A Mathematical Model of Indirect Solar Drying of Dairy Products (Jameed)

Ghassan M. Tashtosh*, Mohammad Jaradat, Shadi Zuraiakt, Mohamad Aljarah

Jordan University of Science and Technology, Mechanical Engineering Department, P.O.Box 3030, Irbid, 22110 Jordan

*Corresponding Author: gtash@just.edu.jo

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Abstract A Mathematical modeling of indirect natural convection solar dryer was designed for drying one of the famous dairy product in Jordan called Jameed. The intended solar dryer system is environmentally friendly and consumes zero electricity. The dryer consists of a flat plate solar collector having dimensions of 0.1 m height, 0.8 m width and 1.2 m length. A drying chamber consisting of four trays separated equally from each others at a distance of 0.2 m. The chamber is 1 m long made of wood. Each tray has a cross section of 0.8 m x 0.4 m. The solar collector is studied separately to establish the effect of changing its width or length on the air outlet temperature and mass flow rate. The drying chamber is used to dry 4 kilograms of jameed, each 1 kilogram is distributed on each tray. The total solar irradiation on the collector surface and chamber walls at each hour of the day was also calculated at the 21st of May in Jordan. At these specific solar irradiation, the flat plate solar collector efficiency was almost constant having an average efficiency of 37% and a maximum outlet temperature of 41 °C at 1p.m. The drying time for trays 1, 2, 3 and 4 were 16.4, 19.14, 22.6 and 25.71 hours, respectively.

Keywords Solar Drying; Dairy Products; Mathematical Model; Moisture Content.

1. Introduction

Nearly one-fourth of the world's food supply is lost as a result of microbial spoilage. Due to this, preservation of food and agriculture products is necessary for storing and maintaining their quality for a longer period of time. This can be done in several methods such as refrigeration, heat treatments, radiation, filtration, drying and many other methods. Dehydration is the simplest method of all. Drying generally means removal of relatively small amount of water from material. The water is usually removed as a vapor by air. Microorganisms that cause food spoilage and decay cannot grow and multiply in the absence of water. Also many enzymes that cause chemical changes in food and other biological materials cannot function without water. When

the water content is reduced below about 10% by weight, the microorganism are not active [1]. Drying processes can be categorized according to the physical conditions used to add heat and remove water vapor:

1. In direct drying, heat is added by direct contact with heated air at atmospheric pressure, and the water vapor formed is removed by the air.
2. In vacuum drying, the evaporation of water proceeds more rapidly at low pressures and the heat is added indirectly by contact with a metal wall or by radiation.
3. In freeze drying, water is sublimed from the frozen material.

The potential of using solar energy in the agricultural sector has increased due to fluctuation in the price of fossil fuel, environmental concerns and expected depletion of conventional fossil fuels. Solar assisted drying system is one of the most attractive and promising applications of solar energy systems in Jordan. Solar drying systems are a direct drying technique, where the air is heated using solar radiation to dry food products. Sun drying methods are not new in Jordan, people in rural areas used to dry their products by spreading them on flat surface with or without exposure to the sun in the open air. Direct sun drying requires large open space area, and very much dependent on the availability of sunshine, susceptible to contamination with foreign materials such as dusts, litters and are exposed to birds, insect and rodents. Hence, most agricultural products that are intended to be stored must be dried first. Otherwise insects and fungi, which thrive in moist conditions, render them unusable.

Basically, there are four types of solar air-contact dryers; direct solar dryers, indirect solar dryers, mixed-mode dryers, and hybrid solar dryers. In direct drying, the drying material is subjected to direct sun radiation to be dried, while in indirect drying the air enters a solar collector where it is heated first, and then enters a drying chamber. In mixed mode, air is heated in a collector and flown in to the chamber, in addition to solar radiation subjected on the drying material through the chamber. Hybrid dryers use external unit to heat the air, such as heaters. However, the purpose of this project is to encourage people living in rural areas in Jordan with less financial capabilities to dry their products in a relatively

low cost system that requires zero electricity benefiting them in accelerating the time for drying, control the final moisture content and reduce wastage through bacterial action.

The simplest of solar cabinet dryer was presented by Othieno [2], it was very simple, and consists essentially of a small wooden hot box. The sides and bottom can be portable and can be constructed from wood or metal sheet. A transparent polyethylene sheet was used as cover at upper surface. Air holes are located on the sides of the drier for circulation. Portable indirect solar dryers also fabricated; made of wood and plywood as reported by Amouzou et al. [3]. The absorber is made galvanized sheet metal painted black. The drying chamber can dry 10–15 kg of product in 3 days. The wooden frame was not weather-resistant (rain or wind), and the problem of waterproofing arose. Its useful life was 4 years. The multipurpose cement dryer was the same as the brace-type but made from breezeblock instead of wood. It is 4.82 m x 2.82 m and has load capacity of 80–100 kg. Both the collector for preheating the air and the drying chamber are covered with nine glass panel. To reduce the cost of the absorber, the black metal sheet was replaced with charcoal, a product that is available in rural areas. Bolaji [4] developed and evaluated a solar dryer using a box type absorber collector. The dryer consists of an air heater, an opaque crop bin, and a chimney. The box-type absorber collector made of a glass cover and black absorber plate was inclined at angle of about 20 degree to the horizontal to allow the heated air to rise up the unit with little resistance. He reported that the maximum efficiency obtained in the box-type absorber system was 60.5% while those of flat plate absorber and fin-type absorber were 21% and 36%, respectively. He calculated also the maximum average temperature inside the collector and drying chamber were 64 and 57.8°C, respectively, while the maximum ambient temperature observed was 33.5 °C. Bolaji and Olalusi [5] constructed and evaluated performance of a mixed-mode solar dryer for food preservation. They reported that the temperature rise inside the drying cabinet was up to 74% at about 3 hours immediately after noon. The drying rate and system efficiency were 0.62 kg/h and 57.5%, respectively. The rapid rate of drying in the dryer reveals its ability to dry food items reasonably rapidly to a safe moisture level. Results showed that during the test period revealed that the temperatures inside the dryer and solar collector were much higher than ambient temperature during most hours of the day-light.

