Uplift of Renewable Air Energy Quality by Heat Pump Technology for Biomaterial Drying in South African Climate Conditions

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***Abstract*—Experimental optimization of an air source heat pump for drying fruits was conducted by varying the refrigerant charge, condenser fan speed and the ambient conditions to obtain the optimum operating parameters of the heat pump and the dryer as a single integrated unit. The results showed that, the Coefficient of Performance (COP) of the overall system and the cycle increased with the increase of condenser fan speed, ambient temperature and refrigerant charge. However, at high refrigerant charge and speed of the condenser fan, the COP of the overall system decreased because of the decreased heating capacity possible due to accumulation of refrigerant in the condenser and increased fan power consumption, respectively. For the developed system, the optimum refrigerant charge was observed to be 1650 grams and 840 rpm of condenser fan speed (60% of the full speed) and the appropriate operating ambient temperature of 20 ℃. At this point, the COP of the overall system and the heat pump cycle were 3.75 and 5.20, respectively.**

***Index Terms*—air energy, heat pump, COP**

I. Introduction

South Africa's climatic conditions generally range from Mediterranean in the south-western corner of South Africa to temperate in the interior plateau, and subtropical in the northeast. A small area in the northwest has a desert climate. Most of the country has warm, sunny days and cool nights. There is very little difference in average temperatures from south to north, for example, the average annual temperature in Cape Town is 17 ℃, and in Pretoria, 17.5 ℃, although these cities are separated by almost ten degrees of latitude. Climatic conditions vary noticeably between east and west, air temperatures in Durban, on the Indian Ocean, average nearly 6 ℃ warmer than temperatures at the same latitude on the Atlantic Ocean coast. Maximum temperatures often exceed 32 ℃ in the summer, and reach 38 ℃ in some areas of the far north. The coldest temperatures have been recorded about 250 kilometres northeast of Cape Town, where the average annual minimum temperature is -6.1 ℃. The climate conditions in South Africa are shown as in Fig. 1. Therefore, compared to the temperature profiles of the rest of world, the air temperature is relative higher.

Manuscript received July 25, 2015; revised January 6, 2016.

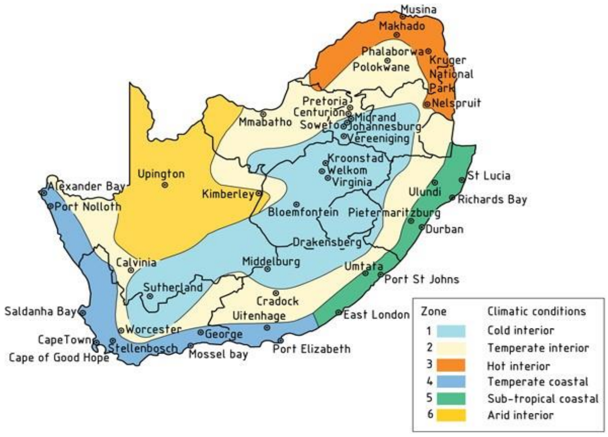

Figure 1. Climate conditions in South Africa

Recently, it has been discovered that, the use of heat pumps for drying purposes is an efficient method of energy utilization with significant contribution to energy conservation and mitigation of greenhouses gas emissions [1]. The drying of fruits is a subject of great importance, dried fruits have gained commercial importance and their growth on a commercial scale has become an important sector of the agricultural industry. Lack of proper processing causes considerable damage and wastage of seasonal fruits in many countries, which is estimated to be 30–40% in developing countries [2]. It is necessary to remove the moisture content of fruits to a certain level after harvest to prevent the growth of mould and bacterial action. For example, commercially, banana is supposed to be dried to less than 20% final moisture content for quality long storage. It is possible at such a level of moisture content, dried banana slices can have a shelf life of at least 6 months [3]. Therefore, this research proposes a choice of using a vapour compression heat pump cycle for drying sub-tropical fruits. Fruit drying using a heat pump drying system could reduce energy cost with fairy low and controllable drying air temperature to meet product quality requirements [4].

