Design and applications of controlled-atmosphere dehumidifier fruit driers

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Drying fruit in a controlled atmosphere can lead to improved product quality. In this paper several system design options are assessed for their suitability and cost effectiveness in commercial drying applications. A prototype design of a commercial controlled atmosphere dehumidifier kiln is also outlined. It is shown that the added cost of the controlled atmosphere is relatively small in comparison with the value of the dried product. A number of directions for future research are also identified.

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1. Introduction

Drying and storing fruit and foods in a controlled atmosphere (CA) can lead to improved product quality, because displacing oxygen with other gases such as N_2 and CO_2 retards the oxidation process. Considerable commercial success has been achieved in the area of CA fruit storage and transport [1,2]. Similar opportunities have also been identified in the area of fruit drying, particularly in terms of eliminating the use of any chemical preservatives or other additives [3,4].

This paper presents a review of the process of controlled-atmosphere fruit drying. The economics and operational feasibility of various system design options are also assessed. Because CA drying necessitates the use of a closed drying environment, a heat pump drier would be suitable where excess moisture and energy can be removed without outside air exchange [5,6].

2. Process characteristics

In comparison with the well established process of CA storage, the development of CA drying technology is still its initial stage. The following features may be identified in the process of CA drying.

Time scale

CA storage is generally used to keep the products fresh (prolonging the shelf life of the products) over a period of several months. By comparison, CA drying is generally a much shorter process, lasting only a few hours or days. Thus if the gas is not recovered after each drying cycle, the gas turnover rate would be much higher. Rapid establishment of the target kiln environment is also required for CA drying.

Process conditions

The process conditions used for CA drying generally involve higher temperatures (40-70°C) than those for CA storage (0-2°C). There is also a significant difference in the target oxygen level between the two methods. From laboratory experiments it has been found that 0.5% oxygen concentration is usually required for CA drying [4] in comparison with typically 2% in the coolstore [2]. This would require higher purity of incoming gas than that of CA storage. A tighter control of kiln infiltration loss is also consequently required. Nitrogen gas is typically used in the purging process of CA drying.

Process constraints

To accelerate the drying process, relatively high speeds (1–4 m/s) of gas flow are usually required for CA drying. This would require the accommodation of kiln fans and ductwork which reduces the available space for the product. The overall size of drying kilns is also usually considerably smaller than storage facilities.

3. Evaluation of system design options

In this paper, several system design options will be evaluated for their operational feasibility and economics. These include:

(1) the use of oxygen scavengers or scrubber machines to achieve the target level of oxygen concentration or to reduce the required load during the subsequent gas purging process;

(2) the design options for the product handling system so that gas loss during the loading/unloading period can be minimised;

(3) the methods for increasing the effective product volume so that the gas consumption per unit of product can be reduced;

(4) the possibility and cost-effectiveness of alternative nitrogen generation methods

3.1 Use of oxygen scavengers and scrubber machines

To reduce the drying gas requirement during the purging process, it has been suggested that oxygen scavengers and scrubber machines may be used initially to reduce the kiln oxygen concentration to an intermediate level. Assuming a complete mixing and using a previously derived gas exchange equation [7]:

$$N = \ln[(I - G)/(F - G)] \qquad (1)$$

where G is the oxygen concentration of the intake gas, I and F are the initial and final kiln oxygen levels, and N is the number of required gas exchanges, it can be seen from Figure 1 that if the oxygen scavenger has been used to reduce the initial oxygen concentration from the original level of 20.95% to an intermediate level of 5%, then instead of 3.7 gas exchanges, only 2.3 gas exchanges would be required to reduce the final oxygen level to 0.5%. Alternatively, to reduce the oxygen concentration from 2% down to 0.5%, 1.4 gas exchanges are required.

In reality, it has been found that both oxygen scavengers and scrubber machines are quite expensive. They are also very slow in removing oxygen (typically taking several days as in the case of CA storage). These characteristics render them largely unsuitable in a “rapid” industrial drying process. In the case of oxygen scavengers, it has been found that currently available commercial scavengers would typically cost about $US0.2 per litre of air scavenged or $US5,000 for use in a 25 m^3 kiln.

3.2 Stack isolation and gas recovery system

Because of the short duration of the drying cycle and the requirements for very low oxygen concentration, it is desirable that nitrogen gas be recovered as much as possible after each drying cycle. This may be achieved either by pumping the gas into an external receiver or by retaining the existing gas inside the kiln. In both cases, the control of unnecessary gas loss would be very important.

The performance of a plenum/stack gas isolator for reducing gas loss during the product loading/unloading period is discussed as follows. The purpose of this isolator is to separate the product stack from the remaining plenum space during the product loading/unloading period so that kiln gas inside the plenum could be retained. Using a pair of currently available high-grade commercial gas dampers (worst-case gas leakage rate: 4.5 litres/second at a pressure differential 20 Pa), it is found that due to the stack pressure (kiln internal temperature: 60–65^{o}C) and wind effects, the gas infiltration rate for these dampers may be up to 0.1–0.3 m^3/minute. This could be quite significant if the drier internal space is assumed as 25 m^3 (10–15 m^3 plenum space). This system could also significantly increase operational complexity and maintenance cost. Currently each such damper costs around $4,500.

