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THE EFFECT OF COOLSTORE DESIGN AND OPERATION ON AIR RELATIVE HUMIDITY

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ABSTRACT

Coolstore air relative humidity (RH) is an important factor affecting the quality of horticultural products, particularly via product moisture loss. RH also has an important effect on the performance of the refrigeration evaporators and can affect the strength of paper-based packaging materials. In a large New Zealand apple coolstore, RH increased from about 75% early in season to 90% at the end, as activities in the coolstore and external conditions changed.

A steady-state analysis of sensible and latent heat entry and heat removal during four typical operational periods over the season was carried out. Predicted RH was in good agreement with measured data. For the coolstore studied, evaporator surface area and the occurrence of pre-cooling within the coolstore were the design and operational factors having greatest effect on RH. Door protection and management, and floor insulation were the next most significant factors. The method of analysis has more general application and could be used in a variety of situations so that design for optimum RH can be performed systematically.

Key Words : Relative Humidity, Coolstore, Design, Operation, Heat Load Analysis

INTRODUCTION

In recent years, there has been an increase in demand for fresh horticultural produce as consumers become more health and quality conscious. Generally tighter control of storage conditions is needed for chilled fresh produce than for product preserved by freezing, canning or drying due to higher inherent rates of quality deterioration in fresh produce. Although auxiliary treatments such as atmospheric modification through modified atmosphere packaging (MAP) or controlled atmosphere (CA) storage are beneficial, control of temperature remains the prime means of quality preservation. Better temperature control, and MAP or CA storage make longer storage times possible, but this allows more time for weight loss. Hence weight loss control is increasingly important, both because of the direct revenue loss, but also because dehydration can lead to deterioration of other quality attributes.

The rate of evaporative weight loss from product is related to relative humidity (RH). Generally for horticultural coolstores high RH is desirable to minimise the loss. However for some products there can be an upper RH limit due to the potential for microbial growth and spoilage. In addition, too high RH can lead to a loss of strength of paper-based packaging due to moisture uptake. There is therefore an optimum RH for any coolstore where the best balance of these effects is achieved. RH also affects performance of refrigeration evaporators with consequences for their design. For many refrigerated coolstore systems RH is not a design or controlled variable, rather the value achieved is a consequence of coolstore design and operation. To avoid the need to use specialised designs such as air wash systems, which have greater costs, it is desirable to be able to design for and control relative humidity to optimum levels in coolstores using conventional refrigeration system designs.

In operational practice, RH is determined by the balance between the rate of water vapour entry into the air and the rate of water vapour removal from the air. Entry is mainly through doorways and by evaporative water loss from product. Removal is principally by condensation or frosting on the refrigeration evaporators, but also by condensation or frosting on other surfaces, such as walls near the source of moisture entry, and adsorption by packaging materials. RH continuously adjusts to maintain the balance between entry and removal rates. The conceptual relationships between RH and the various mechanisms for moisture transfer in coolstores for horticultural products are illustrated in Figure 1.

The aim of this paper is to explore whether the type of methodology implied by Figure 1 can be used in a quantitative manner to predict RH for a New Zealand apple coolstore, and to carry out sensitivity analyses for the main design and operational variables.

MATERIALS AND METHODS

Apple Coolstore Description

The apple coolstore has floor dimensions of 57 m by 60 m and is 10.6 m high. It has the capacity to store 3760 tonnes of apples when full and is operated for about six months each year starting mid February. All fruit is handled as pallets of fifty 20 kg cartons (18.5 kg of fruit, 1.5 kg of cardboard packaging). The coolstore provides both bulk storage of apples at 0.0 ± 0.5°C, and pre-cooling of fruit early in the season. It has an uninsulated 150 mm thick concrete floor; walls and roof have a sheet steel exterior supported by a steel portal frame with 50 mm thick sprayed polyurethane foam insulation on walls and 65 mm thick on the ceiling. Two manually operated main doors (3.7 m high by 2.8 m wide) open from an outside area and are both unprotected. Two personnel doors are seldom used. The coolstore has four pump-circulated ammonia evaporators, each with a heat transfer surface area of 2224 m^2, located behind a false wall at one end of the coolstore. Associated with each evaporator is a two speed fan drawing air from the coolstore. Two fans discharge into the coolstore in the immediate vicinity of the evaporators, whilst the remaining two fans discharge into a central duct carrying the air to the far end of the coolstore. By appropriate pallet placement, the space through which return air passes to each of the four fans can be used as a pre-cooler; cooling 96 pallets of fruit from about 15 - 20 °C down to about 5 °C over 24 hours. The fans are operated on high speed (30 kW, 37.5 m^3/s) during pre-cooling, and low speed (13 kW, 22.5 m^3/s) whilst on coolstore duty. Water defrosting of each evaporator is performed daily.