Simate [6] designed, constructed and tested two different types of natural convection solar dryers. They reported that, in both configurations, the dryer width is the same as the collector width. Airflow in the dryer is driven by buoyancy pressure created in: (1) the single covered collector with flow over the absorber, (2) the space below the grain bed, (3) the grain bed (4) and the space above the grain bed. For the mixed-mode, the drying chamber cover is transparent whereas for the indirect mode it is opaque. His calculated showed that the optimization gave a shorter collector length

for the mixed-mode solar dryer (1.8 m) than for the indirect-mode dryer (3.34 m) of the same capacity (90 kg). The drying cost of the mixed-mode dryer is 12.76 US\$/tonnes which was about 26% lower than that of the indirect-mode; the quantity of dry grain obtained from the mixed-mode for the whole year was about 2.81 tonnes and was less than that from the indirect mode by 15%.

Madhlopa et al. [7] developed a solar dryer which had composite absorber systems on the principles of psychometric. The dryer consists of a flat plate collector, wire mesh absorber, glass cover, chimney and drying chamber. The drying chamber frames and both the collector were constructed from wooden sheets painted pink. Both the collector was integrated to a drying chamber for food dehydration. Results showed that the temperature rise of drying air was up to 40.8 °C during noon hours. The thermal efficiency of flat plate collector and wire mesh absorber were approximately 21% and 17% respectively at flow rate 0.0083 kg s⁻¹.

A mixed-mode wind-ventilated natural convection solar dryer has been reported by Ekechukwe and Norton [8] in their review. The drying system consists essentially of a solar air heater integrated to the drying chamber at the base, and a rotary wind ventilator at the top of the dryer chimney. The warm air outlet of the air heater is connected to the base of drying chamber. To reduce the heat losses, the north-facing wall and bottom horizontal panel are blackened. Addition drying also is achieved from direct solar radiation falling over the product through transparent side, front, and top panels. The rotary wind ventilator was built from moving corrugated vane rotor.

2. Description of Apparatus

A mathematical modeling was held for a simple indirect natural convection solar dryer as shown in figure 1. The dryer consists of a flat plate solar collector attached to a drying chamber made of wood. The collector is 1.2 m long, 0.1 m height and 0.8 m width. The black sheet is made of aluminum of 0.01 m thickness and the insulation from wood of 0.09 m thickness. The cover is PMMA transparent plastic with negligible thickness. The drying chamber consists of four trays separated equally from each others at a distance of 0.2 m; each tray is 0.4 m length and 0.8 m width.

The basic mechanism of dairy product drying was by heat and moisture transfer between the product material and the air. The heat is transferred to the surface of the material by conduction and convection from adjacent air at temperature above that of the material being dried. If the air is passed through the material at a relative humidity of less than that of moisture content in the material, the air will absorb moisture from the material while increasing its absolute and relative humidity. The drying process was very much close to the evaporative cooling process, in which the air temperature is decreased and its humidity is increased.

Figure 1. Simple natural convection solar dryer schematic diagram.

3. Solar Irradiation in Jordan

Before starting the modeling, it is of various importance to calculate the ambient temperature through the day and the total irradiation from the sun in Jordan. The direction of the sun's rays can be detected if three fundamental equations are known [9 and 10]:

1. Location on the earth's surface.
2. Time of the day.
3. Day of the year.

These three quantities can be described by giving the latitude (L), the hour angle (h), and the sun's declination (δ), respectively. For Jordan the latitude is equal to 31.95° , the longitude is 35.95° and the declination angle is taken for the 21st of May to be 20.6° . Equations to determine the hour angle, solar altitude angle (λ), angle of incidence between the sun's rays and the normal to the horizontal surface (Θ_H) and to the vertical surface (Θ_V) are taken from [10]. To calculate the hour angle, local solar time (LST) must be determined using:

$$LST = LCT + EOT \quad (1)$$

Where, LCT is the local civil time needed through the day. The hour angle can be determined as:

$$h = 12 - LST \quad (2)$$

The equation of time (EOT) also taken at May to be 3.3 minutes [10]. Determining of solar altitude angle (λ), angle of incidence between the sun's rays and the normal to the horizontal surface (Θ_H) and to the vertical surface (Θ_V) is continued using the following equations [10]:

$$\sin(\lambda) = \cos(L) \cdot \cos(h) \cdot \cos(\delta) + \sin(L) \cdot \sin(\delta) \quad (3)$$

$$\cos(\Phi) = (\sin(\delta) \cdot \cos(L) - \cos(\delta) \cdot \sin(L) \cdot \cos(h)) / \cos(\lambda) \quad (4)$$

$$Y = \Phi - \Psi \quad (5)$$

The surface azimuth (Ψ) (facing direction) measured clock

wise from north and is taken to be 180° .

$$\cos(\Theta) = \cos(\lambda) \cdot \cos(Y) \cdot \sin(\xi) + \sin(\lambda) \cdot \cos(\xi) \quad (6)$$

Where, the tilt angle (ξ) is the angle between the normal to the surface and the normal to the horizontal surface. Hence, a horizontal surface has a tilt angle of zero; a vertical surface has a tilt angle of 90 deg. Equation 6 for horizontal and vertical surfaces become:

$$\cos(\Theta_H) = \sin(\lambda) \quad (6.a)$$

$$\cos(\Theta_V) = \cos(\lambda) \cdot \cos(Y) \quad (6.b)$$

After determining the angles, the total solar irradiation on the vertical and horizontal surfaces can be calculated using ASHRAE clear sky model [10], starting by calculating the normal direct irradiation (G_{ND}) using the equation:

$$G_{ND} = A / \exp(B / \sin(\lambda)) \quad (7)$$

Where A is the apparent solar irradiation at air mass equal to zero and is found to be 1106 W/m^2 . B is the atmospheric extinction coefficient equals to 0.177 and it is a dimensionless number. It should be kept in mind that these values are taken at the 21st of May and the sky is pretty clear (clearness number=1). The direct solar radiation (G_{DH}), diffuse radiation (G_{dH}) and total solar radiation is calculated on a horizontal surface using:

$$G_{dH} = c \cdot G_{ND} \quad (8)$$

$$G_{DH} = G_{ND} \cdot \cos(\Theta_H) \quad (9)$$

$$G_{Tot,H} = G_{dH} + G_{DH} \quad (10)$$

For vertical surface,

$$G_{dV} = G_{ND} \cdot \cos(\Theta_V) \quad (11)$$

$$G_{RV} = G_{Tot,H} \cdot F_{wg} \cdot \text{ref} \quad (12)$$

Reflectivity of the ground is taken to be 0.33. Configuration or angle factor from vertical surface to ground (F_{wg}) is defined as:

$$F_{wg} = (1 - \cos(\xi)) / 2 \quad (13)$$

And is equal 0.5 for vertical surfaces.

