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PRACTICAL APPLICATIONS OF TRANSPIRATION COEFFICIENT OF HORTICULTURAL PRODUCE

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ABSTRACT

PRACTICAL APPLICATIONS OF TRANSPIRATION COEFFICIENT OF HORTICULTURAL PRODUCE

Like the thermal properties and the heat generation of products, the transpiration coefficient will find a column in the tables on product properties.
The following applications are mentioned: mass loss, safe dimensions of packages, centre temparature in packages during cooling down processes, keepability and quality loss, air circulation, level of moisture loss protection, relative humidity in cold rooms.

Keywords

Transpiration coefficient

Safe dimensions

Packages

Heat generation

Moisture loss

1. INTRODUCTION

About 6 years ago Sastry, e.a. (1) discussed the transpiration of stored fruit and vegetables.

His literature review showed that the transpiration coefficient is a function of a lot of factors. He discussed effects of air movement, respiration, size, shape, etc. The paper also gave a rather short list of measured transpiration coefficients of certain fruits and vegetables. In the meanwhile Ficek (2) published a much longer list and the Sprenger Institute has measured the transpiration coefficient in a current project. This paper therefore will not deal with the measurement of transpiration coefficients and the 'disturbing' factors, but will give a review of the practical applicability of transpiration coefficients with one important exception: the transpiration coefficient as a function of the vapour-pressure deficit. The relation commonly used is: transpiration rate = transpiration coefficient * vapour pressure deficit. This relation is always valid but the transpiration coefficient can not be considered as a constant product property. Our experience is that the transpiration coefficient, especially above 90% r.h., low temperatures and little air movement does not form a constant. Therefore this paper starts with a discussion of this phenomenon and then will proceed with practical applications.

2. EFFECT OF VAPOUR PRESSURE DEFICIT ON THE TRANSPIRATION COEFFICIENT

The transpiration coefficient is defined as the moisture loss of a product per time per vapour pressure deficit.

$$k = \frac{\Delta m}{\bar{m} \cdot \Delta p \cdot \Delta t} \qquad (1)$$

The vapour pressure deficit is the difference between the vapour pressure of the intercellular spaces in the product and the vapour pressure of the surroundings. The initial freezing point of a product gives relevant information, because 1 K below $0^{\circ}C$ equals a decrease of 1% r.h. Most leafy products have an initial freezing point of $-0.5^{\circ}C$ leading to a product internal relative humidity of 99.5%. The internal relative humidity can be considered as constant, only under extreme conditions. At $20^{\circ}C$ and 50% r.h. of the surrounding air (waterpotential -936 bar), the internal relative humidity just below the skin of an apple was 98.2% while near the centre of the apple a relative humidity of 99.0% was measured by Woensel (3).

Another complicating factor is the measurement of the moisture loss by means of mass detection.

One has to correct the mass loss for carbon-loss in order to get the moisture loss of fresh respiring products. These corrections are necessary if one measures the transpiration coefficient under small vapour pressure deficits. It is observed that the transpiration coefficient increases with decreasing vapour pressure deficits especially with an air movement of 5 to 15 cm/s.

Fockens (4) explained this observation by introducing the shape of the epidermal cells. With small vapour pressure deficits these cells are turgid and spherically shaped, introducing air channels between cells and therefore increasing permeability. Under elevated vapour pressure deficits the cells are flattened, thereby closing the air channels and decreasing skin permeability.

Other possible explanations are change of permeability of epidermal wax or change of stomata or lenticel opening at high relative humidity. Table 1 indicates that only rhubarb and cucumber show a significant change of stomata opening at a high relative humidity during storage in the dark at $10^{\circ}C$. Experiments on the permeability of epidermal wax are executed with tomatoes because this product has no stomata. Corolla and stem opening were sealed water tight and the transpiration coefficient (based on unit surface) was 30%

Table 1. Percentage open stomata of certain products stored at 10°C in the dark

product	relative humidity	
	80%	96%
snap bean	42	50
cucumber	60	77
rhubarb	12	35
endive	92	97
witloof chicory	33	33

more at a high relative humidity (96%) compared with a low relative humidity. These experiments show that the transpiration coefficient is influenced by actions of the living product, thereby complicating the use of the transpiration rate equation ($\Delta m = k \cdot \bar{m} \cdot \Delta t \cdot \Delta p$) in practical applications.