In the literature, most of the research works have reported the performance of heat pump dryers with concentration on optimization of the drying parameters (drying air temperature, airflow velocity and relative humidity) [5], [6]. However, the overall performance of the heat pump drying system, which consists two

doi: 10.18178/ijoee.4.1.11-16

subsystems, the vapour compression heat pump cycle and the drying system, depends on working conditions and the two subsystems interact with each other. If the working conditions change, such as refrigerant charge, air flow rates due to the change of condenser fan speed and the ambient conditions, the operation to obtain the best performance of the heat pump and the dryer must also change accordingly. In this light, the heat pump and the dryer should not be examined or optimized separately [7]. Wallin and Berntsson [8] investigated the potential of heat pump application in industries. They demonstrated that the heat pump and the industrial heating process had to be considered as one integrated unit and in doing so the potential for heat pumps in the industry was higher than was anticipated earlier. However, this is not yet clearly reported on the heat pump dryers. It is important to note that, a better COP of the heat pump does not necessarily guarantee a better performance of the dryer and vice versa [9]. The amount of refrigerant in the heat pump dryers is one of the primary parameter influencing energy consumption. Undercharge or overcharge of refrigerant into the heat pump will degrade performance and deteriorate system reliability [10]. Therefore, the heat pump dryers should be charged with an optimum amount of refrigerant in order to operate with high performance over its lifetime. In addition, some of the studies reported that an increase of drying air velocity due to an increased condenser fan speed caused a reduction on the drying air temperatures [11]. In order to achieve higher drying temperatures to the required set point, auxiliary electric resistances/heaters were placed downstream of the condenser to increase the air drying temperatures. Since these auxiliary electric resistances consume power, it was not clearly reported if the power consumed was determined and used for calculating the overall COP of the system. Addition of auxiliary electrical resistances to the heat pump dryers can result in lower overall system COP. Thus, an optimization of condenser fan's speed of the heat pump dryer is of great importance in order to achieve appropriate drying temperatures and higher COP values instead of adding electrical resistances.

Therefore, in the present study, an air source heat pump dryer was designed, constructed, installed and analysed for thermal and drying process performance. The developed system was experimentally optimized as a single integrated unit by varying condenser fan speed, refrigerant charge and the operating ambient conditions to evaluate its impact on thermal and drying performance. South African bananas were chosen as sample fruit in the present study.

II. Materials and Methods

A. *Experimental Setup*

The heat pump dryer experimental rig is presented in Fig. 2, which is an open cycle system. This configuration was preferred in the present study purposely to examine the impact of ambient conditions on the performance of the developed heat pump dryer. The open cycle was reported elsewhere in the literature to perform better than a closed cycle system [12]. In this configuration, the heat pump dryer uses ambient air as the energy source and energy sink. It draws air through evaporator and discharges it to the other end of the evaporator. It also draws air from the surroundings through the condenser where it is heated, passes through the dryer (moist materials) and is discharged to the environment. This configuration is simple, cheap and is easy to design. The refrigerant R134a was used in the heat pump unit.

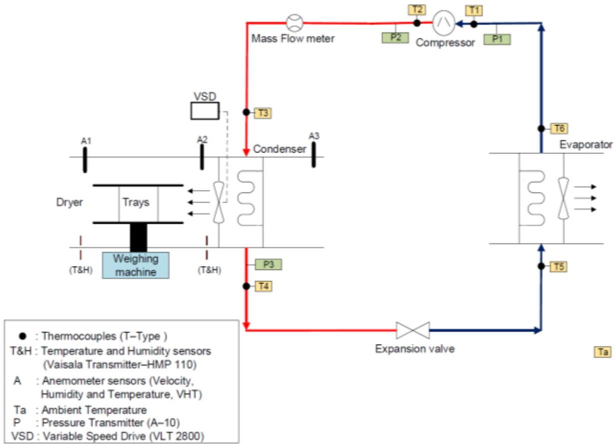

Figure 2. Schematic diagram of the heat pump drying system and measurement points

B. *Experimental Procedure*

To examine the optimal charge amount of the refrigerant in the developed system, the refrigerant charges were varied from 1350 grams to 1800 grams at intervals of 150 grams. After completion of recording data at each refrigerant charge, the refrigerant was taken out and the heat pump system was evacuated and recharged to another amount. The speed of condenser fan was varied from 560rpm to maximum speed of 1400rpm at intervals of 280rpm using a variable speed drive to observe its impact on thermal performance of the heat pump and drying parameters while the evaporator fan was left to run at manufacturer settings (speed of 1400rpm). In addition, the room temperature was also varied from 15 to 25 ℃ at intervals of 5 ℃ to examine its impact on thermal and drying performance of the developed heat pump dryer.