If $\cos(\Theta_V)$ is larger than -0.2,

$$G_{dV} = (.55 + .437 \cdot \cos(\Theta_V) + .313 \cdot (\cos(\Theta_V))^2) \cdot G_{dH} \quad (14)$$

Otherwise,

$$G_{dV} = 0.45 \cdot G_{dH} \quad (14.a)$$

$$G_{Tot,V} = G_{dV} + G_{RV} + G_{DV} \quad (15)$$

These equations were solved simultaneously using engineering equation solver software (EES) to obtain the total solar irradiation on the horizontal and vertical surfaces of the solar collector and the drying chamber at each hour of the day. To determine the ambient temperature theoretically, the following equation were used [10]:

$$T_{amb} = T_{db} - DR \cdot X \quad (16)$$

Where the design dry bulb temperature (T_{db}) for Jordan is 29.1°C , the daily range (DR) is 10.2°C and the percentage of daily range (X) multiplied by 100 are given in [10]. The

results were presented and discussed in the discussion part.

4. Mathematical modeling

The assumptions for the system as follows:

1. Calculations were based on steady state conditions.
2. Constant specific heat of the air.
3. Air and water vapor was considered to be as an ideal gas.
4. Incompressible flow.
5. Only buoyancy force was responsible for the air flow induced.
6. The total vertical solar irradiation on each surface of the drying chamber is the same.
7. The walls of the drying chamber are considered to emit 20% of the absorbed solar radiation to the air inside the chamber.
8. The product being dried has a spherical shape.
9. The average relative humidity at May in Jordan stays almost constant through the day and is assumed to be 0.0113kg_w/kg_a.

A. Solar Collector

Figure 2. Schematic diagram of the heat transfer modes in the solar collector.

The solar collector model is shown in figure 2. Based on the energy conservation law, a set of equations were constructed along the length of the solar collector. An energy balance on the surface of the glass results in:

$$Q_{solar, H, glass} + Q_{r, black\ sheet-glass} = Q_{glass-ambient} + Q_{r, glass-ambient} + Q_{glass-air, in} \quad (17)$$

Substituting the heat relations in equation (17),

$$\sigma * ((T_{sb} + 273)^4 - (T_{sg} + 273)^4) / (1/\epsilon_{bs} - 1 + 1/\epsilon_G) + \alpha_G * G_{TotH} = h_o * (T_{sg} - T_{amb}) + \epsilon_G * \sigma * ((T_{sg} + 273)^4 - (T_{amb} + 273)^4) + h_i * (T_{sg} - T_{air}) \quad (17.a)$$

The energy balance equation for the black sheet and insulation is:

$$Q_{solar, H, black\ sheet} = Q_{black\ sheet-air, in} + Q_{r, black\ sheet-glass} + Q_{loss\ to\ ambient} \quad (18)$$

Substituting the heat relations in equation (18) results in:

$$\tau_G * G_{TotH} * \alpha_{bs} = h_i * (T_{sb} - T_{air}) + \sigma * ((T_{sb} + 273)^4 - (T_{sg} + 273)^4) / (1/\epsilon_{bs} - 1 + 1/\epsilon_G) + (T_{sb} - T_{amb}) / (t_{bs}/k_{bs} + t_{ins}/k_{ins} + 1/h_o) \quad (18.a)$$

The energy balance equation for the air in the solar collector is:

$$Q_{net, air} = Q_{black\ sheet-air, in} + Q_{glass-air, in} \quad (19)$$

Substituting the heat relations in equation (19) results in:

$$m_a * C_{pa} * (T_{ao} - T_{ai}) = h_i * b * L_c * (T_{sb} + T_{sg} - 2 * T_{air}) \quad (19.a)$$

Temperature of the air inside the collector (T_{air}) is assumed to be an average between the inlet and outlet temperature,

$$T_{air} = (T_{ai} + T_{ao}) / 2 \quad (20)$$

The internal convection heat transfer coefficient in the collector is taken as 5 W/m². °C as indicated in [10] for plane air spaces. The convection heat transfer coefficient due to the wind is given by [9] as follows:

$$h_o = 2.8 + 3 * V_{amb}$$

Figure 5. Schematic diagram of the drying chamber (21)

Table 2. Theoretical results for different absorber length.

Ambient temperature (°C)	Solar radiation (W/m ²)	Absorber length (m)	Inlet collector dimensions (a x b)(m x m)	Air flow rate (kg/s)	Outlet temperature (°C)
25	200	2.0	0.1 x 0.8	0.01965	30.55
	400			0.02473	34
	600			0.02813	36.86
	800			0.03073	39.38
	1000			0.03284	41.66
25	200	3.0	0.1 x 0.8	0.02181	32
	400			0.0275	36.45
	600			0.03128	40.17
	800			0.03414	43.47
	1000			0.03646	46.45
25	200	4.0	0.1 x 0.8	0.02336	33.2
	400			0.02948	38.52
	600			0.03353	43
	800			0.03658	46.97
	1000			0.03904	50.58
25	200	5.0	0.1 x 0.8	0.02454	34.23
	400			0.03101	40.33
	600			0.03526	45.48
	800			0.03845	50.06
	1000			0.041	54.25
25	200	6.0	0.1 x 0.8	0.02547	35.13
	400			0.03222	41.94
	600			0.03663	47.71
	800			0.03993	52.86
	1000			0.04255	57.57

Table 3. Theoretical results for different inlet collector dimensions.