3. APPLICATIONS

3.1. Transpiration coefficient in court

On Januari 22 of last year a journal in the Netherlands showed the headline: "Auction cleared of blemish".

The court's decision was based on the transpiration coefficients of Golden Delicious and Schone van Boskoop apples. The charge was that the auction did embezzle 600 ton or 8.5% of a lot of intervention fruit. Intervention is a system to secure the grower a minimum prize fulfilling the conditions that the fruit must be excluded from the market.

The transpiration coefficient of Golden Delicious and Schone van Boskoop is $0.54 \cdot 10^{-10}$ and $0.95 \cdot 10^{-10}$ kg/(kg · Pa · s), respectively resulting in a moisture loss depending on the vapour pressure deficit. The carbon loss can be estimated using the temperature of the apples (see application 3.2). Another important mass loss phenomenon, in this case, is the moisture loss of the wooden crates. In the cold room the mean relative humidity is 96.6%, while the mean relative humidity of the outside conditions is 80%. Every kg of dry wood will lose 9% because of the transition from cold room to outdoor conditioning, resulting in an apparent mass loss of the apples of 2%. Table 2 shows the result of the calculations, indicating that a loss of 8,5% can be explained.

Table 2. Mass loss (%) of apples during 6 weeks of storage in outside conditions

T °C	moisture loss G	moisture loss S	carbon loss	desorption loss of wood	mass loss G	mass loss S
- 5	1.20	2.10	0.10	2	3.3	4.2
0	1.92	3.36	0.14	2	4.1	5.5
5	2.76	4.86	0.19	2	5.0	7.1
10	3.84	6.78	0.43	2	6.3	9.2
15	5.34	9.42	0.62	2	8.0	12.0
20	7.32	12.9	0.80	2	10.1	15.7

G = Golden Delicious

S = Schone van Boskoop

3.2. Moisture loss≠mass loss

The calculation of carbon loss with the respiration equation $C_6H_{12}O_6 + 6\ O_2 \Rightarrow 6\ H_2O + 6\ CO_2 + 2824$ kJ, using the heat production of the product, is no problem because a carbon loss of 0.66%/month ⇔ 0,1 kW/ton. However, it is more convenient to use a nomogram and correlate mass-, carbon-and moisture loss using the heat production as a parameter (see fig. 1). If q is the heat production then the horizontal distance to b is the carbon loss. From the mass loss at a and the intercept c, the effective heat generation q_{eff} is found. The effective heat generation effects the safe dimensions of packages filled with heat generating and moisture losing products.

3.3. Safe dimensions of packaging at steady temperatures

The choice of packagings and unit loads is normally based on standardized dimensions (ISO, OECD*), package cost, stacking strength, etc. All these factors are influenced by product properties. In practice the combination product-packaging must demonstrate the expectations, but it is possible to estimate whether the dimension of packaging unit load is safe in regard of the keepability of the product. First of all the temperature spread in the load, during storage when the temperature is steady, must not exceed as a rule of thumb 1°C. Secondly the dimensions of the packaging must allow the necessary "quick" cooling down using ordinary room cooling. The steady state temperature spread in packages or unit loads is:

$$\Delta T = \frac{q_{eff}\ X^2}{n\ \lambda} \qquad (2)$$

symbol	unit	quantity
ΔT	^oC or K	temperature difference
q_{eff}	W/m^3	effective heat generation
X	m	smallest distance from centre to surface
n	-	shape factor
λ	$W/(m \cdot K)$	thermal conductivity of the bulk

* ISO : International Standardisation Organisation
OECD: Organisation for Economic Cooperation and Development

The shape factor normally is 3.5 (cube = 4.4, wall = 2, cylinder = 4, sphere = 6), the thermal conductivity is almost always 0.3 W/(m · K) with spherical products and 0.2 W/(m · K) with leafy products, and X must be calculated ΔT = 1 K, yield $X_s = \sqrt{\eta\ \lambda / q_{eff}}$. The safe dimension of cut flowers depends on the heat generation (for example: roses - about 100 W/ton at 5°C) and the transpiration coefficient, which is approximately $65 \cdot 10^{-10}$ kg/(kg · Pa · s).

