AIR SOURCE HEAT PUMP SYSTEM FOR DRYING BIOMATERIAL

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ABSTRACT

Need for a more economic method of drying biomaterial, from paper to fruit, in South Africa has for long been sought. This paper explains research into an advanced air source heat pump drying (ASHPD) system, designed, manufactured and installed for drying South African fruit and taking into account local climactic conditions. The effect of ambient temperature and condenser fan speed on the coefficient of performance (COP) of the heat pump (HP) was evaluated, also the influence of drying temperature and air velocity analysed. Using banana slices (the sample fruit selected for this study) results indicated the moisture content of bananas produced in Mpumalanga Province averaged 75.5±1.5% on a wet basis. The COP of the HP was found to be significantly high - an average 4.7. The influence of the evaporator temperature on the COP was important since it assisted in temperature control during the drying process. It was also observed the COP increased with an increase in room temperature. Drying process results indicated for drying South African bananas a possible optimal drying temperature range was 30 – 40 °C with 1.5 m/s drying air velocity. Generally, the study demonstrated an ASHPD system was suitable for use in South African climatic conditions. Now South Africa has an opportunity to continue research and to design applications for this green and efficient drying technology - especially for drying biomaterial. This could reduce high energy consumption, something all of South Africa is striving towards.

1. INTRODUCTION

Heat pump drying (HPD) processes have been evolved into a mature technology over the past two decades. However, greater use in different areas was a strong consideration. Initial cost, system design and integration remained challenging problems, but introduction of HP in drying processes was imperative as it was an efficient technology with a short payback period. HPD technology was able to dry biomaterial - mostly thermal and oxygen sensitive - at low temperature and in an oxygen-free atmosphere with less energy consumption than common South African traditional drying methods using direct/indirect sunlight, wood burning, fossil fuel burning, electrical heaters and diesel engine heating [1].

Drying agricultural products increased shelf life, reduced packaging, and transportation cost, by lowering weight and volume, giving improved appearance and more importantly maintained original flavour and nutritional value. Conventional dryers required enormous energy for heating and removing water. To reduce energy consumption it was necessary to choose an efficient heating system. HP was an efficient technology and environmentally-friendly because of low energy consumption [2, 3]. HPs were air-conditioning devices which pumped heat from a low temperature source (at or near ambient conditions) to a high temperature sink. HPs had been used for several industrial and domestic applications, such as heating, ventilation, and air conditioning, however, in the last two decades HPD had been of great interest for drying fruits and vegetables. HPD is the integration of an H system and a dryer[1].

Compared to electrical heaters, HPD had many advantages such as high energy efficiency (up to 60% reduction in energy cost) [3, 4] a controlled temperature profile to meet product requirements - sensors and advanced controllers adjusting condensers and evaporators to optimum drying temperature. Also, there was a possibility of controlling condenser fan speeds to achieve maximum drying air flow. Excellent control of the environment (reduction in global warming and halting depletion of the ozone layer); 60 – 100% reduction in emissions [5].In addition, HPD had an ability to operate independently from inclement outside weather [5].

The rapid expansion in SA's biomaterial drying industry meant high energy consumption industrially and domestically. Drying was an energy-intensive operations accounting for up to 7– 15% of all industrial energy consumption in an industrialised country [6]. Drying played an important role in many manufacturing fields such as wood, paper, clothing, tea, biltong and herbs. It was also a significant part of agriculture for drying, grains, fruits and nuts. Drying processes consumed up to 70% of the total energy required in wood products' manufacturing, 50% in textiles and more than 60% in farms' corn production [7].Therefore, application and more research into HPD systems was imperative as an economical and environmental friendly drying technology producing good quality products.

Most research into HPD was in the US, Europe and Asia [1]. Since performance was significantly affected by climatic conditions[1], results were based on specific conditions in different regions. It is believed South Africa's energy consumption could be reduced by 6% if HPD was utilised effectively [6]. In the last decade the marketing of HP systems for water/space cooling/heating had developed well in South Africa, but the development of HP for industrial and agricultural drying remained scarce because:

(1) HPD products were relatively new in South Africa;
(2) There was a lack of awareness of Hp as a major drying principle;
(3) The surge in fossil price was a recent phenomenon.

Literature indicated little research had been conducted throughout southern Africa).