The initial moisture content of untreated bananas was determined by drying it using an air-oven drying method according to AOAC standards (Association of Official Agricultural Chemists, 2012). The heating temperature was set at 105 ℃, for the period of 24 hours. Three replications were carried out and an average value was used. The initial moisture content was expressed on a wet basis. The average initial moisture content of South African fresh banana during experiments from the period of March to October was 75.5 ±1.5% on wet basis, which means that, the average of dry mass was 25% of the original mass. For the drying process, bananas were peeled, weighed and cut into cylindrical pieces of about 5mm. Five hundred and fifty grams of untreated ripe bananas slices were used for each experiment. Banana slices were placed on a stainless steel mesh tray supported by an electronic weighing scale as depicted in Fig. 2 and was evenly spread to cover the entire surface area of the drying tray. The initial weight was immediately recorded and the experiment was started. Weight losses and all other data were recorded every after 20 min. The experiments were continued until no change in the weight loss of the drying banana slices.

C. Performance of the Heat Pump Cycle

The performance of the vapour compression heat pump cycle was presented primarily by COP, which is calculated as per (1) and (2) by inserting the real measured values from the heat pump system. The dependence of thermo-physical properties on temperature and pressure at a certain point or state was calculated using Engineering Equation Solver.

$$COP_{HP} = \frac{Q_H}{W_C} \quad (1)$$

where Q_H is heat rejected at the condenser and W_c is compressor work input.

$$Q_H = Q_{Desuperheating} + Q_{Condensation} \quad (2)$$

The integration of a heat pump system into a dryer requires an additional energy consuming unit which is a blower/fan of the condenser and evaporator. In order to be precise, the energy input to this device must also be included in the calculations and COP is termed as the overall system COP ($COP_{Overall}$) of the heat pump dryer and is defined as:

$$COP_{Overall} = \frac{\dot{Q}_H}{P_C + P_f} = \frac{\dot{m}_r \Delta h}{P_c + P_f} \quad (3)$$

where P_f is the total measured power input to the condenser and evaporator fans, P_c is measured power input to the heat pump dryer, $\dot{m}_r$ is measured refrigerant flow rate and Δh is the enthalpy change (kJ/kg) at the condenser. Errors and uncertainties in experiments can arise from instrument selection, instrument condition, instrument calibration, environment, observation and reading and test planning [13]. In the present study, similar calculation procedure explained in details by Hepbasli and Akdemir [13] were used in calculating the uncertainties; the obtained uncertainties in calculating the $COP_{Overall}$, COP_{HP} and Q_H were ± 5.38%, ± 4.59% and ± 4.99%, respectively.

III. Results and Discussion

A. Effects of Refrigerant Charge on COP and Heating Capacity

Fig. 3 depicts the impact of refrigerant charge on the COP of the overall system and that of the heat pump cycle at full speed of the condenser fan (1400rpm) and various ambient temperatures. The COP was used as a measure of performance for the developed heat pump. The results showed that, the COP values of the overall system and that of the heat pump cycle increased with the increase of refrigerant charge. However, at a high refrigerant charge of 1800 grams, the COP values were slightly lower compared to 1650 grams. The maximum COP of the heat pump cycle (5.60) and the overall system COP of 3.70 was recorded at 1650 grams of refrigerant charge and at the ambient temperature of 20 ℃. This implied that the maximum amount of charge the system can take is not necessarily the optimum amount of charge. The lower COP values recorded at the high refrigerant charge of 1800 grams was because the power consumption of the heat pump increased due to a rise of refrigerant flow rate (Fig. 4) and compression ratio. Also, possibly at 1800 grams charge, a significant amount of liquid refrigerant accumulated in the condenser which led to degradation in heating capacity (Fig. 4) and reduced the COP values. Similar trend of results were previously reported by Choi and Kim [10]. In addition, for the case of undercharged conditions (1350 grams) the COP values were reduced possibly due to the high discharge temperatures and low refrigerant flow rate [10]. From the results, it can be concluded that, even if the system is charged to the maximum amount of charge, it does not necessarily perform with the highest efficiency. There is always an optimum amount of charge where the system has the best performance. Therefore, for this particular system, the optimum amount of the refrigerant charge was observed to be 1650 grams.

