Solar Dryer Exergetic and Energetic Efficiency Analysis

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Abstract: The geometry and the mechanisms under which a dryer chamber are relevant for a good dehydration performance are presented herein. We report the thermal hydrodynamics COMSOL simulations for a solar dryer design, with an emphasis in the thermodynamic efficiency through an exergetic and energetic analysis.

Keywords: Drying chamber, exergy analysis.

1. Introduction

A solar dehydrator is a device used for the extraction of moisture (humidity) from different kind of food products in order to extend their shelf life. These kind of devices show a lower environmental impact when compared with electric or gas apparatus due to their main energy source is the thermal radiation from sunlight.

The physical phenomena that govern the dehydrator performance are the three heat transfer mechanisms (conduction, radiation and convection).

In this contribution, we report the thermal hydrodynamics COMSOL simulations for a solar dryer design, with an emphasis in the thermodynamic efficiency through an exergetic and energetic analysis. We compare the effect of conductivity against inlet velocity.

2. Design of the drying chamber

Concerning with the design, a sketch in the Fig. 1 shows an inclined plate -where the radiation is captured- with a slit that permits the air circulation, as it is described in the Fig. 1.

The geometry includes a 2D model of the chamber with a single tray and an upper chamber, we compare results for two different materials and two different inlet velocities (Case A and B as defined in Table 1).

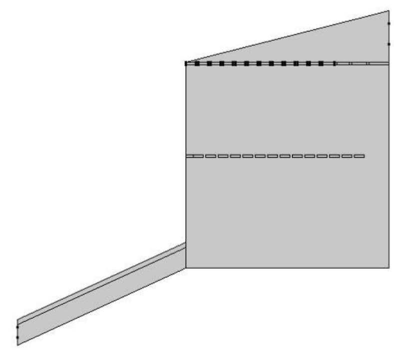

Figure 1. Sketch of the solar dehydrator model.

The materials took into account for simulation purposes were the presence of a gas into the drying chamber, e.i., air. The main function of the gas is the vehicle for the heat transfer into the chamber. For each simulation (case A and B) we proposed the usage of different metals for modeling the tray thermal properties in order to verify the effect of the geometry as a parameter for the calculation of the thermal efficiency of the system. The variables supplied to the model were the inlet temperature (T), density (ρ), dynamic viscosity (μ), thermal conductivity (k), specific heat (C) of the air, pressure into the chamber (p) and the normal air inlet velocity (U).

COMSOL simulations were conducted using the same thermal properties but changing the air inlet velocity, Case A considered and inlet velocity of 2.0 m/s, when in Case B this value was fixed to 1.0 m/s. For Case A the trays were modeled as aluminum and in Case B we proposed cooper.

3. Thermo-hydrodynamics for a drying chamber

Using the air as a working thermodynamic material, we describe its heating using the solar radiation as a heat source. Accordingly, we use the mass, momentum and energy balance equations, with its corresponding constitutive equations, namely, the Navier-Newton and the Fourier laws,

$$\rho\frac{\partial u}{\partial t}+\rho(\mathbf{u}\cdot\nabla)\mathbf{u}=\nabla\cdot\left[-p\mathbf{I}+\mu(\nabla\mathbf{u}+(\nabla\cdot\mathbf{u}))^{T}-\frac{2}{3}\mu(\mathbf{u}\cdot\right.$$

$$\frac{\partial\rho}{\partial t}+\nabla\cdot(\rho\mathbf{u})=0$$

$$d_z\rho C_p\frac{\partial T}{\partial t}+d_z\rho C_p\mathbf{u}\cdot\nabla T=\nabla\cdot(d_z k\nabla T)+d_z Q+Q_{oop}$$

where in the last equation, we have included the heat radiation in the last terms.

Concerning with the boundary conditions, we have for the exit flow the next condition,

$$\left[-p\mathbf{I}+\mu(\nabla\mathbf{u}+(\nabla\cdot\mathbf{u}))^{T}-\frac{2}{3}\mu(\mathbf{u}\cdot\nabla)\mathbf{I}\right]\mathbf{n}=-p_o\mathbf{n}$$

we account for adiabatic walls through the condition,

$$-\mathbf{n}\cdot(d_z k\nabla T)=0$$

and the solar radiation collection is described with the following condition

$$-\mathbf{n}\cdot(-d_z k\nabla T)=d_z q_o$$

3.1. Figures

Case A

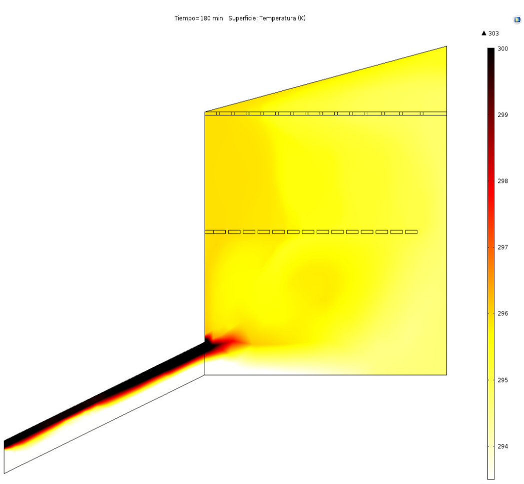

Figure 2a. Temperature field at t = 5 min.