Ambient temperature (°C)	Solar radiation (W/m ²)	Absorber length (m)	Inlet collector dimensions (a x b)(m x m)	Air flow rate (kg/s)	Outlet temperature (°C)
25	200	2.0	0.1 x 0.1	0.002437	30.58
			0.1 x 0.2	0.004895	30.56
			0.1 x 0.4	0.009812	30.55
			0.1 x 0.6	0.01473	30.55
			0.1 x 0.8	0.01965	30.55
			0.1 x 1.0	0.02456	30.55
			0.1 x 1.2	0.02948	30.55
25	400	2.0	0.1 x 0.1	0.003068	34.05
			0.1 x 0.2	0.006163	34.02
			0.1 x 0.4	0.01235	34
			0.1 x 0.6	0.01854	34
			0.1 x 0.8	0.02473	34
			0.1 x 1.0	0.03092	33.99
			0.1 x 1.2	0.03711	33.99
25	600	2.0	0.1 x 0.1	0.00349	36.93
			0.1 x 0.2	0.007011	36.89
			0.1 x 0.4	0.01405	36.87
			0.1 x 0.6	0.02109	36.86
			0.1 x 0.8	0.02813	36.86
			0.1 x 1.0	0.03518	36.86
			0.1 x 1.2	0.04222	36.85
25	800	2.0	0.1 x 0.1	0.003812	39.47

			0.1 x 0.2	0.007657	39.42
			0.1 x 0.4	0.01535	39.39
			0.1 x 0.6	0.02304	39.38
			0.1 x 0.8	0.03073	39.38
			0.1 x 1.0	0.03842	39.38
			0.1 x 1.2	0.04611	39.37
			0.1 x 0.1	0.004074	41.77
			0.1 x 0.2	0.008182	41.71
			0.1 x 0.4	0.0164	41.67
25	1000	2.0	0.1 x 0.6	0.02462	41.66
			0.1 x 0.8	0.03284	41.66
			0.1 x 1.0	0.04105	41.66
			0.1 x 1.2	0.04927	41.65

The average velocity of the wind in Jordan at May is taken as 5 m/s. Solar collector results. Upon solving equations related to solar collector, results were obtained for the outlet temperature and the air flow rate as the length of the collector and the inlet conditions were varied. Table 2 and 3 shows these results.

b. Drying chamber

The drying chamber consists of four trays and was divided in to four zones as shown in figure 5. Each zone and tray was subjected to the energy conservation law. The energy balance equation for the air in zone 1 is:

$$ma \cdot C_{pa} \cdot (T_b - T_a) = 20\% \cdot 2 \cdot (W + l) \cdot s \cdot \alpha_{wall} \cdot G_{Tot,V} \quad (22)$$

The energy balance equation through tray 1 is:

$$ma \cdot C_{pa} \cdot (T_b - T_c) = hf_l \cdot N \cdot Af \cdot (T_b - T_{sfl}) + m_{w1} \cdot hfg_l \quad (23)$$

The evaporated water flow rate from the drying product is calculated using the mass transfer equation given in [11],

$$m_{w1} = kg1 \cdot Af \cdot N \cdot (W_{wet1} - w_{z1}) \quad (24)$$

The mass transfer coefficient for the first tray ($kg1$) is found using Lewis number (Le). Lewis number for air-water system is equal [12]:

$$Le = hf_l / (C_{pa} \cdot kg1) = 1 \quad (25)$$

The temperature of the surface of the product (T_{sfl}) is equal to the wet bulb temperature of the inlet air since a drying process is taking place on the surface of the product. The driving force for mass transfer is the difference between the concentration of water in the air entering the tray and the moisture content in the food. Hence, the difference between the humidity of the entering air (w_{z1}) and the humidity of the air film surrounding the food (W_{wet1}) which is in moisture equilibrium (saturated) at the surface temperature of the food (T_{sfl}). Surface temperature of the food is determined from psychrometric chart using a built in function in EES that obtains the wet bulb temperature as a function of the total pressure, inlet air temperature and inlet humidity ratio of the air as follows:

$$T_{sfl} = WETBULB(AirH2O, T = T_b, P = P, w = w_{z1}) \quad (26)$$

The wet humidity ratio (W_{wet1}) is calculated using the

psychrometric relation,

$$W_{wet1} = 0.622 \cdot P_{s1} / (P - P_{s1}) \quad (27)$$

Saturated pressure (P_{s1}) is calculated by also using a built in function in EES as follows:

$$P_{s1} = P_SAT(\text{Water}, T = T_{sfl}) \quad (28)$$

A mass balance equation for the air going through tray 1 allows the determination of the humidity ratio of the air leaving the tray. The mass balance equation is:

$$w_{z2} = m_{w1} / ma + w_{z1} \quad (29)$$

The convection heat transfer coefficient for the surface of the product (hf_l) is determined using the correlation due to Churchill for spheres [10],

$$Nu_D = hf_l \cdot D / K_{filml} = 0.589 \cdot Ra_{D1}^{(1/4)} / (1 + (0.469 / Pr)^{(9/16)})^{(4/9)} + 2 \quad (30)$$

Equation (30) is satisfied for Prandtl number $Pr \geq 0.7$ and for $Ra_D \leq 10^{11}$. Rayleigh number is calculated using:

$$Ra_{D1} = g \cdot \beta_{filml} \cdot (T_b - T_{sfl}) \cdot D^3 / (v_{filml} \cdot \text{diff}_{filml}) \quad (31)$$

$$\beta_{filml} = 1 / (T_{filml} + 273) \quad (32)$$

$$\text{diff}_{filml} = k_{filml} / (\rho_{filml} \cdot C_{pa}) \quad (33)$$

Formulas used to calculate the fluid physical properties at any temperature are given by empiric correlations fitted using air tables and water tables these properties are:

$$h_{fg1} = ((6254828.56 - 11742.338 \cdot T_b + 6.337 \cdot T_b^2 - 0.049241 \cdot T_b^3)^{0.5}) \cdot 1000 \quad (34)$$

$$K_{filml} = 1.52 \cdot 10^{-4} + 4.42 \cdot 10^{-5} \cdot (T_{filml} + 273) + 8 \cdot 10^{-9} \cdot (T_{filml} + 273)^2 \quad (35)$$

$$v_{filml} = -1.1555 \cdot 10^{-14} \cdot (T_{filml} + 273)^3 + 9.5728 \cdot 10^{-11} \cdot (T_{filml} + 273)^2 + 3.7604 \cdot 10^{-8} \cdot (T_{filml} + 273) - 3.4484 \cdot 10^{-6} \quad (36)$$

$$\rho_{filml} = 360.77819 \cdot (T_{filml} + 273)^{-1.00336} \quad (37)$$

$$T_{filml} = (T_b + T_{sfl}) / 2 \quad (38)$$

Prandtl number was assumed to be constant for the air and equals 0.7 since the operating temperature range in the system will result in negligible change in the Prandtl number. Upon going through the three other trays and zones the equations stays the same, while the temperature, humidity ratio, mass flow rate of the air and drying rate is changed

from zone to zone. These equations are summarized as follows:

