INFLUENCING OF SOLAR DRYING PERFORMANCE BY CHIMNEY EFFECT

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Abstract

The aim of this paper to study effect of a chimney installed in solar drying system. A chimney is device usually used to remove the air to the atmosphere. Free convection is obtained with using a chimney which permits to have a good air speed by free convection and homogeneous distribution of the heated air inside the drying chamber. It allows also having better control of the drying process.

The greenhouse effect achieved within the collector drives the air flow through the drying chamber. The hot air rises and escapes through the upper vent in the drying chamber (chimney) while cooler air at ambient temperature enters through the lower vent in the collector. Therefore, an air flow is maintained, as cooler air enters through the lower vents and hot air at a temperature leaves through the upper chimney vent.

Keywords

balance equation, control, convection, design, solar collector

1. Introduction

The use of the solar energy is getting a greater importance in the agriculture as because of the growing energy prices and the importance of the environment protection. At the same time the quality control and quality preservation becomes also more and more important items for processing of agricultural products. A traditional and very widely used product preservation is the drying. Main drawbacks of drying are the relatively high energy consumption and changing product properties during the heat and de-watering treatment. However, the attractiveness of drying methods can be improved by using advanced control and optimization techniques for reducing the energy consumption [1].

The chimney itself is the plant's actual thermal engine in most of the solar dryers using natural ventilation effect. It is a pressure tube with low friction loss (like a hydroelectric pressure tube or penstock) because of its optimal surface-volume ratio. The up thrust of the air heated in the collector is approximately proportional to the air temperature rise ΔTcollector in the collector and the volume of the chimney. In a large solar chimney the collector raises the temperature of the air by about 35 K. This produces an up draught velocity in the chimney of about 15m/s. It is thus possible to enter into an operating solar chimney plant for maintenance without difficulty. Chimneys 1,000 m high can be built without difficulty. The television tower in Toronto, Canada, is almost 600 m high and serious plans are being made for 2,000 metre skyscrapers in earthquake-ridden Japan. But all that is needed for a solar chimney is a simple, large diameter hollow cylinder, not particularly slender, and subject to very few demands in comparison with inhabited buildings. There are many different ways of building this kind of chimney. They are best built freestanding, in reinforced concrete. But guyed tubes, their skin made of corrugated metal sheet, as well as cable-net designs with cladding or membranes are also possible. All the structural approaches are well known and have been used in cooling towers. No special development is needed.

The principle of the solar chimney effect is a combination of solar stack-assisted and wind-driven ventilation. Air in the chimney expands due to solar heating and being relatively lighter, rises out of the chimney outlets, drawing the cooler air into the interior through the fenestrations. This pull effect is further complemented by the push effect from the ambient wind. The stack pressure difference driving

the air movement is a combination of the different densities between the interior and ambient environment as well as the stack height where the greater the stack height and temperature difference, the stronger the pressure difference. In solar assisted stack ventilation, the temperature difference is achieved from heat gained due to solar irradiance. Research has determined the operability of implementing solar chimneys in the hot, cloudy and humid tropics. This paper aims to discuss the performance of solar chimneys by varying the design parameters and examining their effects on the interior air temperature and speed.

Many different parameters affect the performance of the solar chimney. Solar irradiance is the most widely research parameter and also the most conclusive. Researchers find that air speed and temperature within the solar chimney increase with increasing solar irradiance. Within the interior, there is also a temperature drop and temperature lag. However, the value of solar irradiance is fairly constant during the hot tropical afternoon and the interior will already be thermally comfortable during low solar irradiance.

The inclination angle of the solar chimney is another widely research upon parameter, from fully horizontal to fully vertical. The greater the inclination angle, the higher the stack height, the lesser the flow resistance and the better the performance; however, the smaller the angle, the greater the exposure to solar irradiance and also the better the performance.

A chimney is device usually used to remove the hot flue gas or smoke to the atmosphere. It uses the stack effect to induce the movement. In buildings, the chimney also is used in natural ventilation, taking advantage of the differences of temperature between in-outside the building

A solar chimney is a kind chimney that uses the solar radiation to increase the temperature inside generating the stack effect to move the air. Usually it is used as a way to improve the natural ventilation for a building, solar collectors or solar drying technology. Also it can be used to generate electrical energy, but in this cases the size it considerably bigger, for example the solar tower built in Manzanares, Spain was 195 m high obtaining a maximum output power of 50 kW. This paper is focus only in the solar chimney as a way to improve the air speed in solar dryer.

There are significant number of papers are dealing with the investigation of the chimney effect in solar drying system as for example: Dawit et al. [2], Ekechukwu and Norton [3], Afriyie et al. [4], Elias [5] and Alex and Nyuk [6].