Meyer and Greyvenstein [6] completed economic analysis in dying of grain with HP and compared it to other traditional methods such as direct electrical heaters and diesel engine burners in South Africa. In their study, they found HPD more economical than other methods, provided the apparatus was employed for more than a year. However, in their study they did only economic analysis of HPD in terms of investment and running costs compared to other South African traditional drying methods. But, they did not experimentally suggest how the climatic conditions of South Africa affected the HPD performance, be it positively or negatively; the effects of various ambient temperatures on HPD performance were not clearly discussed [8-10].This was important because HPD performance was significantly affected by climatic condition. Also, Meyer and Greyvenstein [6] did not elaborate in detail on coefficient of performance (COP) of their HP. COP is a virtue parameter to be determined as it underlines the saving in energy consumption. Moreover, the effects of drying parameters, such as temperature and air velocity, were not reported as per South African climatic conditions.

This study, therefore, is among few conducted in South African on HPD as per South Africa climatic conditions. Its aim was to design, manufacture and install an air source HP for drying South African fruit in local climatic conditions. Sensors were installed in the system to record all necessary data such as temperature, drying air velocity and pressures at suction and discharge side of the HP. The COP of HPD was evaluated to meet South African conditions; also, the effects of ambient temperature and condenser fan speed on the HPD were examined. The influence of drying temperature and air velocity were also analysed.

2. HEAT PUMP DRYING EXPERIMENTATION

2.1 MATERIALS

Bananas from Mpumalanga Province, South Africa, were chosen as the sample fruit to be dried in this study. The reason for choosing bananas above other fruit such as apples, mangoes, plums etc was because bananas were one of the highest daily consumed tropical fruits in South Africa and readily available throughout the year. Also, it contributed soundly economically to farmers and the nation. During the 2009/10 marketing season bananas contributed 57% (R1.2 billion) to the total gross value of subtropical fruits (R2.1 billion) produced in South Africa [11]. This made bananas the most important sub-tropical fruit grown in the country.Therefore, this project was envisaged to develop a novel technology for drying South African fruit, especially seasonal and easily perishable fruits, for longer storage. Refrigerant R134A was used in the HP unit; it was obtained from KOVCO (Pty) Ltd, Pretoria, South Africa.

2.2 EXPERIMENTAL APPARATUS/ MEASUREMENTS

Figure 1 depicts the assembled HPD. It consists of two systems, HP (refrigeration) system and a dryer. The HP is basically an air-conditioner cycle consisting of four main components namely: evaporator, compressor, condenser and expansion valve. In the HP, cooling and air dehumidification was provided in the evaporator as low temperature refrigerant entering as a mixture of liquid and vapour was vapourised by thermal input from its surroundings. The refrigerant vapour entered the suction line of the compressor in a saturated or slightly superheated condition that raised the pressure and, consequently, the temperature of the refrigerant. The high pressure and temperature refrigerant vapour entered a condenser heat exchanger using ambient air to cool the refrigerant to its saturation temperature, prior to fully condensing it to a liquid condition. At the condenser, the refrigerant underwent two-phase condensation, changing from vapour to a liquid phase. During this process, heat was rejected by the condenser to heat the moist biological materials in the dryer. A throttling device, such as thermal expansion valve, was used to expand the liquid refrigerant which caused some refrigerant to vapourise as its temperature and pressure reduced. After the expansion process, the refrigerant entered the evaporator in a two-phase state and the cycle was repeated.

The HP and the dryer were connected by an adjustable air- duct system enabling the HPD to be operated in an open or closed cycle. The open cycle system was preferred in the present study, as previous studies reported to perform better than with a closed cycle system [10]. It proved the simplest method of drying, involving blowing heated air from the condenser over the material and venting the moist air to the atmosphere.

To obtain the required experimental data, a number of instruments was installed in the HPD system as depicted in Figure 2 and Table 1. Thermocouples were installed at the evaporator and condenser coils to measure the average refrigerant temperatures, also to measure ambient air temperature. A hot wire multichannel anemometer (Kanomax system 6242, model: 1550) was used to measure the temperature and air velocity of process air at the dryer. It was assumed air velocity was relatively uniform throughout the dryer. The condenser fan's speed was varied on 20-30 Hz using variable speed drive (VSD Danfoss model: VLT 2800) and drying temperature was varied by varying condenser temperature using multi-range temperature process controller (From Technos Company Ltd, Japan, Model: JCS-33A-R/M).The weight of the dried products/banana slices was measured continuously by using an electronic weighing scale. Weight losses were recorded every 20 minutes. The temperatures measured by thermocouples and HMT120transmitter probe at the dryer were continuously recorded using a computer installed with Labview software.

