THE MULTI-COMMODITY HEAT PUMP DRYER

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Abstract: A multi-commodity heat pump drying (MCHPD) system was designed, fabricated, assembled and evaluated following basic refrigeration and air-conditioning. The drying chamber sized 1.22 m x 2.43 m x 1.22 m, and, dehumidifier with 2hp rotary, heavy-duty compressor; air-cooled type condenser; 2.0°C TD evaporator; thermostatic expansion valve and attached- filter dryer. The system has a maximum 50°C operating temperature and minimum 10% drying air to favorably dry heat sensitive commodities. Onion as a sample commodity is presented to evaluate the drying, thermal and dehumidifying efficiencies of the system. Moisture content was reduced from 83.0 % to 15.0% and satisfactorily dried for 33.0 hours with 0.029 kg/hr moisture reduction. Drying time and moisture loss was highly significant at R^2 =0.97. Drying efficiency was 37.83 %, higher than the reported 33.0% efficiency by Canmet, 1988. The specific moisture extraction rate (SMER) described the total energy used during the process was the accumulated heat from the drying air and latent heat released from onion converted to sensible heat. Refrigerant 134a's coefficient of performance (COP) calculated 97.34 % thermal efficiency meeting the claim of Ragupathy (2004) that, the drying process of the system is circulatory, hence, approaches 100%. The relative humidity of the ambient and drying air described 67.03% dehumidifying efficiency. The high efficiencies of the system meant that its configuration was very efficient in producing a dehydrated onion safe for storage with reduced color degradation.

Keywords: latent heat, sensible heat, drying efficiency, thermal efficiency, dehumidifying efficiency

1 INTRODUCTION

A lot of energy is used in air conditioning. Utilization of the heat rejected by refrigeration and air-conditioning systems is a promising technology. This is actually unwanted heat, and when recovered can be used efficiently to dry heat sensitive yet high value commodities. The recovered air is clean, low in temperature and relative humidity thus favorable in retaining the nutritional values embedded in the food product and can improve the overall efficiency of the system

Drying systems integrating a dehumidification cycle, such as the heat pump drying system has been developed. This would conserve energy and handle the product gently. It operates according to a basic air conditioning cycle involving five major components: the evaporator, compressor, condenser, expansion valve and the drying chamber.

At first, establishing the system seemed prohibitive because of the financial investment in procuring the major components and probably the thought that high grade energy which is electricity is to be used. However, the expected results would be:

Total energy (sensible heat) = latent heat + heat from the drying air (1)

2 SIGNIFICANCE OF THE STUDY

The technology is already proven; however as space cooling during summer likewise for heating during winter in countries, such as Canada, Australia, and the United States. In the Philippines, particularly in Cebu City, heat pump for drying applications was used to demonstrate fruit drying as part of the ASEAN-CANADA Project on Solar Energy in Drying Processes. Based on the testing and evaluation, the heat pumps performed better in terms of energy efficiency than the present system of drying fruits using Liquefied Petroleum Gas (LPG). Based on the heat pump used for fruit drying, the energy cost per kg water removed is PhP 0.57 compared to the existing systems of PhP 2.83 to 2.68 (Chou, 1996).Presently in the locality there is no existing equipment being used. In fact one of the dryers evaluated and demonstrated for fruit drying in Cebu City has been transferred to Thailand. In the region, there are lots of potential produce. If these could be processed using the technology, market driven products will be developed thereby problems on food losses will be addressed. Thus there is a need to design, fabricate and evaluate a system that would offer the following advantages as reported by Chou (1996): ensured hygienic process of drying; enable consistent product capacities of the food product; improve the overall energy efficiency of the drying process; longer period in the retention of product flavors; reduction in the color degradation of the food product when dried under the most favorable drying conditions and reduction in the loss of thermal sensitive vitamins embedded in the food product.

3 OBJECTIVES OF THE STUDY

Generally, the study aimed to design, fabricate, assemble and test a multi-commodity heat pump dryer.

Specifically:

1. To design a system using the basic principles of refrigeration and air - conditioning;
2. To fabricate a drying chamber insulated with locally available materials and assemble a dehumidifier with major components such as a refrigeration/ air conditioning system;
3. To organize a dehumidifier and a drying chamber into heat pump system that can attain a maximum operating temperature of 50°C and minimum relative humidity of 10% favorable in drying heat sensitive commodities; and
4. To test the drying, thermal and dehumidifying efficiencies of the system, various heat sensitive commodities were used.