3.3 Kiln design improvements

The overall design of the dehumidifier kiln is critical to the commercial viability and success of CA drying. To obtain the best results, it is desirable to maximise the effective product/kiln volume ratio so that in each drying cycle more fruit can be dried with less gas use. To achieve this objective, it is suggested that instead of the overhead fan arrangement, the kiln fan may be located in front of the fruit stack. Increasing the product stack depth and

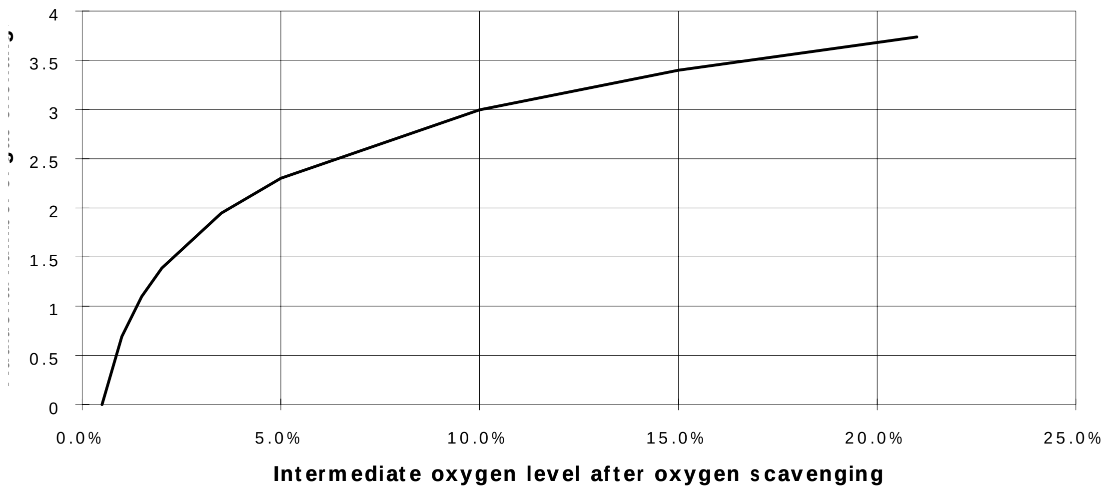

FIGURE 1: The relationship between the intermediate oxygen level after oxygen scavenging and the required number of additional pure gas purges. The final kiln oxygen concentration is assumed as 0.5%.

rounding of the kiln corners could also lead to an increase in effective product/kiln volume ratio. There may also be opportunities to use an external duct system to further increase the effective product/kiln volume ratio.

3.4 Gas production method

Currently there are essentially three methods of on-site nitrogen production: pressure swing absorption (PSA), hollow fibre membrane separation (HFMS), and liquid nitrogen supply [2]. The first two are based on air separation techniques while the latter is vaporised for on-site delivery. Although liquid nitrogen supply can be very rapid and requires lower capital outlay because tanks and vaporisers are usually leased, the long-term running cost of this method could be very significant.

Research on the performance characteristics of the PSA and HFMS methods has revealed that the HFMS method is generally more expensive for drying operations than PSA, because of its higher compressor pressure requirement. As a result, PSA has been chosen for use in the current system analysis. It has been estimated that a PSA gas generation unit with a generating capacity of 10 m^3/hr 99.5% purity nitrogen would cost around $35,000 ($22,000 for air separator, $11,000 compressor and $2,000 receiver). To complete the system, it has also been identified that an additional cost of $52,000 would be required for other parts of the gas handling facility (Table 1). This brings the total capital cost for the PSA method to approximately $87,000, which is close to a price previously quoted for a CA fruit disinfestation unit [8].

TABLE 1: Estimated costs for the gas handling facility of a CA fruit drying kiln.

Description	Cost
Gas generation unit	$35,000
Foundation and installation	$30,000
Gas delivery and control system	$17,500
Drier gas sealing	$4,500
Total	$87,000

4. Analysis of a prototype CA fruit drier

Combining all the relevant measures together, a prototype design of a commercial kiln is outlined in Figure 2, with the effective product/kiln ratio being approximately 50%. Initial computer simulations [9] have indicated that at 60°C drying temperature, this drier would be capable of batch drying 3000 kg of fresh apple wedges from 440% initial moisture content (dry basis), to 20% final moisture content in approximately 32 hours, producing some 83 000 kg dried apples per annum (assuming 6 months drier use or 130 annual drying cycles). This computer model has been modified from an earlier model developed for timber drying operation [10]. The apple drying rates were obtained from laboratory experiments [9].