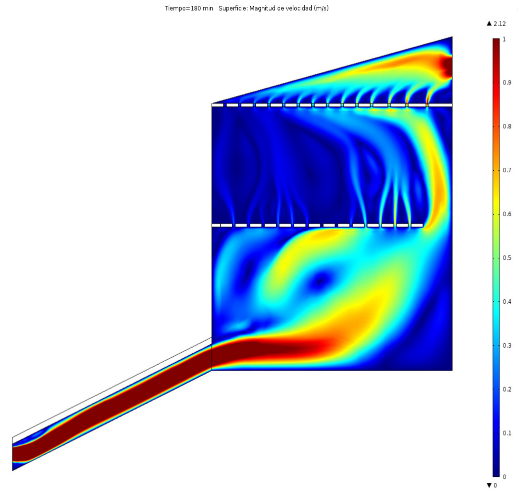

Figure 2b. Velocity field at t = 180 min.

Case B

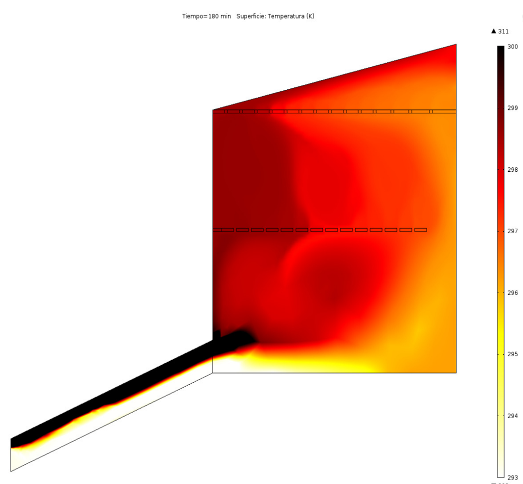

Figure 2c. Temperature field at t = 5 min.

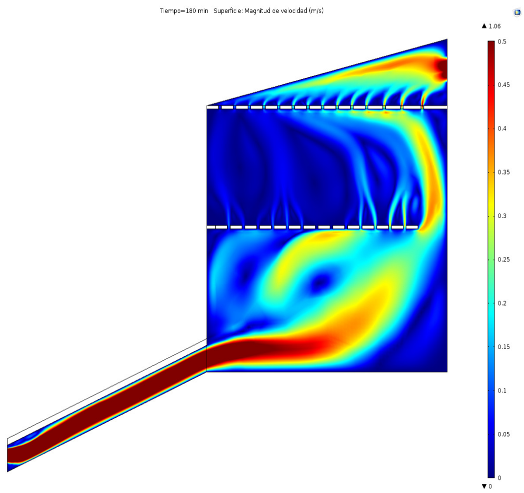

Figure 2d. Temperature field at t = 180 min.

Figure 2 shows the history of heating inside the drying chamber for each Case at 5 and 180 minutes respectively.

4. Results and discussion

The exergy is defined as the maximum amount of work that can be produced by a given flux until the equilibrium conditions are obtained [3]. We use the heat transport module coupled to diffusion for an initial non isothermic laminar flux.
The outlet velocity obeys:

$$\mathbf{u} = -U_o \mathbf{n}$$

The inlet heat flux transferred from the solar collector satisfies:

$$-\mathbf{n}\cdot\left(-d_z k \nabla T\right) = d_z q_o$$

The exergy values are calculated to obtain the efficiency of the chamber [3], given by:

$$Ex_{dci} = C_{pda}\left[\left(T_{dci} - T_a\right) - T_a \ln\frac{T_{dci}}{T_a}\right]$$

$$Ex_{dco} = C_{pda}\left[\left(T_{dco} - T_a\right) - T_a \ln\frac{T_{dco}}{T_a}\right]$$

$$Ex_{loss} = Ex_{dci} - Ex_{dco}$$

$$\eta_{Ex} = \frac{Ex_{dco}}{Ex_{dci}} = 1 - \frac{Ex_{loss}}{Ex_{dci}}$$

where Ex_{dci} and Ex_{dco} are the exergy at the driying chamber inlet and outlet respectively, C_{pda} is the specific heat of the air, T_{dco} and T_{dci} are the temperature at the air inlet and outlet respectively, T_a is the temperature of the environment, finally η_{Ex} is the exergy lost.

Table 1 shows the conditions imposed to the model for each case and the calculated results obtained from COMSOL simulation.

Table 1. Conditions for each model and results

Variable	Units	Case A	Case A1	Case B
Inlet Velocity	m/s	1	2	1
Thermal conductivity	W/(K*m)	155	155	400
Efficiency	%	19.80	15.06	14.85
General heat inlet flux= 500W/m^2 [4] Air temperature=293.15 K				

The air inlet velocity is a governing aspect of the temperature distribution into the drying chamber; as can be observed in Figure 2, when diminishing the inlet air velocity the chamber temperature decreases. Furthermore, after the efficiency calculation we observed that the highest value was reached when the lowest air velocity was imposed to the system, this suggest that the optimal design is ruled by slow air velocity values instead large one.

5. Conclusions

The highest efficiency was obtained for a low conductivity and low inlet velocity because the drying process is governed by an adiabatic behavior inside the chamber.

Finally, it can be observed from analyzing the exergy equations that it is required to produce the same inlet and outlet air temperature in order to maximize the exergetic efficiency of the system, this requires more geometric proposals to be tested.

6. References

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7. Acknowledgements

The authors thank to Universidad Autónoma del Estado de México for financial support throughout grant number 3814/2014/CIA.