Zone 2:

$$ma * Cpa * (T_d - T_c) = 0.2 * 2 * (W + l) * s * \alpha_{wall} * G_{Tot,V} \quad (39)$$

Tray 2:

$$ma * Cpa * (T_d - T_c) = hf_2 * N * Af * (T_d - T_{sf2}) + m_{w2} * hfg_2 \quad (40)$$

$$T_{sf2} = WETBULB(AirH_2O, T=T_d, P=P, w=w_{z2}) \quad (41)$$

$$m_{w2} = kg_2 * Af * N * (W_{wet2} - w_{z2}) \quad (42)$$

$$Kg_2 = hf_2 / Cpa \quad (43)$$

$$W_{wet2} = 0.622 * Ps_2 / (P - Ps_2) \quad (44)$$

$$Ps_2 = P_SAT(Water, T=T_{sf2}) \quad (45)$$

$$w_{z3} = m_{w2} / ma + w_{z2} \quad (46)$$

$$hf_2 = (0.589 * Ra_{D2}^{(1/4)} / (1 + (0.469 / Pr)^{(9/16)})^{(4/9)} + 2) * (k_{film2} / D) \quad (47)$$

$$Ra_{D2} = g * \beta_{film2} * (T_d - T_{sf2}) * D^3 / (v_{film2} * diff_{film2}) \quad (48)$$

$$\beta_{film2} = 1 / (T_{film2} + 273) \quad (49)$$

$$diff_{film2} = k_{film2} / (\rho_{film2} * Cpa) \quad (50)$$

$$K_{film2} = 1.52 * 10^{-4} + 4.42 * 10^{-5} * (T_{film2} + 273) + 8 * 10^{-9} * (T_{film2} + 273)^2 \quad (51)$$

$$v_{film2} = -1.1555 * 10^{-14} * (T_{film2} + 273)^3 + 9.5728 * 10^{-11} * (T_{film2} + 273)^2 + 3.7604 * 10^{-8} * (T_{film2} + 273) - 3.4484 * 10^{-6} \quad (52)$$

$$\rho_{film2} = 360.77819 * (T_{film2} + 273)^{-1.00336} \quad (53)$$

$$hfg_2 = (6254828.56 - 11742.338 * T_d + 6.337 * T_d^2 - 0.049241 * T_d^3)^{0.5} * 1000 \quad (54)$$

$$T_{film2} = (T_d + T_{sf2}) / 2 \quad (55)$$

Zone 3:

$$ma * Cpa * (T_f - T_c) = 0.2 * 2 * (W + l) * s * \alpha_{wall} * G_{Tot,V} \quad (56)$$

Tray 3:

$$ma * Cpa * (T_f - T_g) = hf_3 * N * Af * (T_f - T_{sf3}) + m_{w3} * hfg_3 \quad (57)$$

$$T_{sf3} = WETBULB(AirH_2O, T=T_f, P=P, w=w_{z3}) \quad (58)$$

$$m_{w3} = kg_3 * Af * N * (W_{wet3} - w_{z3}) \quad (59)$$

$$Kg_3 = hf_3 / Cpa \quad (60)$$

$$W_{wet3} = 0.622 * Ps_3 / (P - Ps_3) \quad (61)$$

$$Ps_3 = P_SAT(Water, T=T_{sf3}) \quad (62)$$

$$w_{z4} = m_{w3} / ma + w_{z3} \quad (63)$$

$$hf_3 = (0.589 * Ra_{D3}^{(1/4)} / (1 + (0.469 / Pr)^{(9/16)})^{(4/9)} + 2) * (k_{film3} / D) \quad (64)$$

$$Ra_{D3} = g * \beta_{film3} * (T_f - T_{sf3}) * D^3 / (v_{film3} * diff_{film3}) \quad (65)$$

$$\beta_{film3} = 1 / (T_{film3} + 273) \quad (66)$$

$$diff_{film3} = k_{film3} / (\rho_{film3} * Cpa) \quad (67)$$

$$K_{film3} = 1.52 * 10^{-4} + 4.42 * 10^{-5} * (T_{film3} + 273) + 8 * 10^{-9} * (T_{film3} + 273)^2 \quad (69)$$

$$v_{film3} = -1.1555 * 10^{-14} * (T_{film3} + 273)^3 + 9.5728 * 10^{-11} * (T_{film3} + 273)^2 + 3.7604 * 10^{-8} * (T_{film3} + 273) - 3.4484 * 10^{-6} \quad (70)$$

$$\rho_{film3} = 360.77819 * (T_{film3} + 273)^{-1.00336} \quad (71)$$

$$T_{film3} = (T_f + T_{sf3}) / 2 \quad (72)$$

Zone 4:

$$ma * Cpa * (T_h - T_g) = 0.2 * 2 * (W + l) * s * \alpha_{wall} * G_{Tot,V} \quad (73)$$

Tray 4:

$$ma * Cpa * (T_h - T_i) = hf_4 * N * Af * (T_h - T_{sf4}) + m_{w4} * hfg_4 \quad (74)$$

$$T_{sf4} = WETBULB(AirH_2O, T=T_h, P=P, w=w_{z4}) \quad (75)$$

$$m_{w4} = kg_4 * Af * N * (W_{wet4} - w_{z4}) \quad (76)$$

$$Kg_4 = hf_4 / Cpa \quad (77)$$

$$W_{wet4} = 0.622 * Ps_4 / (P - Ps_4) \quad (78)$$

$$Ps_4 = P_SAT(Water, T=T_{sf4}) \quad (79)$$

$$w_{z5} = m_{w4} / ma + w_{z4} \quad (80)$$

$$hf_4 = (0.589 * Ra_{D4}^{(1/4)} / (1 + (0.469 / Pr)^{(9/16)})^{(4/9)} + 2) * (k_{film4} / D) \quad (81)$$

$$Ra_{D4} = g * \beta_{film4} * (T_h - T_{sf4}) * D^3 / (v_{film4} * diff_{film4}) \quad (82)$$