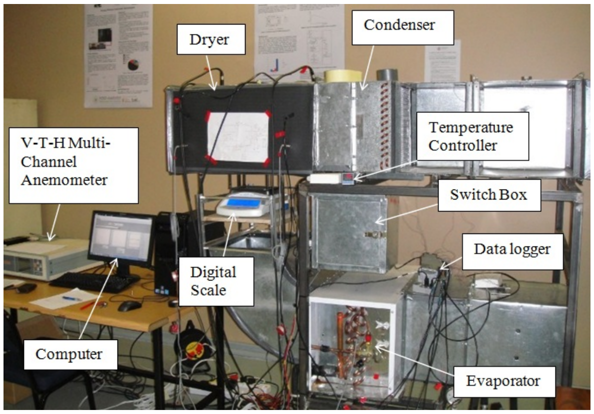

Figure 1: HPD experimental set up

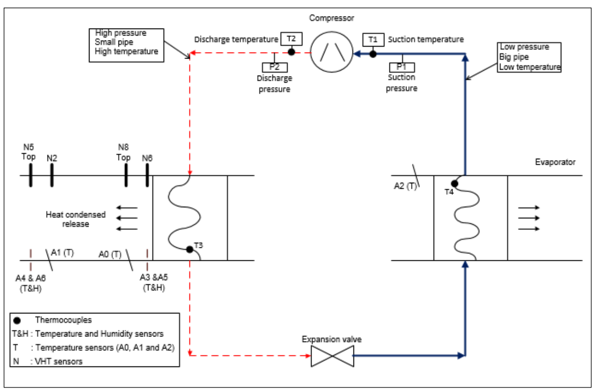

Figure 2: Measuring instruments arrangement

2.3 DRYING EXPERIMENTAL PROCEDURE

The initial moisture contents of banana were determined by drying it using an oven at 100 °C, for 24 hours. The initial moisture contents were determined for bananas grown at different times in South Africa from Mpumalanga Province. Three replications were carried out and an average value used to interpret data. The initial moisture content was expressed on a wet basis. For the drying process, banana were peeled, weighed and cut into cylindrical pieces of about 5 mm. Five hundred and fifty grams of untreated ripe bananas were used for each experiment. Banana slices were placed on a stainless steel mesh tray, supported by an electronic weighing scale and evenly spread to cover the entire surface area of the drying tray. Drying air velocity and temperature at the dryer were varied from 1.5 to 3 m/s and from 30 to 50 °C respectively, to analyse the effect on the drying process. Also, to observe the effect of ambient/room temperature, the drying process was conducted at various ambient/room temperature from 15 to 25 °C from March to November. All experiments were repeated at least three times and the averages used to analyse data. The experiments were continued until a constant mass of the dried fruit was obtained for at least eight hours.

Table 1: Details of measuring instruments:

Instruments	Properties	Range	Accuracy
Temperature sensors	4 – 20 mA	-20 – 120 °C	±0.1°C
Thermocouples	T type	0 – 100 °C	±0.1°C
T & H sensors	4 – 20 mA; 4 – 20 mA	0 – 80 °C; 0 – 100% RH	±0.1°C; ±0.2% RH
Pressure sensor	4 – 20 mA	0 – 4 bar 0-40 bar	±0.1%
V-T-H Multi-Channel anemometer	Air Velocity; Temperature; Relative Humidity	0.1 – 50 m/s; 0 – 60 °C; 5 – 95%	±0.01 m/s; ±0.1 °C; ±0.2% RH
Digital balance	220 V	0 – 4500 g	±0.1 g
Power meter	Wireless Data recording	110 – 600V; 50mA – 90A	< 10%; < 10%
Data acquisition	Current Module	32 channels	
	Thermal Couple Module	16 channels	
	Data Logger (Labview)		

2.4 HEAT PUMP PERFORMANCE

The performance of HP was presented by COP. The COP was a characteristic - the ratio of the heat rejected from the condenser to the input power of the compressor. The COP of a HP wascalculated as per equations 1 and 2 by inserting the real measured values from the HP system (refrigeration system);

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

Where Q_H: heat rejected at the condenser and W_c: Work input to the compressor

$$Q_H = Q_{subcooling} + Q_{condensation} \quad (2)$$

2.5 MOISTURE EXTRACTION RATE (MER)

For drying analysis, MER was used to examine the drying rate of banana slices. MER was calculated using equation 3:

$$MER = \frac{m_i - m_t}{\Delta t} \qquad (3)$$

Where m_i is the initial weight of the sample, m_t is the weight of the sample at time t in grams and Δt is the time difference in hours.