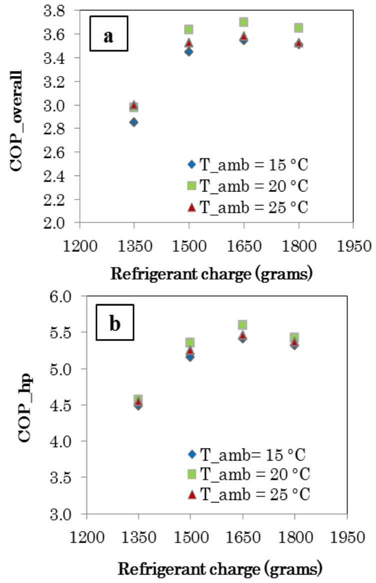

Figure 3. Impact of refrigerant charge on COP of (a) overall system and (b) heat pump at 1400rpm of condenser fan speed and various ambient temperatures

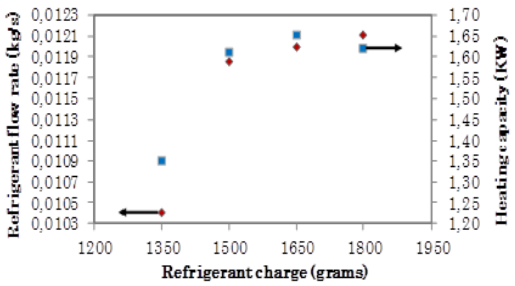

Figure 4. Impact of refrigerant charge on refrigerant flow rates and heating capacity at a condenser fan speed of 1400rpm and the ambient temperature of 20 ℃

B. Effects of Ambient Temperature on Heat Pump Performance and Drying Parameters

The ambient air was the medium for the developed heat pump drying system. Since the ambient temperature at a location might greatly vary, the heat addition and rejection temperatures (the evaporating and condensing temperatures) might do likewise. As result it affects the performance of the heat pump dryer. It is easy to study the effect of condensing temperature on the heat pump performance by keeping evaporator temperature constant or vice-versa. However, in the present study, both evaporating and condensing temperatures were varying depending on working conditions. It was observed that the COP values of the overall system and that of the heat pump cycle improved as the ambient temperatures increased. The results seemed plausible because the increase of ambient temperature (heat source) increased thermal input to the evaporator, which increased evaporator temperature (Fig. 5) and enhanced the COP values. This implies that the low temperature refrigerant entering the evaporator absorbed heat from the surrounding and it vapourised before entering the compressor, as result, it reduced compressor work and improved the heat pump performance [14], [15].

However, at higher ambient temperature (25 ℃), the COP of the overall system (3.58) and that of the heat pump cycle (5.46) were lower compared to those at 20 ℃ as depicted in Fig. 3. It should be noted that it was expected at higher ambient temperature, the COP values to be higher compared to the low ambient temperatures due to the increased thermal input, but slightly higher COP values were recorded at the ambient temperature of 20 ℃ than at 25 ℃. This was possibly attributed to the effect of high increase of condensing temperature at high ambient temperature while there was a slight increase in evaporator temperature as depicted in Fig. 5. The results concurred with previous results reported that increment of evaporator temperature improved the COP values while increasing condensing temperature upped the compressor's workload, and reduced the COP values [15]. From the results (Fig. 3 and Fig. 5), it can be seen that the best performance of the developed heat pump dyer was at the ambient temperature of 20 ℃.

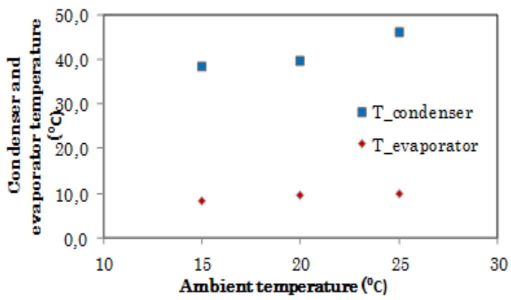

Figure 5. Impact of ambient temperature on condenser and evaporator temperature at a refrigerant charge of 1650 grams and condenser fan speed of 840rpm