Forgetting moisture loss, which acts as a negative heat generation, the safe dimension is $X_s = \sqrt{3.5 * 0.2/20} = 0.19$ m. The value of $q_{eff} = 20$ W/m³ is caused by using a bulk density 0.2 ton/m³ of the roses. A safe dimension of 19 cm appears to be unprofitable using transport containers, while every unit load of 40 cm * 40 cm * 40 cm needs an air channel of some centimeters.
With moisture loss the effective heat generation is:

$$Q_{eff} = 1.063 * Q - h_{fg} * \frac{\Delta m}{m \Delta t} \qquad (3)$$

while the moisture loss is:

$$\frac{\Delta m}{m \Delta t} = k \cdot \Delta p \qquad (4)$$

symbol	unit	quantity
Q	W/kg	heat generation
$h_{fg} = 2,48 \cdot 10^6$	J/kg	heat of evaporation
Δm	kg	moisture loss
m	kg	product mass
Δt	s	time
k	kg/(kg · Pa · s)	transpiration coefficient
$\Delta p = 4,4$	Pa	vapour pressure deficit if r.h. = 99%, T = 5°C

With a mean vapour pressure deficit of 4,4 Pa at a temperature of 5°C the moisture loss is $65 \cdot 10^{-10} * 4.4 = 286 \cdot 10^{-10}$ kg/(kg · s) and the effective heat generation must be $Q_{eff} = 1.063 * 0.1 - 0.071 = 0.035$ W/kg = 35 W/ton. The assumption of the value of the vapour pressure deficit around the roses determines the effective heat generation according to table 3.

Table 3. Safe Dimension of packagings or unit loads of roses
as a function of relative humidity at 5°C

r.h. %	q W/m³	q_{eff} W/m³	X m
99.5	20	20	0.19
99.0	20	7.2	0.31
98.5	20	-6.8	0.32
97.5	20	-20.9	0.18

If it is possible to maintain a relative humidity of 98.7% at the product and a temperature of 5°C in packages of roses, there is no restriction for the dimension of the packaging unit. Applications 3.8 deals with the vapour pressure profile in packagings. Knowing the fact that it is nearly impossible to control the relative humidity the safest Safe Dimension is still 20 cm.

3.4. Centre temperature in packagings during cooling down processes

Cooling down rates of products in the centre of unit loads are especially a function of the heat generation. If the latent heat of transpiration exceeds the heat generation of the products, the effective heat production in the load is negative. The centre temperature of a unit load of Chineese cabbage, with dimensions 0,6 m x 0.8 m x 1 m, cooling down from 20°C to 0°C, will be 5°C after 100 hours when the effective heat production is 0 W/m³. With an effective

heat production of -30 W/m^3 this temperature is achieved after 65 hours. Although transpiration normally identifies quality loss, moisture loss during cooling down processes must be considered as a big help.
Long cold storage of horticultural produce in fact seems to be impossible without moisture loss.

3.5. Moisture loss is quality loss

The difference between 98% and 97% is not 1% but 100%, when it comes to moisture loss of products with an equilibrium relative humidity of 99%. A factor of importance determining the quality of fruits and vegetables is the wrinkling of the skin. The conclusion of numerous experiments is that the maximum allowable moisture loss of leafy products, like endive, flowers, spinach, is 10% and of all other products (like cucumber, leek) 4%.
With this information and the transpiration coefficient it is possible to calculate for example the shelf life of a cucumber at 15^{o}C and 50% r.h.
The transpiration coefficient of a cucumber is $2.5 \cdot 10^{-10}$ kg/(kg · Pa · s) and the vapour pressure deficit equals $\Delta p = 1705 * 0.5 = 825$ Pa.
Moisture loss is $\Delta m/m = 0.04$ so the calculated shelf life is, according to equation 4:

$$\Delta t = \frac{\Delta m}{m \cdot k \cdot \Delta p} = 25 \text{ hours.}$$

This result is useful to convince retail-owners not to display fruits and vegetables in the sunshine or unprotected conditions.

3.6. Moisture loss is money loss

Of course moisture loss is money loss if fresh fruits and vegetables are sold by kg, and the relation is linear, except if the moisture loss is accompanied by shrinking. This phenomenon causes for example that apples of size 75-70 mm at the beginning of the storage are shifting partly to size 70-65 mm. At the end of the storage this shift mostly has a negative effect on profits as table 4 shows.