3. RESULTS AND DISCUSSION

3.1. MOISTURE CONTENT

The average initial moisture content of South African fresh bananas from Mpumalanga Provinceduring experiments from the period of March-November was 75.5±1.5 % on a wet basis, meaning the average bone-dry mass was 25% of the original. This value agreed well with reports from literature. Wills *et al*. [12] reported higher moisture content for banana harvested in January - 77.8 ±1.4 % on a wet basis. This value also agreed with results from other authors [13-16], but there slight differences in the results, possibly because of varying local climatic conditions. Commercially, banana was supposed to be dried to less than 20% final moisture content for quality long storage [17, 18] or down to 14-15% final moisture content (on a dry basis) [19]. This corresponded to 70.5% mass loss (18% final moisture content), in this work. It is possible at such a level of moisture content, dried banana slices could have a shelf life of at least 6 months [18].

3.2. PERFORMANCE OF ASHPD SYSTEM

It was clear the higher the COP of the HP the more the energy saving[7]. In this study, the COP of HP was found to be at the average of 4.7 as depicted in Figure 5 for March-November at various ambient/room temperature of 15 to 25 °C.The results concurred with the results reported by Prasertsan *et al.*[10]. In their study, they investigated the HPD of agricultural materials and banana was among products investigated. The COP obtained was lower (at an average of 4.4) compared to the results of this study under similar working condition of ambient temperature 20 – 25 °C. The difference in results might be attributed by differences in drying loads, also. In their study, it was also not clearly stated if they varied the speed of the condenser fan which impacted on COP as depicted in this study (Figure 5). Additionally, process air temperature of about 50 – 60 °C was reported in their study which was higher than those used in the present study (30 – 50 °C).

3.2.1 Effect of ambient temperature on ASHPD performance

It should be noted natural air was the cooling medium for the air source HP systems. Since the ambient temperature at a location might greatly vary, the heat addition and rejection temperatures (the evaporating and condensing temperatures) might do likewise. This affected the compressor's performance and hence the HP system. It was easy to study the effect of condensing temperature on compressor performance by keeping evaporator temperature constant or vice-versa. However, in the present study, both evaporating and condensing temperature were varied depending on working conditions such as an increase or decrease in ambient temperature (Figures 3, 4 and 5).

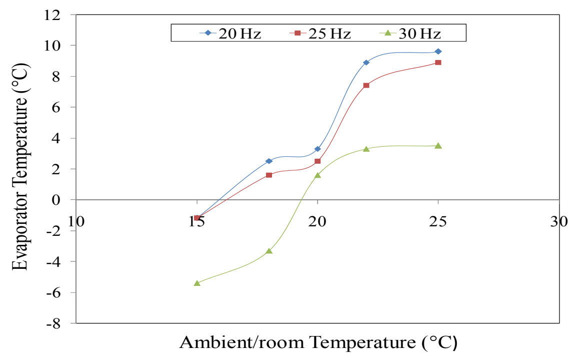

Figure 3: Effect of ambient/room temperature on evaporator temperature at different condenser fan speeds

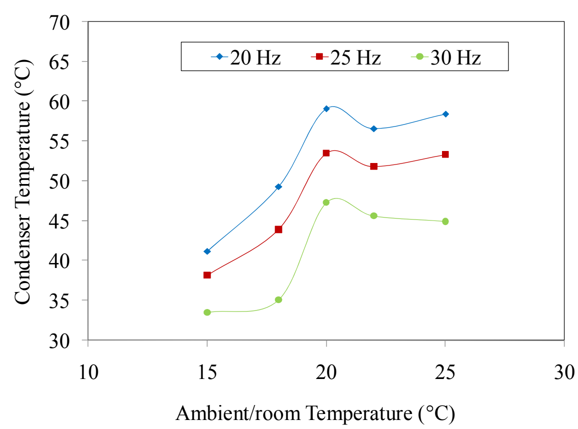

Figure 4: Effect of ambient/room temperature on condenser temperature at different condenser fan speeds