During the 1990 season a detailed survey of temperature and RH through the coolstore as well as ambient and refrigeration system parameters was performed. Details are reported elsewhere (Amos *et al.*, 1993). The average air temperature was held reasonably close to the setpoint of 0°C as there was surplus refrigeration capacity available. Figure 2 shows measured RH data for a typical position in the coolstore commencing 29 April when pre-cooling had been completed for the season. Daily mean RH values measured during full coolstore surveys on 12 March, 7 May and 23 May were 76%, 79% and 86% respectively. The general trend of increasing RH over the season could well occur in other horticultural product coolstores.

Sensible and Latent Heat Load Analyses

The coolstore operating season was split into four distinct operating periods, labelled A to D. Period A represented the start of the season when ambient temperatures were high, there was considerable activity moving fruit into and out of the store, all pre-coolers were being used and amount of fruit in long-term storage was low but increasing. In Period B ambient conditions had cooled, door activity was the same as Period A as fruit was moved out of the store for shipment to export markets, and half the number of pre-coolers were used. In Period C pre-cooling had stopped, the store was nearly full with bulk stored fruit and there was little loading or unloading activity. In Period D ambient conditions were coolest, but work activity was greater than in Period C as stored fruit was unloaded for shipment to overseas markets. Table 1 summarises the operating characteristics for each of these periods.

Steady-state analyses of latent (water vapour) and sensible heat entry and removal rates were performed for each period using the "Room" program of the RADS package (Cleland, 1985; Cornelius, 1991). Heat loads and removal were averaged over a 24 hour period. In these analyses product weight losses were predicted using the transpiration coefficient data of Gaffney *et al.* (1985) and the measured RH. Respiration loads were estimated using the relationships for apples given by Gaffney *et al.* (1985). Standard methods were used to predict product sensible heat, wall and door loads (ASHRAE ,1990; Cleland and Cleland, 1992; Cornelius, 1991). Floor heat loads were calculated using measured underfloor temperature data at 0.5 m below the concrete slab (Table 1). Water removal due to adsorption by packaging (negative latent load) was determined using moisture isotherm data given by Wink (1961). It was assumed that equilibrium moisture contents were quickly achieved after packaging entered the coolstore. Water removal by condensation on other surfaces was ignored. Defrost heat load was also ignored because little of the heat added could enter the store air due to the particular equipment configuration.

Within the RADS package the model used to describe heat removal by the evaporator coil was (Cornelius, 1991):

$$\Phi_{tot} = \Phi_{sens} + \Phi_{lat} = \frac{\Phi_{sens}}{\mathrm{SHR}} = \frac{UA\ (\ T_{on} - T_e\ )}{\mathrm{SHR}} \qquad (1)$$

where:

$$\mathrm{SHR} = \frac{1}{1 + \dfrac{L\,(H_{on} - H_s)}{c_a\,(T_{on} - T_s)}} \qquad (2)$$

$$T_s = T_{on} - 0.85\,(T_{on} - T_e) \qquad (3)$$

and: ϕ_{tot} = total heat load (kW)
ϕ_{sens} = sensible heat load (kW)
ϕ_{lat} = latent heat load (kW)
SHR = sensible heat ratio
UA = coil sensible heat rating based on air-on TD (kW/°C)
L = latent heat of condensation and freezing (kJ/kg)
c_a = specific heat capacity of dry air (kJ/kg °C)
T_{on} = air-on temperature (°C)
T_e = refrigerant evaporation temperature (°C)
T_s = average evaporator surface temperature (°C)
H_{on} = Air-on humidity (kg H_2O/kg Dry Air)
H_s = Air saturation humidity at T_s (kg/kg)

Iterations on evaporation temperature and coolstore RH were performed until balance was achieved between both:

- the total heat load entering the air and the total being removed by the evaporators; and
- SHR for the heat load entering the air and the SHR for heat removed by the evaporators.