Ekechukwu and Norton [3] are represented the method to design and measure the performance of solar chimney used for natural-circulation solar energy dryers. The chimney that used consists of a 5.3 m high and 1.64 m diameter cylindrical polyethylene-clad vertical chamber, supported structurally by a steel framework and draped internally with a selectively absorbing surface. The performance of the chimney which was monitored extensively with and without the selective surface in place is also reported.

Alex and Nyuk [6] are tested the effect of the solar chimney's stack height, depth, width and inlet position on the interior performance as well as proposes an optimal tropical solar chimney design. The study shows that the output air temperature remains constant while the solar chimney's width is the most significant factor influencing output air speed. The solar chimney's inlet position has limited influence on the output air speed although regions near the solar chimney's inlet show an increase in air speed. To optimize solar chimney in the tropics, the recommendation is to first maximize its width as the interior's width, while allowing its stack height to be the building's height. Lastly, the solar chimney's depth is determined from the regression model by allocating the required interior air speed.

Because of the chimney effect concerning to the solar dryer a special attempt is carried out developing a low range air speed sensor for measuring natural ventilation during the solar drying process which can be used with a usual data logging system. Seres and Farkas [7] after choosing the working principle, they developed and constructed a one dimensional prototype of the sensor. Based on the measurements the optimal setting of the sensor was determined. Additionally, the set-up of a two dimensional sensor prototype is also presented, along with its measurement results.

Studying the flow conditions in a solar dryer, as the first step, the natural convection is to be studied due to the incoming solar radiation. In the applied model of Seres and Farkas [8] the collector was considered as a simple tube and in case of the low air speed of the natural convection the air flow is considered to be stationer.

The aim of this paper is to study the main parameters and characteristics for small air chimney that used with solar drying system.

2. Description of the solar dryer

On the basis of the explanations given before a small size dryer operated by solar energy seems to be

realistic in many reasons. Such a dryer can cover the drying demand of a single farm. It is not planned to use as a raw corn drying or to replace the large-volume oil and gas heating dryers used from the mass grain production. Taking into account the high energy prices, environmental considerations and that the equipment has to operate in the fields far from the electrical grid the use of solar energy was planned for the artificial ventilation.

The solar dryer planned for such purposes has three main parts:

–a dryer (drying cabin) with different trashes for the different products. A trash holder with 4 trashes was developed for the surface drying when the product is too fine to flow the drying air through it. In this case the trash holder forces the air to flow above the product. Another trash holder with 7 trashes was developed for bulk drying, when to air flows through the product layers. The drying cabin has a size of about 0.8 m x 1 m x 0.65 m, and it has four legs with the height of 1 m.

–a PV module with the maximum power of 2x20 W and an electrical fan for artificial air circulation. The PV unit is installed in the front side of the dryer with changeable elevation angle, suitable to the different angle of the sunshine in the different periods of the year. Two switches allow the fan use at half or at whole power of the PV module.

–an air solar collector of about 1 m² attachable to the dryer for preheating the inlet air. The solar collector has the size of 2 m x 0.5 m x 0.2 m. It has a transparent cover on the top and thermal insulation at the bottom side. For the better energy reception a perforated plastic absorber plate was installed on the half height of the collector body.
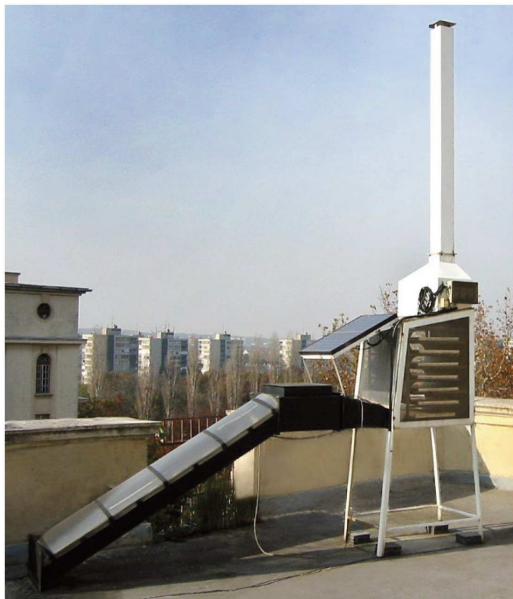

Figure 1. The solar drying system

Because of the modular construction of the dryer it can be operated in different modes:

–Natural ventilation of ambient air. To assist this operating mode a chimney was planned to strengthen the air flow which is installed in the top of the drying cabin.

–Artificial ventilation of ambient air when the PV module is applied.

–Artificial ventilation of the drying air preheated by a solar air collector.

–The combination of the above modes can also be used.

The layout of the solar dryer studied in this paper is shown in Fig. 1 [9].