The experimental results showed the COP was found to improve with the increase in ambient/room temperature (Figure 5), which was plausible because increase of ambient temperature increased thermal input to the evaporator, which increased evaporator temperature[20], as shown in Figure 3. This implies low temperature refrigerant entering the evaporator as a mixture of liquid and vapour it absorbed heat from its surroundings/evaporator coils and it vapourised *before* entering the compressor. As result, it reduces the work of the compressor and improved HP performance (COP) [8, 20]. The evaporator absorbed heat from its surroundings/ambience which was supposed to be cooled. However, increase in COP with increase in ambient temperature was not constant, as depicted in Figure 5. For example, COP at 15 and 18 °C ambient temperature was slightly higher than that at 20 °C ambient temperature; possibly attributable to the effect of an increasing condensing temperature - see Figure 4. From previous studies, it had been reported that, increment of evaporator temperature reduced the work of a compressor and improved the COP, while increasing condensing temperature upped the compressor's workload, but reduced the COP. As the condensing temperature increased, the pressure ratio increased, hence, both volumetric efficiency and mass flow rate decreased [8].

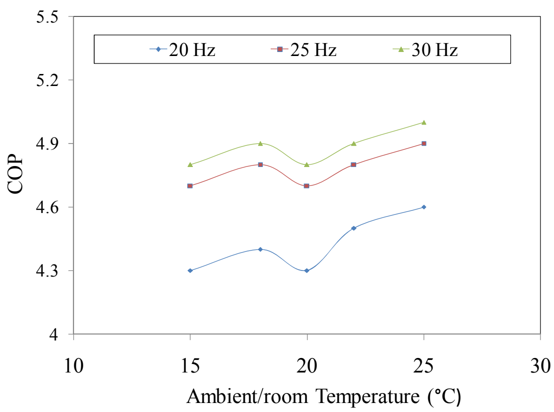

Figure 5: Effect of ambient/room temperature on COP at different condenser fan speeds

3.2.2 Effect of condenser fan speed on ASHPD performance

In this study condenser fan speed was varied from 20 to 30 Hz to observe impact on HP performance as depicted in Figures 3, 4 and 5. It was observed as the COP of the HP was increased so the speed of the condenser fan increased (Figure 5) and vice-versa for evaporator and condenser temperatures as shown in Figure 3 and 4 respectively. For example, at 25 °C of ambient temperature, the COP was 4.6, 4.9 and 5.0 at 20, 25 and 30 Hz, respectively. This possibly, could be attributed to the decrease in condensing temperature as the speed of the condenser fan increased (Figure 4). For the ambient temperature of 15 to 25 °C (Figure 4), the average condensing temperature was 51.2, 46.7 and 41.3 at 20, 25 and 30 Hz of the condenser fan speed respectively. The decrease in condensing temperature reduced difference between the evaporator and the condenser temperatures, as result it increased energy efficiency in the HPD - in line with the effect of such temperatures in a reverse Carnot refrigeration system. This result concurred with the results reported by Daghigh *et al*.[8].

3.3. DRYING PROCESS

3.3.1 Dryer type

The batch type dryer was preferred in this study as depicted in Figure 6, showing banana slices on a stainless steel tray inside the dryer. A batch dryer was used simply because, as reported previously in the literature, batch drying systems allow total recirculation with a minimal air leakage rate, giving rise to high thermal efficiency[3]. Also, it was excellent for low capacity needs such as during conducting laboratory experiments [3, 7].

Figure 6: Batch type dryer, inside view with sensors

3.3.2 Effect of drying temperature and air velocity

Drying temperature was observed to have significant impact on drying banana slices as shown in Figure 7. It is evident that more water/moisture content was removed at higher temperature. Drying air velocity and temperature were the key factors influencing the drying process of any agricultural/biomaterial[10].The influence of air drying velocity on the drying process are depicted in Figure 7 and 8. It was observed that, at lower air velocity (1.5 – 2.5 m/s) more water was removed from the product than at high air velocity (3 m/sec). The results concurred with previous studies that reported the drying rate as higher at lower velocities, but at higher velocities the influence lessened [21, 22]. This was possible, because at lower velocities there was a significantly high heat transfer to the product resulting in more moisture content being removed than with higher velocities[21]; increasing the drying air velocity reduced the drying air temperature. These two conflicting parameters influenced each other. However, both drying air velocity and drying air temperature influenced the drying process.