$$\beta_{film4} = 1 / (T_{film4} + 273) \quad (83)$$

$$diff_{film4} = k_{film4} / (\rho_{film4} * Cpa) \quad (84)$$

$$hfg_4 = (6254828.56 - 11742.338 * T_h + 6.337 * T_h^2 - 0.049241 * T_h^3)^{0.5} * 1000 \quad (85)$$

$$K_{film4} = 1.52 * 10^{-4} + 4.42 * 10^{-5} * (T_{film4} + 273) + 8 * 10^{-9} * (T_{film4} + 273)^2 \quad (86)$$

$$v_{film4} = -1.1555 * 10^{-14} * (T_{film4} + 273)^3 + 9.5728 * 10^{-11} * (T_{film4} + 273)^2 + 3.7604 * 10^{-8} * (T_{film4} + 273) - 3.4484 * 10^{-6} \quad (87)$$

$$\rho_{film4} = 360.77819 * (T_{film4} + 273)^{-1.00336} \quad (89)$$

$$T_{film4} = (T_h + T_{sf4}) / 2 \quad (90)$$

To determine the time needed for drying at constant heat supply from the sun based on steady state assumption, the moisture content based on wet basis of the product has to be known. In this experiment the product used to be dried was Jameed. Jameed is very popular in Jordan because it is used in making the national dish, Mansaf. Jameed is hard dry yoghurt made from sheep's milk. Milk is kept in a fine woven cheese cloth to make a thick yogurt. Salt is added daily to thicken the yogurt even more and the outside of the yogurt filled cheesecloth is rinsed with water to allow any remaining whey to seep through. After a few days of salting the yogurt, it becomes very dense and it can be removed from the cheesecloth and shaped into round balls. It is then set to dry for a few days, if it's dried in the sun it becomes yellow and if it's dried in the shade it remains white, it is important that the Jameed is dry to the core because any dampness can spoil the preservation process. However, before Jameed has been dry it contains about 75% water of its weight and it is preferred to be dried to about 10% by weight wet basis.

Knowing the initial and final moisture content of Jameed, its initial mass and the drying rate, one can calculate the time needed for drying using:

$$m_{w1} = M_{w1}/DT_1 \quad (91)$$

$$m_{w2} = M_{w2}/DT_2 \quad (92)$$

$$m_{w3} = M_{w3}/DT_3 \quad (93)$$

$$m_{w4} = M_{w4}/DT_4 \quad (94)$$

The mass of the initial water content in the product (M_w) at each tray depends on the mass of the product at each tray (M_f) and is calculated by:

$$M_{w1} = ((z_i - z_f)/(1 - z_f)) * M_{F1} \quad (95)$$

$$M_{w2} = ((z_i - z_f)/(1 - z_f)) * M_{F2} \quad (96)$$

$$M_{w3} = ((z_i - z_f)/(1 - z_f)) * M_{F3} \quad (97)$$

$$M_{w4} = ((z_i - z_f)/(1 - z_f)) * M_{F4} \quad (98)$$

The initial mass for each tray was taken to be 1 kg.

[1] Figure 3 shows the total irradiation on the solar collector and the walls of the drying chamber versus time. The peaks can be clearly seen at 1p.m.

Figure 3. Total Solar Irradiation.

a . Fluid flow

As the collector absorbed heat from the sun, the air above the black sheet is heated due to convection. The density of the heated air will decrease. Hence, the drying chamber will act as a vertical chimney, where the ambient air that has a higher density will replace the hot air. As a result a buoyancy force acts to produce a draft that will suck air from the collector depending on the temperature the heated air will reach and the pressure drop due to friction and trays as the air leaves the chamber.

A mathematical modeling based on Bernoulli's equation is used to estimate the system flow rate. Since the total pressure in the system is an atmospheric pressure, and the density change of the air is very small, Boussinesq

approximation states that density differences are sufficiently small to be neglected, except where they appear in terms multiplied by the acceleration due to gravity (g). The Bernoulli equation will reduce to:

$$\text{Draft} = g * (\rho_{\text{amb}} - \rho_{\text{ao}}) * L_{\text{ch}} = f * (L_{\text{e}}/D_{\text{h}}) * (\rho_{\text{ao}} * V^2/2) \quad (99)$$

In equation (99) the first term is the draft caused by the drying chamber and the second one is the pressure drop due to trays and total length.

Equation (99) becomes,

$$g * (\rho_{\text{amb}} - \rho_{\text{ao}}) * L_{\text{ch}} = C_{\text{Lch}} * (\rho_{\text{ao}} * V^2/2) + (0.5 * \rho_{\text{ao}} * C_{\text{tray}} * V^2) * 4$$

$$m_{\text{a}} = A_{\text{cs}} * (2 * g * L_{\text{ch}}/C)^{0.5} * ((\rho_{\text{amb}} - \rho_{\text{ao}})/\rho_{\text{ao}})^{0.5}$$

$$C = C_{\text{Lch}} + C_{\text{tray}} + C_{\text{Lc}} = f * L_{\text{ch}}/D_{\text{hch}} + 4 * C_{\text{tray}} + f * L_{\text{c}}/D_{\text{hc}}$$

Where the loss coefficient for the tray (C_{tray}) is assumed to be 2 and friction factor (f) for laminar flow ($Re_{\text{Dh}} < 2300$) is assumed to be 0.02.

$$D_{\text{hch}} = 2 * W * l / (W + l) \quad (101)$$

$$D_{\text{hc}} = 2 * a * b / (a + b) \quad (102)$$

As illustrated previously, formulas used to calculate the fluid physical properties at any temperature are given by empiric correlations fitted using air tables. The equations are:

$$\rho_{\text{ao}} = 360.77819 * (T_{\text{ao}} + 273)^{-1.00336} \quad (103)$$

$$\rho_{\text{amb}} = 360.77819 * (T_{\text{amb}} + 273)^{-1.00336} \quad (104)$$

$$\mu_{\text{ao}} = 3.3 * 10^{-7} * (T_{\text{ao}} + 273)^{0.7} \quad (105)$$

5. Results and Discussion

a. Solar Irradiation

Equations 1-16 were solved using EES software. It appears that the maximum solar irradiation on the collector equals 1025 W/m² and for the vertical wall of the chamber 405 W/m² at 1p.m. Table 1 shows the results for solar irradiation and ambient temperature calculated previously. It is clear that as the solar irradiation increases the outlet temperature from the collector increases. Hence, the temperature difference between the outlet air from the collector and the ambient temperature increases, and so the densities, resulting in increasing the buoyancy force and the mass flow rate of the air. Moreover, as the length of the solar collector increases the time at which the air is heated increases as shown in table 2. Hence, the air will be heated to a higher temperature, increasing the density difference.