Table 4. Decrease of prize in % of pear "Conference" caused by shrinkage and moisture loss

size	to size	mass loss in %		
		4	6	8
55/65	45/55	7	11	15
60/70	55/65	3	7	10
65/up	60/70	5	8	11

3.7. Reducing energy-consumption in cold rooms by reducing the air circulation

Long storage of cabbage is done in some parts of the Netherlands with alternatingly profitable results. The market price of cabbage sometimes is very low, sometimes high, but in the last years the storage managers are anxious about the increasing energy costs. More insulation increases in most cases the costs, so the only way to reduce energy, is to reduce air circulation. Table 5 shows that reducing the air flow through the evaporatorfans considerably decreases the energy consumption, but is a continuous air circulation of 10 m^3/m^3 hour the optimal air movement in cabbage cold rooms? Noting that 81% of the product of cold room nr. 3 was quality class I there seems to be no problem, but this is only one experiment. The theoretical solution of this problem starts with the optimal storage condition of a product, $T \pm \Delta T$ ^{o}C and r.h. $\pm \Delta$ r.h. %.

Table 5. Energy consumption of 3 cabbage cold rooms under influence of air circulation

	cold room nr. 1	2	3
air circulation m^3/m^3 hour	38	18	10
total energy consumption kWh/(ton · week)	4.21	2.15	1.89
compressor %	37.2	56.1	56.1
evaporatorfans %	54.0	39.9	40.6
de-icing %	6.8	2.2	0.1
condensorfans %	2.0	1.8	3.2
class I product % of total	83.2	74.3	81.0

Normally the admissible changes around the optimal point are $\Delta T = 0.5^{\circ}C$ and Δ r.h. = 3%, giving a climatic working area. The change of the air condition during passage of the products is:

$$\frac{\Delta h}{\Delta x} = \frac{Q}{w} + C_w T_p$$

symbol	unit	quantity
h	J/kg	enthalpy of air
x	kg/kg	moisture content of air
Q	W/kg	heat generation of product
w	kg/(kg · s)	moisture loss of product
C_w	J/(kg · K)	specific heat of water
T_p	$^{\circ}C$	temperature of product

The moisture loss w depends of course on the transpiration coefficient of the product and the vapour pressure deficit. Figure 2 shows the development of the air conditions in a heap of potatoes, starting with a temperature of $4^{o}C$ and different relative humidities. The figure shows that $\Delta h/\Delta x$ can have a range of values, depending on the product properties. With most horticultural products the temperature in the first part of the stack will decrease and increase in the last part when the vapour pressure deficit becomes small enough to make the value $\Delta h/\Delta x = q/(k \cdot \Delta p) > 2500$ kJ/kg.

Figure 3 demonstrates a one step algorithme. The optimal point is $T = 2^{o}C$ and $\Delta p = 70$ Pa (= 90%), while the transpiration coefficient $k = 7.1 \cdot 10^{-10}$ kg/(kg · Pa · s) and the heat generation $q = 0.034$ W/kg .

The change of the air condition is $\Delta h/\Delta x = q/(k \cdot \Delta p) =$ 693 kJ/kg demonstrated in the Mollier diagram by the dotted line. This line has two intercepts with the extreme allowable air conditions a and b. The air flow is $g = w/\Delta x = 4.97 \cdot 10^{-8}/(4.07 - 3.75)10^{-3} = 1.55 \cdot 10^{-4}$ kg/(kg ·s) or translated in air circulation rate: $1{,}55 \cdot 10^{-4} \cdot 3600 \cdot \frac{\rho_{bulk}}{\rho_{air}} = 261 \cdot m^3$ air/(m^3 bulk · hour).

symbol	unit	quantity
g	kg/(kg · s)	air turn over
$\rho_{bulk} = 600$	kg/m^3	density of carrots in bulk
ρ_{air}	kg/m^3	density of air

This algorithme can be used to calculate (in many steps) the minimum air turn over during steady storage conditions, using pressure cooling systems or normal room cooling systems. In the last case a whole load is considered as a calculation unit. By the way, the optimal air circulation of cabbage is theoretically 30 m^3/m^3 hour.