It was also observed at the end of drying process, MER at high drying temperature (50 °C and 1.5 m/s) decreased compared to low drying temperatures (30 °C and 1.5m/s). This result seemed reasonable since high drying temperatures possibly hardened the outer layer of banana slices which was impervious to the passing of water. As a result a lower drying rate was achieved at the end of the drying process[22]. Therefore, as reported in previous studies it was rewarding to begin with an appropriate temperature which did harden the outer layer of the product, permitting, therefore, more than 90% of moisture to be removed [22]. As for the results, a drying temperature between 30 – 40 °C and 1.5 m/s of drying velocity was observed to remove more water at the end of the process (above 450 minutes of drying process) and may be recommended to suit South Africa climatic conditions for drying banana slices. Although it might take a longer drying time, it provided a good quality dried product. It should be noted the recommended drying temperature and velocity might differ for other biomaterials/South African fruits depending on environment.

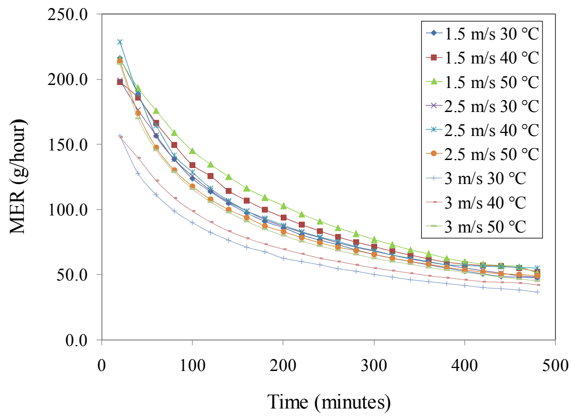

Figure7: Effect of drying temperature and air velocity

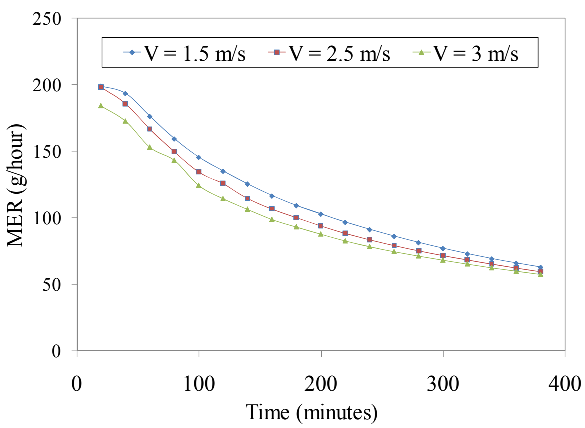

Figure 8: Effect of drying air velocity at 30 °C of drying temperature

4. CONCLUSIONS

In this study, an ASHPD system was designed and constructed for drying South African fruit suitable for South African climatic conditions. Bananas from Mpumalanga Province were chosen as a sample fruit. From results, it was concluded the initial moisture content of banana was at the average of 75.5±1.5% on a wet basis. Also, COP of the HP was found to be significantly high at the range of 4.3 to 5.0 (4.7 in average) between March and November with an ambient/room temperature ranging from 15 to 25 °C.The ambient/room temperature and condenser fan speed had influence on HP performance. The COP was found to increase with ambient temperature and condenser fan speed. Also, the effect of evaporation and condensation temperature was observed to affect HP performance. The influence of the evaporator temperature on COP was of sufficient importance and the value of the COP of the system improved as evaporator temperature rose or condensing temperature decreased. Additionally, drying temperature and air velocity were found to be absolute parameters on the drying process - from results it was observed that, more water/moisture content was removed at higher drying temperatures, while vice-versa for drying air velocity where higher drying rate was at lower velocity; at higher velocities the influence was less. Therefore, it was concluded for drying South African bananas the possible optimal drying temperature range was 30 – 40 °C and 1.5 m/s drying air velocity.In general, it has been found that ASHPD results are promising as per South African climatic conditions.

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