Table 1. Solar irradiation and ambient temperature in Jordan for horizontal and vertical surfaces.

Time (hrs)	Ambient temperature (°C)	Direct radiation on the collector (W/m ²)	Direct radiation on the chamber (W/m ²)	Diffuse radiation on the collector (W/m ²)	Diffuse radiation on the chamber (W/m ²)	Reflected radiation on the chamber (W/m ²)	Total radiation on the collector (W/m ²)	Total radiation on the chamber (W/m ²)
8	20.532	287.0619	0.0	92.65098	16.92495	62.65262	379.7128	79.57757
9	21.858	486.7992	0.0	106.6862	28.45661	97.92509	593.4854	126.3817
10	23.388	661.4286	40.42868	113.7619	39.94283	127.9064	775.1905	208.2779
11	25.122	795.6015	109.936	117.5748	49.74723	150.6741	913.1763	310.3574
12	26.754	878.911	159.0214	119.4847	56.27654	164.7353	998.3957	380.0332
1	27.978	905.172	177.9454	120.0296	58.40569	169.1583	1025.202	405.5093
2	28.794	872.4636	163.6277	119.347	55.75902	163.6487	991.8106	383.0355
3	29.1	783.1801	117.1008	117.2636	48.80289	148.5732	900.4437	314.4769
4	28.794	643.9699	42.81773	113.1809	38.73065	124.9299	757.1508	206.4783
5	28.08	465.718	0.0	105.5921	27.16332	94.26616	571.3101	121.4295
6	26.958	264.4845	0.0	90.318	15.71061	58.54242	354.8025	74.25303

Table 4. Data considering the experimental solar collector.

Time (hrs)	Ambient temperature (°C)	Outlet temperature (°C)	Air mass flow rate (kg/s)	Temperature difference (°C)	Solar collector efficiency %
9	21.86	30.53	0.02482	8.668	37.95
10	23.39	33.74	0.02677	10.35	37.43
11	25.12	36.66	0.02792	11.54	36.94
12	26.75	39	0.02847	12.25	36.57
1	27.98	40.46	0.02854	12.48	36.38
2	28.79	41.02	0.02817	12.23	36.37
3	29.1	40.6	0.02733	11.5	36.53
4	28.79	39.06	0.02597	10.27	36.86
5	28.08	36.6	0.02387	8.518	37.26

Also the effect of changing the width of the collector on the outlet temperature and mass flow rate of the air is studied at different solar radiations as shown in table 3. Obviously table 3 shows that the temperature of the air slightly decreases while the mass flow rate of the air increase as the width of the collector increases. It is of various importance to achieve high air temperatures in drying systems in order to enhance the evaporation of water from the product. Moreover, increasing the mass flow rate of the air will enhance the mass transfer process of water from the product to the drying air. Figure 4 shows the relation between temperature difference of the ambient and the output of the solar collector versus the mass flow rate of the air. According to the solar collector considered in this study, data for the outlet air temperature, efficiency and mass flow rate of the air are given in table 4.

Figure 4. Mass flow rate of the air as function of temperature difference.

b. Drying chamber results

Theoretically, the temperatures at each point shown in figure 5 were calculated, in addition to the humidity ratio in each zone, using equations illustrated for the drying chamber. Figure 6 shows the results for these temperatures. Figure 7 shows the results of the humidity ratio in each zone at each time of the day.

Figure 6. Temperatures at each point in chamber.

Figure 7. Humidity ratios in each zone.

The mass flow rate of the evaporated water from the product differs at each time of the day depending on the mass flow rate of the air, air velocity, mass of product to be dried, initial and final moisture content and drying air temperature.

Results for drying rates at each hour of the day are shown in table 5. In table 5 the drying rate for each tray increases until 2 pm, after that the drying rate starts to decrease since the effect of the sun will start to diminish.

Time needed for products to dry completely, that is, reaching a final moisture content of 10% of its original mass, is a bit confusing; since the solution is based on steady state assumption, the drying time will be estimated considering that the product is subjected to the same solar radiation at all time and the temperatures at each point and humidity ratio at each zone are constant. Hence, giving an approximated time based on the average time at different solar radiations would give a good approximation. The drying time for each tray was sketched versus the time during the day (different solar radiations) based on table 6 as shown in figure 8.

Figure 8. Drying times for each tray at different solar radiations through out the day

According to the data determined in table 6, an approximated drying time for each tray having a mass of 1 kg and 20 particles of Jameed that need to be dried from 75% moisture content (wet basis) to 10% moisture content (wet basis) is shown in table 7.

Table 7. Drying time for each tray for a capacity of 1 kg.

	Tray 1	Tray 2	Tray 3	Tray 4
Drying time (hrs)	16.4	19.14	22.26	25.71

Table 5. Drying rates for each hour

Time (hrs)	Drying rate for tray 1 (kg/s)	Drying rate for tray 2 (kg/s)	Drying rate for tray 3 (kg/s)	Drying rate for tray 4 (kg/s)	Mass flow rate of the air (kg/s)
9	0.000007741	0.000006611	0.000005682	0.000004911	0.02482
10	0.00001001	0.000008628	0.000007485	0.000006533	0.02677
11	0.00001218	0.00001053	0.000009159	0.000008019	0.02792
12	0.00001398	0.00001208	0.00001051	0.000009195	0.02847
1	0.00001513	0.00001304	0.00001131	0.00000988	0.02854
2	0.00001556	0.00001335	0.00001154	0.00001003	0.02817
3	0.00001519	0.00001295	0.00001112	0.000009608	0.02733
4	0.00001394	0.00001177	0.00001001	0.000008573	0.02597
5	0.00001202	0.000009986	0.000008364	0.000007056	0.02387

Table 6. Drying time for each tray.