Sensitivity analyses were also performed to assess the effect of the following design and operational parameters:

- halving evaporator surface area;
- installation of door protection to reduce the door loads by 90%;
- installation of 150 mm polyurethane floor insulation;
- no pre-cooling within the coolstore.

All factors other than the variable of interest were held constant during each analysis.

RESULTS AND DISCUSSION

Table 2 summarises the predicted heat loads and mean coolstore relative humidities. The agreement between the RH predicted by the heat load analysis and the measured RH is good. This suggests that the most important heat loads and mechanisms for water vapour transfer have been modelled accurately. The general trend of RH starting low and increasing through the season is commensurate with high ambient temperatures and pre-cooling occurring at the start of the season, and low ambient conditions and no pre-cooling, at the end.

Influence of Facility Design

The design engineer can influence the ultimate RH by altering the balance between the sensible and latent loads entering the coolstore. For example, if higher RH is desired then one way of achieving this is to decrease the SHR of the loads entering the facility (higher latent or lower sensible load). Given the constraint that it is not desirable to increase the total heat load on the refrigeration system, lowering the sensible component is usually the best option. The sensitivity analysis reported in Table 3 suggests that by insulating the floor a slight increase in RH by about 1-2% could be achieved. Increasing insulation levels on the walls and roof would also be expected to cause a rise in RH. In the coolstore studied the floor load is only 4% of the total load so adding insulation has less effect than it might have in other situations where it is a larger component.

The refrigeration engineer can design the evaporators so that more or less moisture is removed per unit of sensible heat load. For example, a cooling system with a large surface area and small temperature difference (TD) between the air and the refrigerant will generally operate with a higher SHR than one with a small area and large TD. Hence the RH will be higher to achieve the balance between moisture entry and removal rates. Halving the evaporator surface area has the effect of approximately doubling the TD. Table 3 suggests that RH is lowered by 2-4% when the load and TD are quite large in Periods A and B, but is lowered by 6-7% later in the season. This implies that because of the largely sensible heat load, evaporator surface areas for pre-cooling facilities can be kept relatively small without reducing RH significantly . However bulk storage facilities would benefit more from large evaporator surface areas, given their lower SHR.

Table 3 shows that door protection lowers the total heat load on the coolstore resulting in lower evaporator TD. However the predicted mean coolstore RH is lower. Door protection reduces a large source of latent heat thus resulting in a higher mean SHR (e.g. 0.80 without protection, 0.82 with protection for Period A), and leading to lower RH.

Influence of Operation

The operator of the coolstore is constrained by the design of the overall system but can still influence RH and product moisture loss. Factors that can be important are pre-cooling of fruit within a bulk storage facility, door management, and stacking arrangement of pallets.

Table 3 shows that eliminating pre-cooling from the coolstore resulted in a large increase in predicted mean RH from 74% to 86% during Period A and from 84% to 90% during Period B. Table 2 shows that the pre-cooling heat load is the largest load on the coolstore for both Periods A and B, being 50% of the load in Period A and 36% in Period B. The pre-cooling load is predominantly sensible, especially as the packaging associated with pre-cooling fruit adsorbs water vapour. Removal of pre-cooling thus reduces the overall SHR and hence the mean RH increases.

The effect of improved door management to reduce the frequency and duration of openings on RH would be similar to that of door protection.

Close stacking of storage bins can restrict air flow through the product, giving localised increases in RH and decreases in product moisture loss. However if the ventilation rate is too low then the product heat generation due to respiration can cause localised hot spots in the fruit, increasing vapour pressure to an extent which can more than counteract the beneficial effect of localised increase in RH.

CONCLUSIONS

Coolstore RH is determined by the balance between the rate of moisture entry versus the rate of moisture removal. Coolstore design and operation can significantly influence this balance and hence the resulting RH. For an apple coolstore operating under New Zealand conditions a sensible and latent heat load and removal analysis gave good prediction of measured RH data. For the apple coolstore the analysis showed that evaporator coil surface area and pre-cooling within the coolstore were the design and operational parameters having greatest effect on RH. Door protection and management and floor insulation were the next most significant factors. The methodology used should have more general application.