4 LITERATURE REVIEW

Heat pumps are refrigeration machines that involve the removal of heat from a place where it is not wanted and depositing in a place where it makes little or no difference. The heat can be deposited in a place where it is wanted as a heat reclaim (Whitman and Johnson, 1995).A heat pump is an appliance that extracts heat from one environment and discharges it into another. Most heat pumps are powered by an electric motor, but can be powered by a fuel burning motor, as some camper refrigerators are. In heating mode, a heat pump will collect heat from the outdoor unit (condenser) and discharge it inside through the air handler. With the help of the expansion valve, the flow of refrigerant moves in the opposite direction and heat is extracted from the air handler and discharged to the drying chamber through the air handler (Warmair.com).Considerable research effort has been devoted to the application of heat pumps in different industries. Owing to their ability of delivering more energy as heat than they consume as input work, many applications have been found for the vapor compression heat pumps. Chou (1996) further mentioned that the potential of incorporating the heat pump system into the drying system arises from its ability to recover latent heat from the dryer exhaust air. As air moves across the drying chamber, it is laden with latent heat as it removes moisture from the drying product. This humid air if directly vented to the atmosphere would result in the loss of the latent heat of vaporization of this moisture content. The role of the heat pump is then to convert part of this latent heat to sensible heat for raising temperature at the inlet air to the drying chamber, resulting in significant improvement in the overall efficiency

5 METHODOLOGY

5.1 Design Considerations

The following considerations were taken into account during the deign process: a) the surrounding condition, that is, the climatic factors of the area where the facility will be installed; b) product data, this refers to the details of the commodities to be dried and evaluated using the facility; c) product management- this refers to the mode on how the products will be dried inside the drying chamber; d) insulation of the drying chamber- this considered the insulation materials used during the fabrication and assembly; and e).total heat load estimation using the following equation:

Total Heat Load (THL) = ERSH+ ERLH (2)

Where:

ERSH = effective room sensible heat gain
ERLH = effective room latent heat gain

5.2 Actual Heat Load (ACL) = THL/td (3)

Where: THL = total heat load, KJ/hr; Td = total drying time

5.3 Individual Component Design

a. Evaporator Design
b. Compressor Design
c. Condenser Design

6 INSTRUMENTATION

6.1 Thermocouple Wires TT-20 (Copper Constantan)

Ten stations with thermocouple wires (copper constantan) were installed to measure the dry bulb and wet bulb temperature inside the chamber (Fig 1). The mean of dry bulb temperature readings was computed and was considered as the inside drying temperature of the chamber. Relative humidity (RH) was determined by using an online RH calculator where the dry bulb and wet bulb temperature readings were the variables.

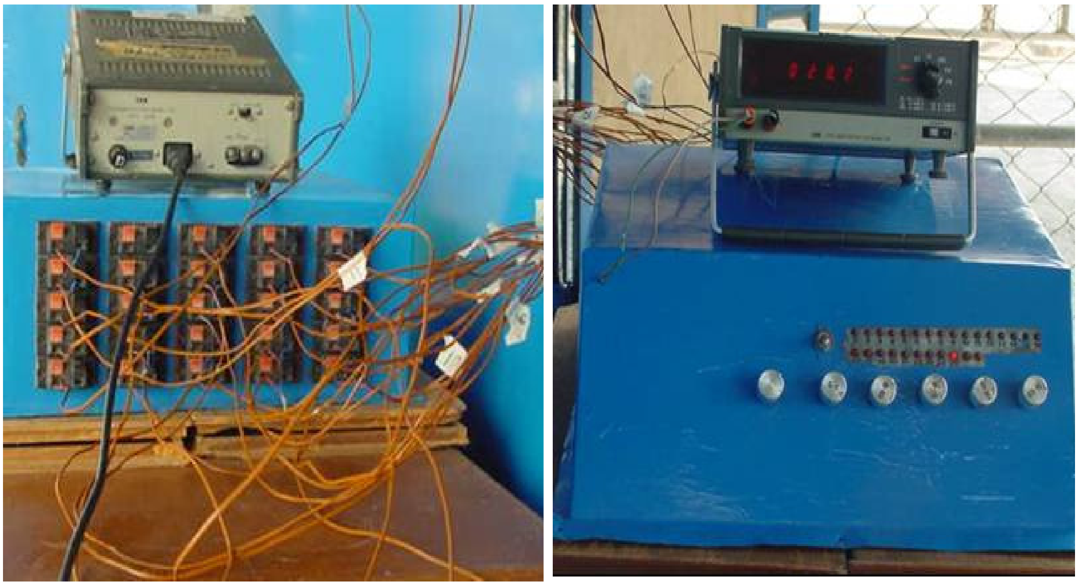


Figure 1. Rear and front views of installed thermocouple wires connected with a channel selector and digital thermometer

6.2 Abbeon Hygrometer

Three were strategically installed inside and outside the drying chamber to measure actual relative humidity (Fig 2).

