer, avoiding the generation of high temperature zones in the interior.

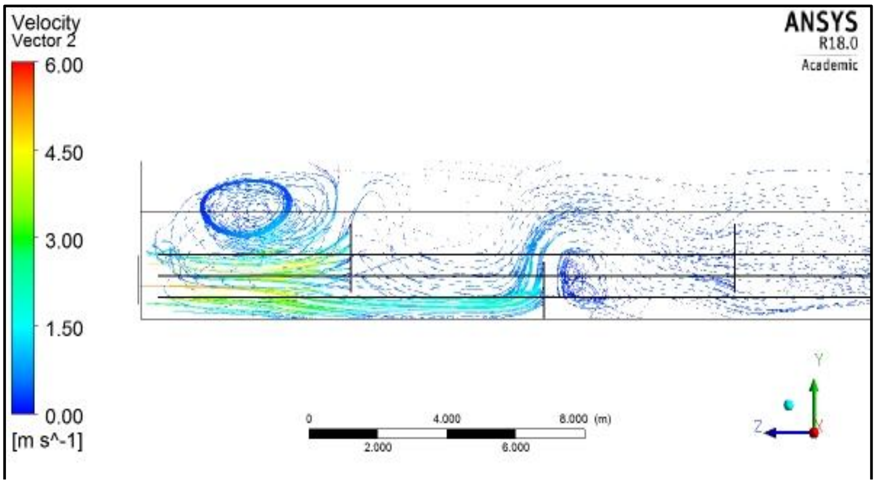

Fig9. Change in direction vectors of the air flow inside the solar dryer when placing the deflectors.

The change in the behavior of the air flow in the dryer has a direct impact on the efficiency of the same, these changes increase the moisture transfer of the grain to the environment, which is reflected in a significant reduction in the drying time. The reduction of the drying time is an aspect of great interest in terms of productivity for the company, this reduction of time is translated in the decrease of the electrical costs in which they are incurred by the action of the fans.It´s necessary to point out that although the distribution of the air flow is improved by placing the fins in the dryer, there are still low air velocities in the middle zone, so it is recommended as an option to use fans with a greater flow capacity and greater power. Another scenario to consider is based on reducing the length of the dryer, keeping the fans installed at present, since, as demonstrated in the numerical modeling developed, these do not have the capacity for the use that is currently being given to them. The improvement of drying conditions in this dryer is a subject of great interest for the company. This dryer to maintain the drying process at a low temperature helps maintain the quality of the grain, to preserve its physical and organoleptic properties.Maintaining the quality of the grains is an aspect of great importance in this type of productive systems, since, the production of coffee in Costa Rica is not characterized as a high volume production, for which the producers compete for quality in the international markets.

IV. CONCLUSIONS

The numerical model established to model the internal fluid-dynamic behavior of the dryer allowed to evaluate the distribution of velocities and flow patterns in the conditions in which parchment coffee is currently drying.It was determined that under current conditions there is no adequate interaction between the grain bed and the air flow, product of the low turbulence produced; therefore deflectors were introduced to improve their behavior.It was possible to increase in a global way the speed of the air flow and the degree of turbulence with which it flows in the dryer, improving the conditions and increasing the efficiency of the drying process.

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