3.8. Level of moisture loss protection of packagings

If one has to describe a whole pallet load as a unit, one has to calculate the mean moisture loss of the products in the packages, while the minimum and maximum moisture loss can also be of interest. In the literature, Cowell (5), Thorne (6), analytical solutions are given, leading to complicated expressions. For practical purposes it is convenient to define a level of moisture loss protection of packages: Protection factor = moisture loss of unpacked product/moiture loss of packed product. A protection factor of 1 indicates that the packaging does not influence the moisture loss. The level of protection is a function of the transpiration coefficient, the dimensions of the packaging and the vent hole area. We use a few rules of thumb: every packaging layer with 6 ot more % vent holes used with leafy products or cut flowers gives a protection factor of 4, every packaging layer used with spherical products like apples, tomatoes gives a protection factor of 2, but in practice it is very easy to measure the protection level of packagings.

3.9. Eggs in packagings and variations in time

The best instrument to measure small vapour pressure deficits in packages is an egg, and very cheap too. The transpiration coefficient of an egg is constant in time and independent of the air velocity. Calibrate every egg (without hair cracks) for one week in air with a constant known vapour pressure deficit and calculate the transpiration coefficient of every egg. Then place the eggs on certain locations in the packaging and measure the moisture loss in mg during at least a period of one week.

The transpiration coefficient of most products is not constant in time. Figure 4 shows measurements on various apple cultivars, indicating that a change of 25% during one storage season can be expected.

A change of a factor 2 must be expected in the value of the transpiration coëfficient with the next season.

3.10. Measurement of relative humidity in cold rooms does not predict moisture loss

In theory it is possible to determine moisture loss from the relative humidity in a cold room, knowing the protection level of the packagings and the transpiration coefficient of the product, and the air flow etc. .... but in this way theory will never fit in with practice. Theory is useful to study effects of changing cold room factors, like more insulation or smaller difference in temperature between the cooling coils and the air, on relative humidity and moisture loss.
The only way to predict the mean moisture loss of products during long storage is to measure the amount of water coming from the evaporators. This method works very well if some conditions are fulfilled: 1. ventilation less than 10 m^3/(hour · 500 m^3) to keep the influence of outside moisture content small and 2. defrosting with electricity or hot gas and 3. no flooding of the floor with water. With a watermeter we were able to show the influence of outside temperatures and temperature difference between the cooling coils and the cold room air, on mean moisture loss of apples stored in a room at the auction Geldermalsen. Table 6 shows that the moisture loss was not much effected by the temperature difference between the cooling coils (with ammonia as refrigerant) and cold room air. The correlation between moisture loss and outside temperatures was nearly 0, so the measured variations in daily waterflow cannot be explained by variation in heat gain through walls.
Moisture loss of products stored in cold rooms seems to depend on a lot of factors as application 3.11 will point out.

Table 6. Moisture loss of 150 ton Laxton as a function of the temperature difference between cooling coils and air

week nr.	ΔT °C	water flow liters/day
1	1.5	17.9
2	1.5	22.2
3	3	28.3
4	3	12.4
5	3	16.8
10	5	15.8
11	5	19.3
12	5	11.0

3.11. Relative humidity in cold rooms

The transpiration coefficient of stored products determines the water load of the evaporator, while the heat load is affected by sources as the wall heat gain, heat generation of product and fan power. The change of the air condition during passage of the evaporator is $\Delta h/\Delta x$ = heat load/water load and in fig. 5 a general representation of $\Delta h/\Delta x$ versus relative humidity is given.
At low relative humidities the vapour pressure deficit is high, resulting in a high water load and a small $\Delta h/\Delta x$. In general this product/cold room line depends on the moisture loss of the stored products. The second line in fig. 5 shows $\Delta h/\Delta x$ if the temperature of the wet coils is known using several relative humidities. With this theory it is possible to calculate the effect of changing cold room factors on moisture loss and relative humidity when, of course, the evaporator works.

In table 7 the moisture loss of apples under standard conditions is 5.7%/6 months with a relative humidity of 94.2%.

Very important is the effect of the transpiration coefficient, for a lower coefficient yields only 4.5% moisture loss surprisingly at 91.6% r.h. A higher coefficient causes more moisture loss at 96.3% r.h. This example shows the importance of the watermeter.