Figure 2. Abbeon hygrometer installed inside and outside the system

6.3 Improvised Moisture Content Meter

An improvised moisture meter with copper coil and submersible pump assembled to measure the actual moisture content of the system set up at the exhaust (Fig 3).

Figure 3. Improvised actual moisture content meter

6.4 **Anemometer**

Inside air flow rate was measured by a digital anemometer AM- 4200 Lutron validated by an analog type vane anemometer (Fig 4).

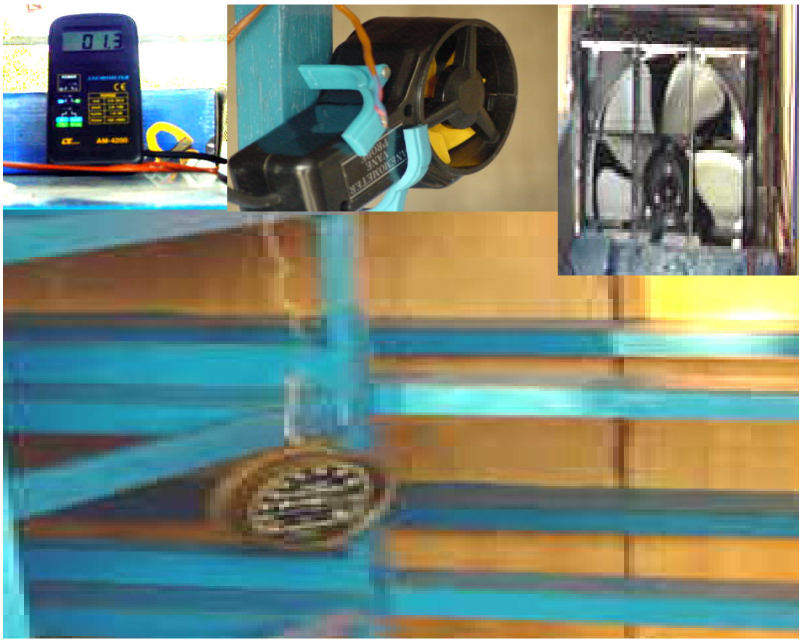


Figure 4. The vane anemometer

6.5 **Watt-hour meter**

Installed and attached at the left side of loading door area to register energy consumption of during every drying activity (Fig 5). The energy consumption was computed into peso equivalent using equation 10.

Figure 5**.** Watt-hour meter installed outside the drying chamber

7 FINAL TESTING AND EVALUATION

The process flow for the final testing and evaluation was followed using Fig 6. Fresh onions of excellent quality were bought at the local super market. This would ensure an excellent dried onion product. The samples were cleaned and cut to a desired size of 1/8 inch recommended by Cuaresma (1989) using a stainless knife. The cut samples were weighed to 1000.0 g as the fresh weight of the sample and were put on the 21 fabricated trays. The total number of samples were 21.0 kg and at 1000.0g per tray. When all the trays were filled with samples, drying activity started at 0 hour and weighing was done every hour thereafter. Data monitored were loss weight and reduction in moisture content (%MC). When three consecutive similar data were recorded, drying activity ended. The dried onions were packed and stored in a cool dry place for safe storage.

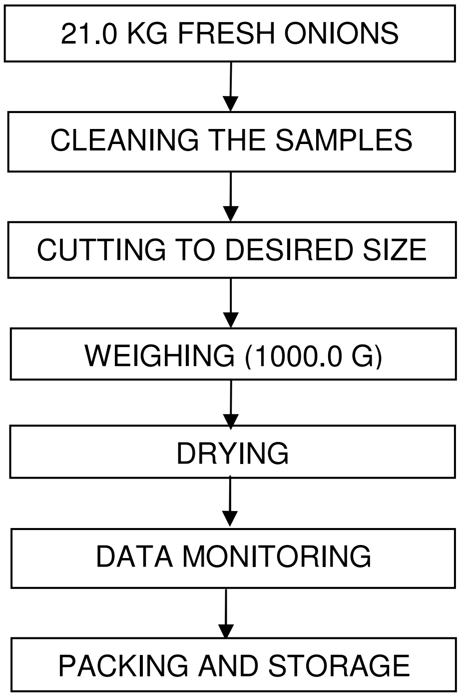


Figure 6. Flow of activities used in the final testing

7.1 Parameters Analyzed

7.1.1 Drying Efficiency of the HPDS (HPDE)= 1/SMER (4)

Where: SMER = amount of water evaporated/energy used (5)