Time (hrs)	Total solar radiation on collector (W/m ²)	Total solar radiation on chamber (W/m ²)	Drying time for tray 1 (sec)	Drying time for tray 2 (sec)	Drying time for tray 3 (sec)	Drying time for tray 4 (sec)
9	593.5	117.9	93299	109240	127117	147050
10	775.2	243.1	72164	83706	96486	110543
11	913.2	344	59316	68610	78851	90058
12	998.4	408.2	51661	59792	68749	78544
1	1025	428.6	47739	55394	63843	73102
2	991.8	403.2	46408	54090	62609	71986
3	900.4	334.6	47532	55770	64970	75171
4	757.2	230.2	51802	61360	72148	84239
5	571.3	103.5	60109	72324	86351	102350

6. Conclusion

The mathematical modeling for a simple solar dryer was constructed, explained and solved using engineering equation solver software (EES). The solar dryer was used to dry Jameed. It is also applicable to dry any type of food product that is acceptable to be dried in direct contact methods (food with low concentration of fat), since the steady state drying process is very dependent on the film of moisture on the surface of the food. Thus knowing the initial mass of the food, its initial moisture content and desired moisture content will be enough to give an acceptable approximation of the drying time needed for the food.

The solar drying system can be optimized to calculate the dimensions of the solar collector to give a higher value of air temperature and flow rate. It is clear that the temperature and air flow rate increases as the length of the absorber increases. Moreover, the width of the collector is inversely proportional to the outlet temperature and directly proportional to air flow rate. In choosing the optimized dimensions one should remember the cost of the system that increases as the material's quantity used increases. Choosing the collector dimensions to be 0.1 m x 0.4 m x 3.0 m (height, width and length) would give a good optimization regarding the mass flow rate and temperature of the air in addition to the price of

the system, but it is not the perfect optimization. To evaluate the perfect optimization one should make use of the optimization techniques such as: Lagrange method, golden section method...etc, to optimize the system for any objective desired. System efficiency can be enhanced in many ways. Flat plate solar collector can be tilted to achieve a highest solar irradiation absorbed. Hundreds of solar collector designs were made, having a higher efficiency than that of the flat plate collector. Materials that are used for insulation can be used to achieve higher resistance of heat transfer. Multi-pass collectors used to achieve higher air flow rate with higher temperature. Drying chamber design can also be modified to enhance the efficiency of the drying system, starting by coating the walls with black paint for higher solar radiation absorption or insulate them for less heat losses to the ambient. Transforming the system from natural convection to forced convection will have a high effect on the drying rate of the products, thus improving the overall performance of the system. This can be done by adding a blower at the inlet of the collector. Blowers are a low demanding power devices thus consumes a small amount of electricity; this will make the system somehow more desirable.

Nomenclature

Units

a	Solar collector height	m
A	Apparent solar irradiation at air mass equal to zero	W/m ²
Acs	Cross sectional area of the solar collector	m ²
Af	Surface area of the food particle	m ²
b	Solar collector width	m
B	Atmospheric extinction coefficient	----
c	Ratio of diffuse irradiation on a horizontal surface to direct normal irradiation	----
C	Loss coefficient	----
Cpa	Specific heat of the air	J/kg.k
D	Diameter of food particle	m
Dh	Hydraulic diameter	m
Dhc	Hydraulic diameter of the collector	m
Dhch	Hydraulic diameter of the chamber	m
diff	Diffusivity of air	----
DT	Drying time	s
EOT	Equation of time	min
f	Friction factor	----
Fwg	Configuration factor of vertical surface	----
g	Gravity acceleration	m/s ²
G	Solar irradiation	W/m ²
h	Hour angle	deg
hf	Convection heat transfer coefficient between the air and the surface of the food at different trays	W/m ² .k
hfg	Latent heat of vaporization for water in the food at different trays	J/kg
hi	Convection heat transfer coefficient inside the solar collector	W/m ² .k
ho	Convection heat transfer coefficient of ambient wind	W/m ² .k
k	Thermal conductivity	W/m.k
kg	Mass transfer coefficient	Kg/m ² .s
l	depth of the drying chamber	m
L	Latitude angle	deg
Lc	Length of the solar collector	m
Lch	Length of the drying chamber	m
LCT	Local civil time	hrs
LST	Local solar time	hrs
m	Mass flow rate	Kg/s
M	Mass	Kg
ma	Mass flow rate of the air	Kg/s
N	Number of food particles on each tray	Particle
P	Pressure	Pa
Q	Heat transfer	W
ref	Reflectivity of the ground	----
s	Distance between trays	m
t	Thickness	m
T	Temperature	°C
V	Velocity	m/s
w	Humidity ratio	(Kg) _{water} /(kg) _{air}
W	Width of the drying chamber	m
X	Percentage of daily range	%
zf	Final moisture content wet basis	%
zi	Initial moisture content wet basis	%
Greek symbols		
α	Absorptivity	----
β	Expansion coefficient	K ⁻¹
γ	Solar surface azimuth	deg
δ	Sun's declination	deg
ε	Emissivity	----
θ	Angle of incidence	deg
λ	Solar altitude angle	deg
μ	Dynamic viscosity	N.s/m ²
ν	Kinematic viscosity	m ² /s
ξ	Tilt angle	deg
ρ	Density	Kg/m ³
σ	Steven Boltzmann constant	W/m ² .k ⁴
τ	Transmissivity	----
ϕ	Solar azimuth angle	deg
ψ	Surface azimuth	deg

Subscripts

a	Point at the entrance of the drying chamber
ai	Air inlet
amb	ambient
ao	Air outlet
b	Point at the entrance of the first tray
bs	Black sheet
c	Point at the exit of the first tray
d	Point at the entrance of the second tray
db	Design dry bulb
dH	Diffuse horizontal
dV	Diffuse vertical
D	Food particle diameter
DH	Direct horizontal
DV	Direct vertical
e	Point at the exit of the second tray
f	Point at the entrance of the third tray
F	Food
film	At film temperature
g	Point at the exit of the third tray
G	Glass
h	Point at the entrance of the fourth tray
H	Horizontal
i	Point at the exit of the fourth tray
ins	Insulation
ND	Normal direct
RV	Reflected vertical
s	saturated
sb	Surface of the black sheet
sf	surface of the food
sg	Surface of the glass
Tot,H	Total horizontal
Tot,V	Total vertical
V	Vertical
w	Water
wall	Walls of the drying chamber
wet	wet bulb temperature
z	zone

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