Table 7. Moisture loss and relative humidity as influenced by changes in cold room factors

change from standard	caused by	r.h. %	moisture loss %/6 months
ambient temperature $20^{\circ}C$ x 2		91.3	9.1
no floor insulation		91.5	8.9
transpiration coeff. x 1/2		91.6	4.5
protection level x 2		91.6	4.5
heat production x 2		92.6	7.6
half load x 1/2		93.5	6.5
ventilation (1 per day)		93.7	6.3
standard		94.2	5.7
water on floor		95.0	4.7
heat generation x 1/2		95.2	4.5
ambient temperature $5^{\circ}C$ x 1/2		95.7	3.9
transpiration coeff. x 2		96.3	6.4

design, use product

surrounding package

3.12. Storability and transpiration coefficient

If you like, it is possible to calculate the storability of fresh products with equations using heat generation and transpiration coefficient. The storability of spherical products like a potato is:

$$H = \frac{160}{q} + \frac{700}{k \cdot 10^{+10} \cdot \Delta p} \qquad (6)$$

symbol	unit	quality
H	weeks	storability
q	W/ton	heat generation at optimal storage temperature
k	kg/(kg · Pa · s)	transpiration coefficient
Δp	Pa	vapour pressure deficit ($60 < \Delta p < 300$)

For example the heat generation of the potato "Saturna" is 7.9 W/ton, the transpiration coefficient is $0.53 \cdot 10^{-10}$ kg/(kg · Pa · s), so the estimated storability is 33 weeks if $\Delta p = 100$ Pa.

Use with leafy products an equation like:

$$H = 7 - \frac{k \cdot 10^{+10}}{4} \qquad (7)$$

4. OUTLOOK

The availability of the transpiration coefficient of horticultural products, together with uncomplicated analytical equations or nomograms describing a specific problem, is very useful to explain certain observations. A few post-harvest applications related with moisture loss of horticultural produce are given in this paper. Some other applications, studied during the last year, are not mentioned: water gift to potted plants in closed packagings, increase of relative humidity in cold rooms when the evaporator does not work, condensation on products in packagings, transpiration coefficient of "scald" apples versus "normal" apples. It turns out as a complicating factor, that the transpiration coefficient is not a constant product property, but probably increases with decreasing vapour pressure deficit under moderate air flows, and also varies in time and season. The results of calculations therefore are only indicative as long as mathematical complications, like coupled heat- and mass transfer and non-constant properties, are not solved in a practical way.

In my opinion research on post-harvest problems related with moisture loss, must concentrate on solving potential and existing problems in a practical (cash and carry) manner to avoid the growth of the distance between research and practice.

Like the heat generation of products, the transpiration coefficient will find a column in the tables on product properties.

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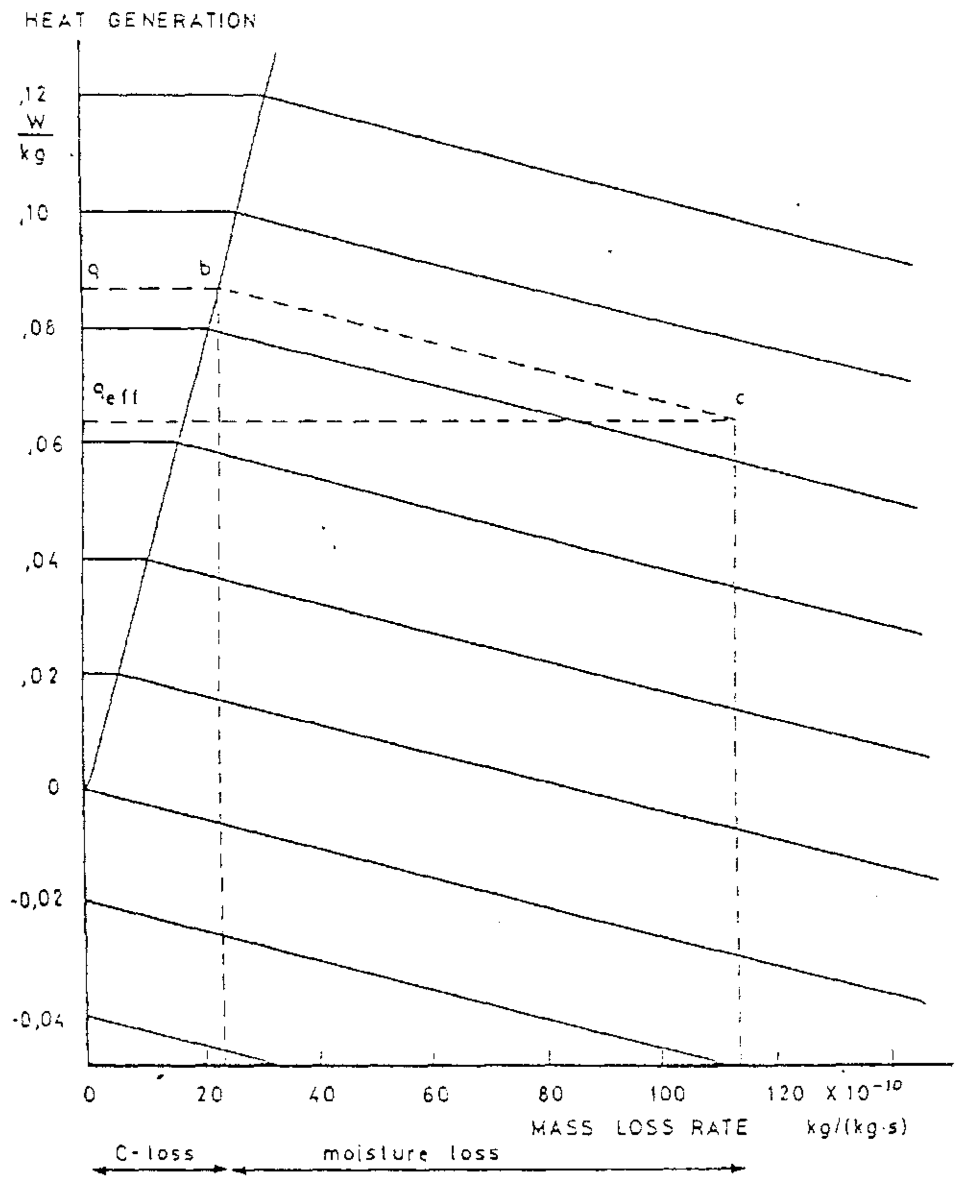