3. Modelling of the air flow

The chimney increases the amount of air flow, through the solar dryer by speeding up the flow of the exhaust air. Hence the effects of natural convection will be improved by adding a chimney in which exiting air is heated even more and enhance the buoyant flow of air. This will have a vital role to the overall design of solar dryers. Some study showed that the installation of three small fans and a photovoltaic cell is equivalent to the effect of a 12 m chimney. However, due to the air passing through the drying food item pick moisture and it possess a high relative humidity, its temperature may reach equal or lower than ambient (Figure 2). In such a case the generation of buoyancy force will be insignificant. To improve such conditions, heating the solar chimney above the ambient temperature would be advisable. The chimney should be designed so that the rate of heat losses within the chimney should be considered in determining the optimum height of the chimney so as not to exceed the height at which the chimney air cools to same temperature as ambient. The design will maintain mean chimney temperatures above ambient temperature.

Buoyancy is the force, along with the gravity, involved in the movement to upper positions of an object or fluid with less density than the fluid surrounding. In ideal gases when the temperature increases, the density decrease, thus a movement between the cold and warm zones appears. This movement is knowledge as Stack effect. The pressure difference of the stack effect is shown in the below equation:

$$\Delta P_{Stack} = g\,H\,\Delta\rho, \tag{1}$$

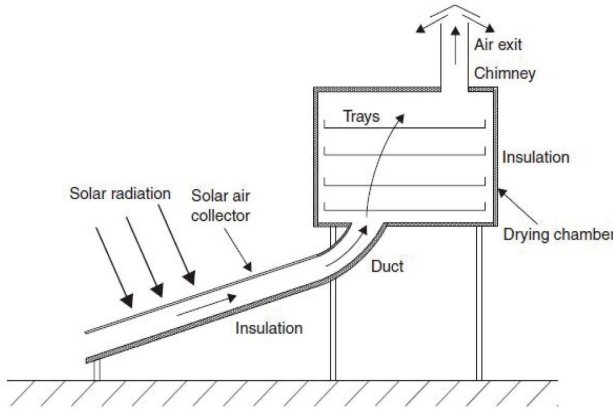$$\Delta P_{Stack} = \rho\,g\,H\,(\Delta T/\,T_i). \tag{2}$$

Figure 2. Schematic diagram of solar drying system

In the convectional solar dryer there are two basic conditions of air flow:

1. No flow condition: In this condition the air temperature and humidity inside the chimney and outside i.e. the ambient is similar. In this case there is no density difference hence there will be no flow through the chimney.

2. Flowing condition: In the flowing condition on the other hand, the mean temperature inside the chimney is relatively higher than the ambient air temperature. In this case, there exists a pressure head which creates an upward air flow. Therefore the relation among the buoyancy force that is the pressure drop that creates the air flow, the height, density difference of the ambient air and chimney is related as follows.

$$\Delta P_b = g H (\rho_a - \rho_{ch}). \qquad (3)$$

The pressure difference due to the buoyant pressure head in term of temperatures is given by:

$$\Delta P_b = g H \beta \rho (T_{ch} - T_a). \qquad (4)$$

Over the temperature range 25-90°C (within which natural-circulation solar-energy dryers would operate), the density of dry air is related to the temperature by the following empirical expression

$$\rho = 1.11363 - 0.00308\ T. \qquad (5)$$

By substituting equation (5) in (4), get:

$$\Delta P_b = 0.00308\ g H (T_{ch} - T_a). \qquad (6)$$

Within the chimney, pressure drops are due mainly to wall friction. Assuming turbulent flow (with a friction coefficient of 0.035), the pressure drop due to friction loss can be given as:

$$\Delta P_b = 0.035\ \dot{\rho}\ (v^2\ H\ /\ 2\ D), \qquad (7)$$

where $\dot{\rho}$ is the average density of fluid through the cylindrical duct (corresponding to the mean chimney air density for the case of the solar chimney). Combining equations (6) and (7),

$$0.035\ .\ \dot{\rho}\ (v^2\ H\ /\ 2\ D) = \\ = 0.00308\ g H (T_{ch} - T). \qquad (8)$$

Thus,

$$v = 0.453\ (D\ g\ \Delta T_{ch}\ /\ \dot{\rho})^{\frac{1}{2}} \qquad (9)$$

as shown in above relation, the velocity is a function of temperature change across the chimney. It should be noted that the above expression is derived without taking into account the additional buoyancy arising from the increased humidity of the air stream. To include this would require assumptions to be made concerning the amount of moisture added to the air stream. The out let area or diameter of the chimney is designed as follows: Assuming no loss, the velocity of the air passing through the chimney.

$$m_a = (\pi/4)\ D^2\ v\ \rho_a. \qquad (10)$$

Then the mass of the air flowing through the cross-section of the chimney is given as follows:

$$m_a = A\ v\ \rho_a. \qquad (11)$$

During designing chimney of solar dryer, the most important emphasis should be on keeping the air temperature inside the chimney relatively higher than the ambient temperature. However; pressure drop due to the wall friction is commonly negligible. Therefore, an efficient solar chimney is designed to have mean inside temperature that is above the ambient air temperatures during operation.