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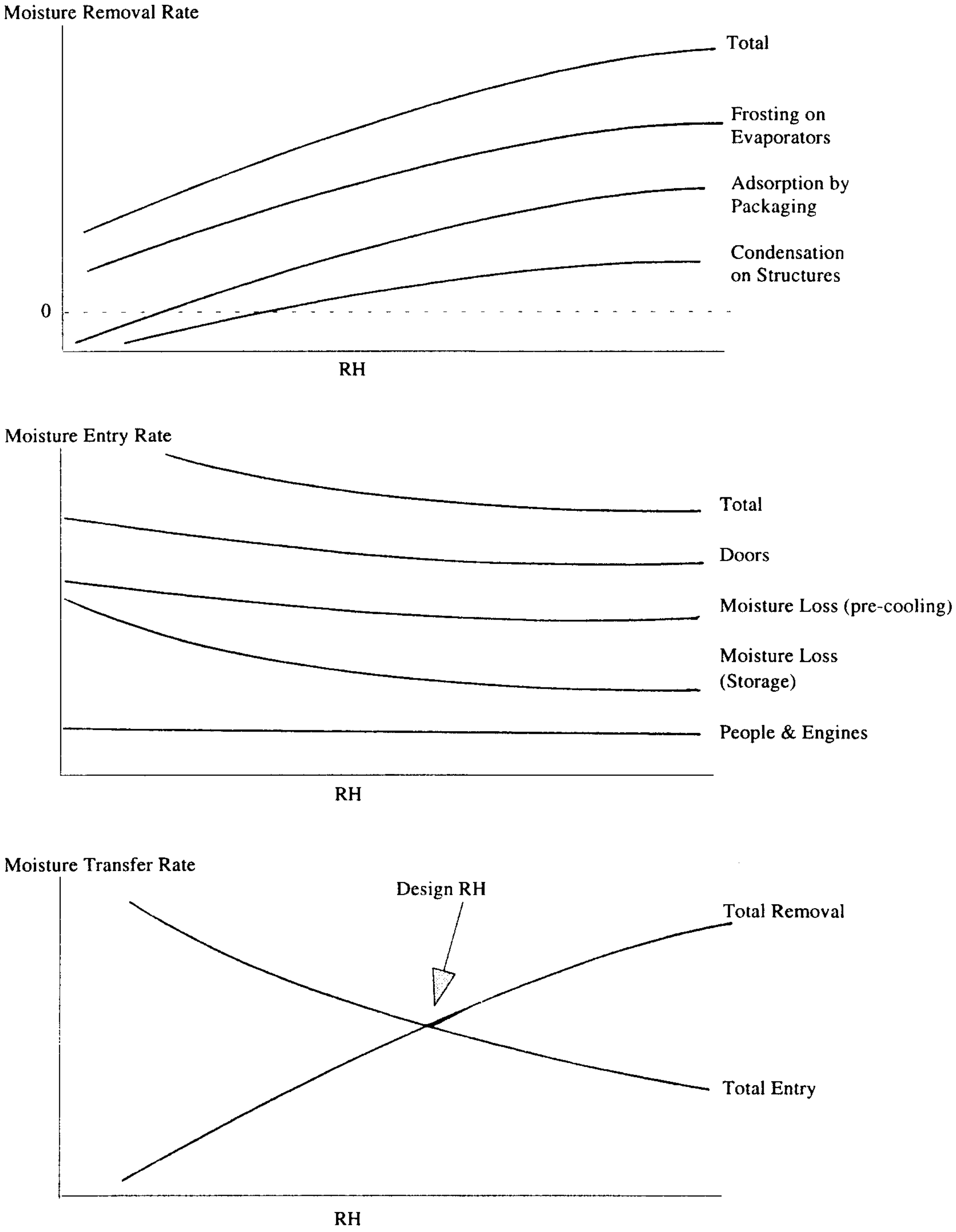

Figure 1. Conceptual representation of effects of RH on water vapour transfer in coolstores