7.1.2 Thermal Efficiency of the HDPS (HPTE)

HTPE = COP of the refrigerant (6)

Where:COP = coefficient of performance of the refrigerant used

7.1.3 Dehumidifying Efficiency of the HPDS (HPDHE)

$$HPDHE = \frac{RHa - RHd}{RHa} \times 100 \quad (7)$$

7.1.4 Mean Drying Rate (MDR) = $\frac{m_i - m_f}{t_d}$ (8)

Where: MDR = mean drying rate, % MC per hour; mi= initial MC %;
mf= final moisture content of % ; td= total drying time, hr

7.1.5 Moisture Reduction Per Hour(MRH) = $\frac{Wi - Wf}{t_d}$ (9)

Where: MRH = moisture reduction per hour, kg/hr
Wi = initial weight of onion, kg
Wf = final weight of onion, kg;
t_d = total drying time, hr

7.1.6 Energy Cost (EC) = Pc x Cw (10)

Where: EC = energy cost, P; Pc = power consumption, kW;
Cw = cost per kilowatt, Php

7.1.7 Moisture Content Determination

$$\% MC\ wb = Wm / Wm + Wd \quad (11.1)$$
$$\% MC\ db = Wm/Wd \quad (11.2)$$

Where: Mc = moisture content, %; Wm =wt of sample, g;
Wd = wt of the dry, g
Wm + Wd = weight total, g

8 DATA ANALYSES

Recorded data were statistically analyzed using means and graphs and were interpreted using Windows Excel Program.

9 RESULTS AND DISCUSSIONS

9.1 The MCHPD

Table 1 shows the computed heat load of each of the parameter considered in computing for the actual heat load and actual heating capacity of the system. The values were used as basis in the designing the sizes of the individual components of the system. The basics of refrigeration and air-conditioning principles were strictly followed during the design process so as to ensure an excellent drying system. The values of each parameter were calculated using equations (2) and (3).

Table 1. Summary of heat load estimation of the heat pump drying system

PARTICULARS	HEAT LOAD
Heat Gain through walls, ceiling and flooring	894.18 kJ/hr
Sun Gain-Glass	15.39 kJ/hr
Lighting Heat Gain	53.81 kJ/hr
Effective Room Sensible Heat Gain(ERSH)	213.73 kJ/hr
Heat Gain through Outside air (by passed)	68,562.98 kJ/hr
Heat Gain from Latent Heat of Vaporization of Onion	192019.08 kJ/hr
Effective Room Latent Heat Gain(ERLH)	260582.06 kJ/hr
Total Heat Load	260795.79 kJ/hr
Actual Heat Load	7902.90 KJ
Actual Heating Capacity	0.024 TR

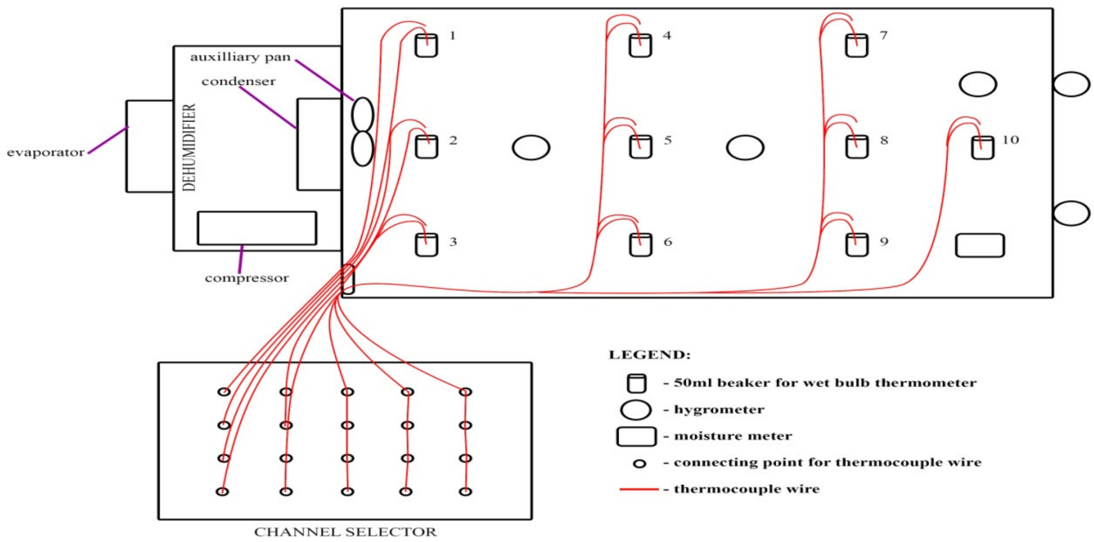
9.2 Fabrication of the Drying Chamber and Assembly of the Dehumidifier