Using the following assumptions:

Annual drying cycles:	130
Total chamber space:	23.0 m^3
Middle stack space:	10.5 m^3
Cost of liquid nitrogen supply and tank rent:	$1.0/$m^3$
Gas purity from PSA generator:	99.5%

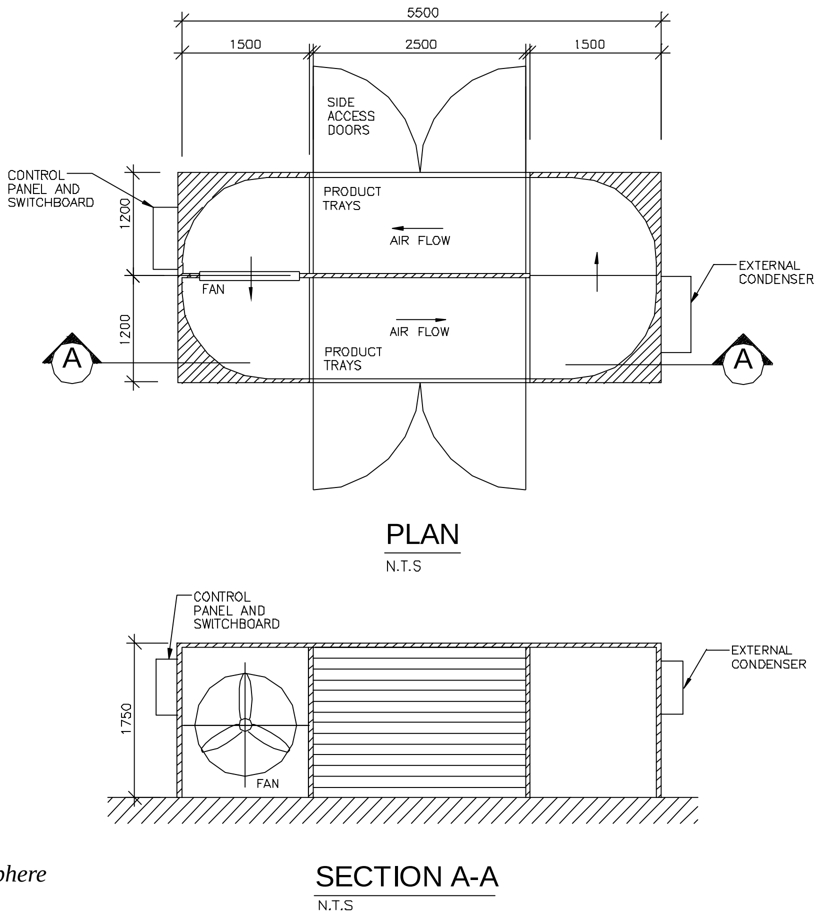

FIGURE 2: A proposed controlled-atmosphere dehumidifier fruit drying kiln.

TABLE 2: Gas cost comparison for two selected design options. The drier use time is assumed to be 6 months (130 drying cycles) per annum.

Option	Gas supply methods	Capital installation cost ($)	Annual gas operating cost ($)	Net present value ($)
1	Bottle supply only	52,000	12,000	168,000
2	PSA plus bottle supply	87,000	4,000	122,500

PSA compressor power rating: 7.5 kW
Electricity cost: $0.10/kWh
Kiln gas charge time between consecutive cycles: 1 hour

the operating and capital costs, excluding the labour and maintenance costs, for the two selected designs of CA gas provision have been evaluated (Table 2):

Option 1: Four bottle charges of pure gas per cycle.
Option 2: Four PSA charges plus one bottle supply.

Here the NPV value has been calculated based on a 5% real discount rate (ie, after inflation) and a 15 year lifetime with no residual value at the end of the period. All the costs listed in Table 2 have also been presented as positive values so that the figures may be interpreted as net present costs. The system with the lowest net present cost therefore represents the most preferred option.

From Table 2 it can be seen that the NPV value of Option 2 (two-staged PSA plus nitrogen bottle supply) is considerably lower than that of Option 1 (pure bottle supply). The benefit is approximately $45,500 over a period of 15 years, or 27% of the net present cost of Option 1. If the drier use time can be extended to a full 12 months, the potential NPV saving during this period would be increased to $125,000, or 43% of the net present cost of Option 1.

Table 2 also indicates that, excluding labour and maintenance costs, the operating cost for CA gas provision of Option 2 is around $4,000 per annum or about $0.05 per kg of dried apples. This is very small compared with the current dried apple wholesale price of $5-10 per kg. It shows that the added cost of the controlled atmosphere is relatively small.

5. Conclusion

This paper has presented a study of the design of a CA dehumidifier fruit drier. The process conditions for CA drying have been identified. A range of technical and design options have also been evaluated. It has been shown that due to the high costs and the extended time of establishing the correct kiln environment, currently available oxygen scavengers and scrubber machines would not be suitable for the use in large-scale applications of industrial drying. There are also some uncertainties in the operation of the proposed plenum/stack gas isolation system.

A prototype design of a commercial CA dehumidifier kiln has been outlined. The cost analysis has indicated that the option of PSA charge plus bottle nitrogen liquid supply would be more viable than that of the pure bottle supply, particularly with extended kiln use time. It has also been shown that the added cost for provision of CA gas for this drier would be relatively small, around $0.05 per kg dried apples.

A number of directions for future research are identified. These include further investigation and improvements of gas loss control and recovery techniques. Further experiments and measurements of fruit properties under different modified atmospheres are also desirable.

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