C. Effects of Refrigerant Charge on Superheat and Sub-Cooling Degrees

The degree of superheating is defined as the difference between the evaporating temperature and the temperature of the refrigerant at the exit of the evaporator. The superheating degree is a controlling parameter which is used for adjusting a refrigerant flow rate through a thermal expansion valve and to make sure that only superheated refrigerant/vapour enters the compressor. The degree of sub-cooling in the heat pump cycle is the difference between refrigerant temperature and refrigerant saturation temperature corresponding to the pressure at the exit of the condenser. The sub-cooling at the exit of the condenser can be increased by three ways: (1) an improvement of condenser capacity, (2) an addition of refrigerant charge, and (3) a rise of restriction on the expansion device [10]. In the present study, the impact of refrigerant charge on both superheating and sub-cooling were investigated and the results are shown in Fig. 6. It was observed that the superheating degree slightly decreased as the refrigerant charge increased due to a rise of the mass flow rate through the evaporator and the control of the thermal expansion valve, it decreased from 9.35 ℃ to 4.82 ℃ at 1350 and 1800 grams of the refrigerant charge respectively. However, the scenario was different for the sub-cooling which was observed to increase as the refrigerant charge increased; recording sub-cooling degree of 5.13 ℃ at 1350 grams of refrigerant charge and 8.35 ℃ at a high refrigerant charge of 1800 grams. This seemed plausible because as the refrigerant charge increased, the condensing pressure increased due to an accumulation of refrigerant in the high-pressure side, and the sub cooling became high. Similar observations were also previously reported in the literature by Choi and Kim [10], Stoecker [16], and Farzard and O'Neal [17]. Also, it can be pointed that since the superheat at undercharged conditions was higher than that at overcharged conditions, it means more significant reduction of evaporator efficiency occurred at undercharged conditions as the result lower COP values were recorded.

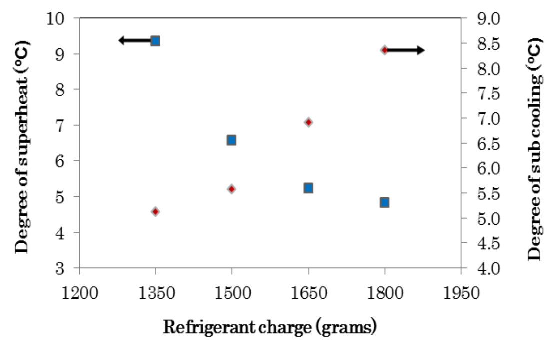

Figure 6. Impact of refrigerant charge on superheat and sub cooling degrees at a condenser fan speed of 1400rpm and the ambient temperature of 20 ℃

D. Effects of Condenser Fan Speed on Heat Pump Performance and Drying Parameters

In this study, the condenser fan speed was varied for two reasons: to examine its impact on thermal performance of the heat pump dryer and also to vary the velocity of process air at the dryer. Fig. 7(a) and Fig. 7(b) depict how significantly condenser fan speed affected drying air velocity and temperature, respectively at 1650 grams of refrigerant charge (the optimal charge) and the ambient temperature of 20 ℃. Drying air velocity at 560, 840, 1120 and 1400rpm of condenser fan speed were at average values of 1.2, 2.0, 2.8 and 3.5m/s, respectively and the drying air temperatures were 45.0, 40.7, 33.5 and 30.2 ℃, respectively. This implies that increasing condenser fan speed increased drying air velocity and caused a reduction in the drying air temperature. The variation of condenser fan speed had significant effect on the performance of the heat pump dryer and drying process as depicted in Fig. 7(a) and Fig. 7(b), respectively. The COP values of the overall system and that of the heat pump cycle improved as condenser fan speed increased. At lower speed of condenser fan (560rpm), the COP of the overall system and the heat pump cycle were 2.76 and 4.36, respectively while at full speed (1400rpm), the former was 3.70 and the latter was 5.60. This increase could possibly be attributed to the decrease in condensing temperature as the speed of the condenser fan increased while slight change were observed on evaporator temperature. The decrease in condensing temperature reduced the difference between the evaporator and the condenser temperatures (i.e., the temperature lift decreased) as a result it increased energy efficiency of the heat pump dryer - in line with the effect of such temperatures in a reverse Carnot refrigeration system. Also, increase of condenser fan speed increased the air flow rates as result it increased the heating capacity and COP values [15].

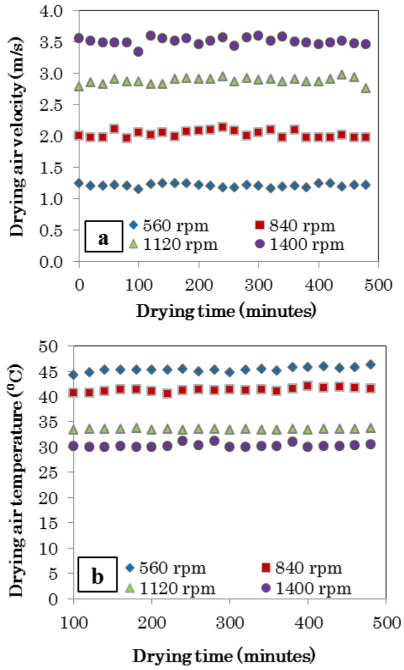

Figure 7. Impact of condenser fan speed on (a) drying air velocity and (b) drying air temperature at 1650 grams of refrigerant charge and ambient temperature of 20 ℃