Specifications of the system are shown in Table 2. The computed specifications were needed as guide in the procurement and assembly of the individual components of the dehumidifier (A) and the fabrication of the drying chamber (B). Both compartments were insulated with marine plywood as the inside insulation, styropore as the middle insulation, and GI sheet as the outside covering. Compartments A and B was put together making up the multi commodity heat pump drying system.

Table 2. Specifications of the heat pump drying system

PART/UNIT	SPECIFICATION
Dehumidifier	
Compressor	2.0 hp, heavy duty- rotary type
Condenser	11 rows, 43 tubes, air- cooled natural convection
Evaporator	0.64 m, 0.47 m,0.29 m, DC, TD = 2 ℃
Expansion	54.0 KPa, , 60 psi, thermostatic valve
Refrigerant	134-A, non CFC environment friendly
No. of blower	1 auxiliary fan
Drying chamber	
Size	Volume =3.62 $m^{3.}$
Drying trays	21 pieces, 0.37 m x 0.42 m
Insulation Materials	Marine plywood, thickness, 63.50 mm Thermal conductance, 9.09 W/m^2- K. Rubberized styropore, thickness, 50.0 mm Thermal conductivity , 0.028 W/m-K

Figure 7 shows the multi-commodity heat pump drying system and how it works. It is an air-to air system that functions like a domestic refrigerator. Dry heated air is supplied continuously to the product or sample being dried to pick up moisture and is recirculated. Some of the humid air that is drawn from the product passes through the evaporator where it condenses, giving up its latent heat of vaporization and is taken up by the refrigerant in the evaporator. The heat is used to reheat the cool dry air passing over the hot condenser of the system. The latent heat recovered in the process is released at the condenser and is used to reheat the air within the dryer. The system is entirely circulatory. The locations of the thermocouples, hygrometers installed inside and outside the drying chamber and the moisture meter is shown in Figure 7. The thermocouples have two ends that measured the dry and wet bulb temperatures. The provision for the wet bulb was wrapped with a cheese cloth and submerged into a 50-ml beaker with distilled water. The data gathered from both were used to compute % relative humidity using a psychometric calculator. The hygrometers installed inside and outside the drying chamber were used to validate the calculated value using the psychometric calculator. The improvised moisture content meter was used to collect the moisture released from the commodity being dried.



Fiigure 7.Schematic diagram of the multi-commodity heat pump drying system

Figure 8 shows the energy reduction and recovery of the heat pump system. The recovered energy from the environment could be used to simultaneously heat and cool a space. Likewise, it's application in the food industry both for multi commodity drying and cooling applications.