4. Energy balance on the collector

In solar collectors the incident solar energy is partially absorbed in the glass and absorber surface, some amount of this energy is transferred to the fluid inside the collector and the remaining is lost to the environment. Thus an energy balance is developed basically that the useful energy gain is the difference between the absorbed solar energy and the thermal losses as shown in figure 2. Then it is solved by equating the total heat gained by the absorber to the total heat loss of the solar collector. Then, it is expressed as follows.

$$I A_c = Q_u + Q_{cond} + Q_{conv} + Q_{rad} + Q_{ref}. \quad (12)$$

To audit all the energy balance the following heat components must be considered. The incident solar radiation (I), top heat loss coefficient, coefficient of convective heat transfer between cover and air, coefficient of convective heat transfer between plate and air (Q_{conv}), coefficient of radiation heat transfer between plate and cover (Q_{rad}.), bottom heat loss coefficient, ambient temperature, collector air temperature and mean plate temperature.

The flat plate solar collector with size 2 m x 0.5 m x 0.2 m has been tested. The solar collector connected to the dryer chamber to heat air flow stream that will enter the chamber. It has a transparent glass cover fixed on the top edges of the solar collector box and good thermal insulation at the bottom base and sides of the metal box. For the better energy collection a black absorber plate was put on the half height of the collector body box. The solar collector in this work is oriented facing south line and tilted at 45o to the horizontal according to the solar chart for Budapest region. To get more absorption of solar radiation and radiation reflection reduction, absorber plate painted with matt black colour.

5. Efficiency of solar dryers

Commonly the efficiency of solar dryers is evaluated either based on the thermal performance or the drying rates (system drying efficiency) of the products. The thermal analysis of a solar collector is quite complex. However, according to the ASHRAE 93-77 standard, the thermal performance of the solar collector is determined in part by obtaining values of instantaneous efficiency for a combination of values of incident radiation, ambient temperature, and inlet fluid temperature. This requires experimental measuring the rate of incident solar radiation on to the solar collector as well as the rate of energy addition to the transfer fluid as it passes through the collector, all under steady state or quasi-steady state conditions. Therefore the instantaneous efficiency of a collector is expressed as follows:

ηc = useful energy collected / incident solar energy.

When the useful energy is expressed in terms of mass flow rate and the change in temperature the collector efficiency is stated as follows.

$$\eta_c = m_a C_p (T_o - T_i) / I A_c. \quad (13)$$

The other important measure for efficiency of solar dryers is the drying rate or the system drying efficiency. The system drying efficiency is defined as the ratio of the energy required to evaporate the moisture from the product to the heat supplied by the drier.

$$\eta_d = m_w h_{fg} / I A_c. \quad (14)$$

Balance equation for the evaporation of water from the products inside the dryer system is

$$W L = m_a c_p (T_1 - T_2). \quad (15)$$

From the above relations, the rate of water evaporated from the products inside the drying chamber related with air velocity inside the drying chamber. The objective of chimney is to increase the velocity of air naturally then will increase the efficiency of drying. From this point, the chimney gets the importance. So, getting good air speed for which product depends on chimney design.

6. Conclusion

The rate of water evaporated from the products inside the drying chamber related with air stream velocity inside the drying chamber. The objective of chimney is to increase the velocity of air naturally then will increase the efficiency of drying. From this point, the chimney gets the importance. So, getting good air speed for which product depends on chimney design (air flow area). But the increasing of air speed more than limits, will give bad side effects for some products.

In the flowing condition on the other hand, the mean temperature inside the chimney is relatively higher than the ambient air temperature. In this case, there exists a pressure head which creates an upward air flow. The velocity is a function of temperature change across the chimney. It should be noted that the above expression is derived without taking into account the additional buoyancy arising from the increased humidity of the air stream. To include this would require assumptions to be made concerning the amount of moisture added to the air stream.

Nomenclature

A	absorber area of solar collector	m^2
C_p	specific heat at constant pressure	kJ/kg.K
D	duct diameter	m
g	acceleration due to gravity	m/s^2
H	height	m
h_{fg}	enthalpy	kJ/kg
I	incident solar radiation	W/m^2
L	latent heat of vaporization of water	kJ/kg
m	mass flow rate	kg/s
P	pressure	Pa

Q	heat transfer rate	W
T	temperature	K
v	velocity	m/s
W	water mass evaporated from product	kg/s

Greek letters

β	bulk coefficient of expansion of air	1/K
Δ	change	----
η	efficiency	----
ρ	density	kg/m^3

Subscripts

a	air
b	buoyancy
c	collector
ch	chimney
d	dryer
i	inlet
1	input
2	output

Acknowledgements

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