In addition, increase of condenser fan speed increased the COP of the heat pump up to the full speed (1400 rpm) but not the COP of the overall system. It was observed that the COP of the overall system increased from 2.76 at 560rpm to 3.75 at 840rpm and slightly decreased to 3.73 and 3.70 at 1120rpm and at full speed (1400rpm), respectively as depicted in Fig. 8(a). This was associated with the increased power consumption of the condenser fan at high speed and reduced the COP of the overall system as per (3). Thus, it is energy-efficient to operate the heat pump dryer with appropriate condenser fan speed. As indicated in Fig. 7(a), at 840 rpm condenser fan speed the highest COP of the overall system (3.75) was recorded, followed by 1120 rpm which displayed overall system COP of 3.73. In this light, the speed of 840 rpm could be taken as optimal speed for this particular system as it displayed high COP of the overall system and also the appropriate drying temperature and velocity, 40.7 ℃ and 2.0m/s, respectively for the drying banana slices as shown in Fig. 8(b). These drying parameters are suitable for drying bananas as it has also been used elsewhere in the literature [18].

Therefore, it can be seen that a better COP of the overall system and that of the heat pump cycle does not necessary guarantee a better performance of the dryer and vice versa. This is demonstrated in Fig. 2 where the maximum COP of the heat pump cycle (5.60) was recorded at 1400rpm of condenser fan speed and the ambient temperature of 20 ℃. However, the drying air temperatures were lower which was associated with high velocity of the drying air as depicted in Fig. 7(a) and Fig. 7(b). Also, high drying air temperatures were recorded at the ambient temperature of 25 ℃ due to the high condenser temperature (Fig. 4), but at this point, the heat pump cycle displayed lower COP values than at 20 ℃ (Fig. 2). Thus, for the heat pump drying system to operate more efficiently, it is imperative to run the system at appropriate operating parameters for both the heat pump cycle and the dryer; this once again serves to demonstrate that the heat pump and the dryer should not be optimized separately [7].

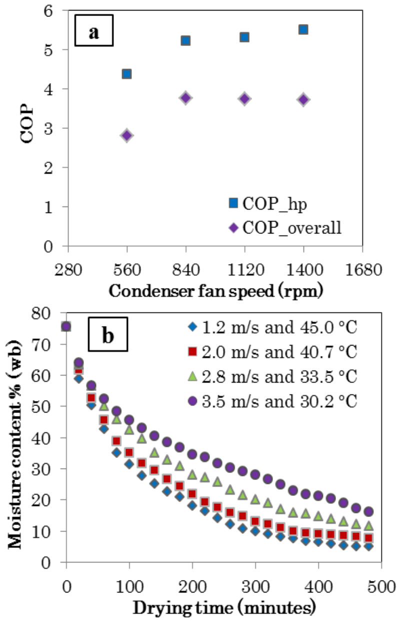

Figure 8. (a) Impact of condenser fan speed on COP Overall and COPHP and (b) moisture content of banana slices at different drying air temperature and velocity at 1650 grams of refrigerant charge and ambient temperature of 20 ℃

IV. CONCLUSIONS

The influence of ambient conditions, refrigerant charge and condenser fan speed on thermal and drying performance of the heat pump drying system was experimentally investigated. From the results, it can be concluded that the optimum refrigerant charge of the developed system was 1650 grams and 840rpm of condenser fan speed (60% of the full speed), recording the COP of the overall system and that of the heat pump cycle of 5.20 and 3.75, respectively at an ambient temperature of 20℃. It was also observed that, an increase in condenser fan speed increased both COP values. However, for the COP of the overall system, it was observed to decrease at high speed of the condenser fan (1120rpm and at full speed - 1400rpm) which was associated with the increase of fan power consumption. The effect of evaporation and condensation temperature was observed to affect the performance of the heat pump drying system. The influence of the evaporator temperature on COP was of sufficient importance and the COP values improved as the evaporator temperature rose or the condensing temperature decrease. The drying temperature and air velocity were found to be absolute parameters on the drying process. It was concluded that, for this particular system the possible appropriate drying air temperature was 40.75℃ and 2.0m/s drying air velocity.

AKNOWLEDGEMENT

The author wish to thank ESKOM for their financial support under the TESP programme.

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