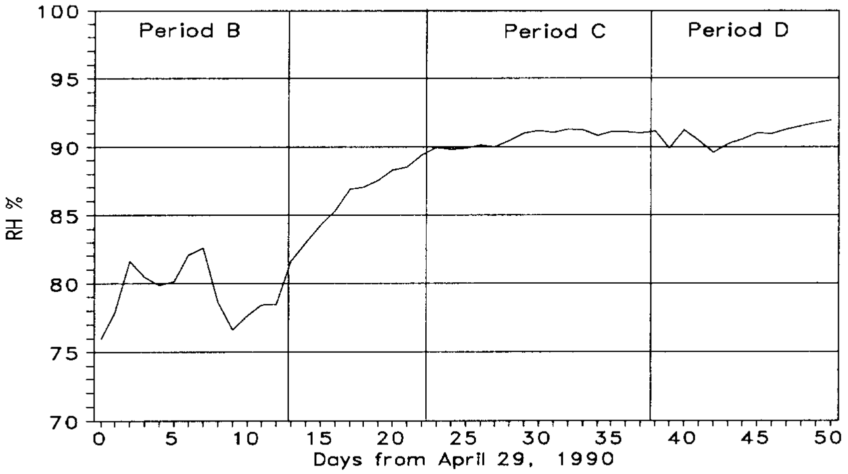

Figure 2. Daily average RH for a position within the bulk storage area of the coolstore

Table 1. Operational Characteristics of the Apple Coolstore

Period	**A** March	**B** Early-May	**C** Late-May	**D** June
Ambient Temperature (°C)	20	15	12	12
Ambient RH (%)	70	76	80	80
Underfloor Temperature (°C)	7	3.2	2.7	2.7
Pre-Cooled Fruit:				
No. of Pallets Loaded Daily	384	192	0	0
Weight Loss (%/day)	0.5	0.3	0	0
Initial Temperature (°C)	20	15	0	0
Packaging Weight Gain (%)	2.1	4.0	0	0
Bulk Stored Fruit:				
No. of Pallets Present	1500	3000	3000	3000
Weight Loss (%/day)	0.07	0.05	0.009	0.009
No. of Doors Used	2	2	0	1
% of Time Doors Open	12.5	12.5	0	15

Table 2. Predicted Coolstore Heat Loads, Evaporation Temperature and Mean RH

Period	A		B		C		D	
Heat Load Component	ϕ_{sens} (kW)	ϕ_{lat} (kW)	ϕ_{sens} (kW)	ϕ_{lat} (kW)	ϕ_{sens} (kW)	ϕ_{lat} (kW)	ϕ_{sens} (kW)	ϕ_{lat} (kW)
Bulk Storage	-15	28	-13	40	20	7	20	7
Pre-Cooling	262	51	103	15	0	0	0	0
Packaging	8	-8	17	-17	0	0	0	0
Doors	35	32	22	18	0	0	7	5
Walls & Roof	58	0	44	0	28	0	28	0
Floor	26	0	12	0	10	0	10	0
Fans	118	0	80	0	42	0	42	0
Miscellaneous	13	0	8	0	6	0	6	0
Total (kW)	505	103	272	57	106	7	113	12
ϕ_{tot} (kW)	608		329		113		125	
SHR	0.83		0.83		0.94		0.90	
T_{on} (°C)	0.0		0.0		0.0		0.0	
T_e (°C)	-8.0		-4.5		-1.8		-1.9	
Predicted RH (%)	74		84		90		90	
Measured RH (%)	76		82		90		91	

Table 3. Effect of Design and Operation on Mean Coolstore RH

	ϕ_{tot} (kW)	SHR	T_e (°C)	RH (%)
Period A:				
Base Case (Table 2)	608	0.83	-8.0	73.5
Half Evaporator Area	608	0.81	-14.8	70.0
Floor Insulation	589	0.78	-7.6	75.0
Door Protection	551	0.86	-7.3	72.0
No Pre-Cooling	312	0.80	-3.7	86.0
Period B:				
Base Case (Table 2)	329	0.83	-4.5	83.5
Half Evaporator Area	329	0.80	-8.6	80.0
Floor Insulation	319	0.83	-3.6	86.0
Door Protection	292	0.85	-4.0	84.5
No Pre-Cooling	198	0.79	-2.7	90.0
Period C:				
Base Case (Table 2)	113	0.93	-1.8	90.0
Half Evaporator Area	113	0.93	-3.1	84.0
Floor Insulation	105	0.93	-1.6	91.0
Period D:				
Base Case (Table 2)	125	0.90	-1.9	90.1
Half Evaporator Area	125	0.90	-3.5	83.0
Floor Insulation	117	0.89	-1.8	91.5