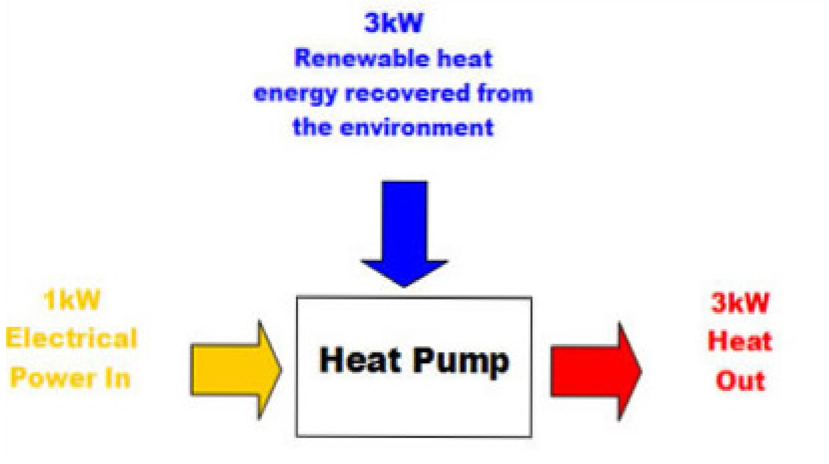


Figure 8. Schematic diagram of the system showing energy reduction and recovery

9.3 Final Testing and Evaluation

Table 3 lists the summary of results using onion as the test commodity in the evaluation of the drying, thermal and dehumidifying efficiencies of the system. Results showed that the multi-commodity heat pump drying system was very efficient in processing primarily a newly developed onion reduced from an initial 83.0 % to 15% MC which is within the recommendation of Adapa, et al (2002). The drying efficiency of the system was higher (37. 83 %) than the 33.0% recommended by Chou (1996). This would mean that the configuration of the system was very ideal. Likewise, thermal efficiency that is, 97.34%, of the system was within the recommendation of Ragupathy, 2004 (approaches 100.0%). This would further explain that the proper selection and use of the rotary compressor was very efficient in achieving an efficient thermal condition of the system. The dehumidifying efficiency of 67.0 was also very efficient in producing an onion with enhanced color retention (Fig 8a and 8b). The dried onion can be processed further as an ingredient to other products.

Table 3. Summary of results of onion drying using the MCHPD

PARTICULARS	RESULTS	STANDARD/IDEAL
Initial mass	1.0 kg	
Final mass (average)	0.03770 kg	
Desired sample size for drying	1/8 inch	1/8 inch , (Cuaresma,1989)
Specific heat of onions before drying	3.81 kJ/kg	
Initial Moisture content	83.0%	
Heat pump drying system	15.0%	Below 18.0% for safe storage (Adapa, et al, 2002).
Drying Time	33.0 hours	
Drying Temperature	35-50 °C	35-50 °C (Chou, S 1996)
Relative Humidity	10-30 %	10-30 % (Chou, S 1996)
Total Energy used	36.4 kW/h	
Weight of water removed	0.9623 kg	
Drying efficiency	37. 83 %	33.0%, Cammet (1881)
Specific Extraction Rate(SMER)	0.026 kg/kW –hr	
Mean drying rate(MDR)	2.05 %MC/hr	
Moisture reduction	0.029 kg/hr	
Thermal efficiency	97.34%	Approaches 100.0%, Ragupathy2004)
Dehumidifying efficiency	67.0 %	


Figure 9a. Fresh onion before drying


Figure 9b. MCHPD dried onion

10 SUMMARY

The heat pump drying technology has been applied to various industries, such as the textile, paper and timber industries. However, in the Philippines, particularly in the locality, the dryer is suited in drying different agro-industrial products.The system is capable of low temperature drying applications from 15^0 C to 50^0C. It also has control over the relative humidity of the air entering the drying chamber as low as 15 - 30%. Chou (1996) reported that application of the system would offer the following:

- ensuring hygienic process of drying
- enable consistent product capacities of the food product
- improve the overall energy efficiency of the drying process
- longer period in the retention of product flavors

- reduction in the color degradation of the food product when dried under the most favorable drying conditions
- reduction in the loss of thermal sensitive vitamins embedded in the food product

The compressor acts as the engine of the system wherein heat released after the condenser was converted into sensible energy. The sensible energy was clean in the sense that the dehumidifier was made into a separate chamber where it houses the major components of the system. The auxiliary fan was located at the outlet joining the dehumidifier and the drying chamber (Figure 7). In this way, the hot air coming from the condenser is free of dirt, however, the system is being cleaned using a vacuum cleaner every after drying activities.

11 RECOMMENDATIONS

1. The designed heat pump drying system successfully dried onions, it could be used to various dry other heat sensitive crops.
2. Evaluation of other design parameters such as size and capacity of the drying chamber used with another set-up of the dehumidifier must be undertaken.
3. To improve the distribution of the drying air within the system, further studies on the location of the auxiliary fan that draws conditioned air from the condenser must be undertaken.
4. For future investigations, use a double stage heat pump dehumidifier.
5. Further studies of a more advanced instrumentation within the drying system must be undertaken.
6. The design of a multi-commodity heat pump **dryer-cooler** is one of the best upgrading to be done to use both the cooling and drying potential of the system.

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