Fig. 1: Nomogram relating heat generation and mass loss

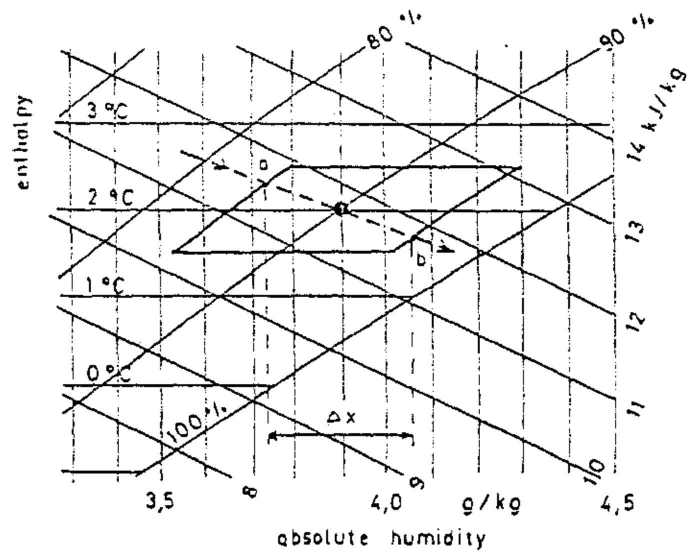

Fig. 3: The slope of Δh/Δx in a stack of carrots

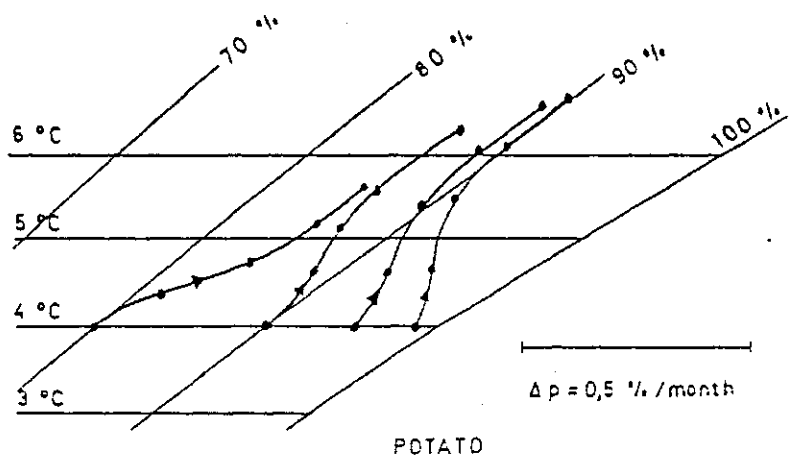

Fig. 2: The change of air conditions in a heap of potatoes

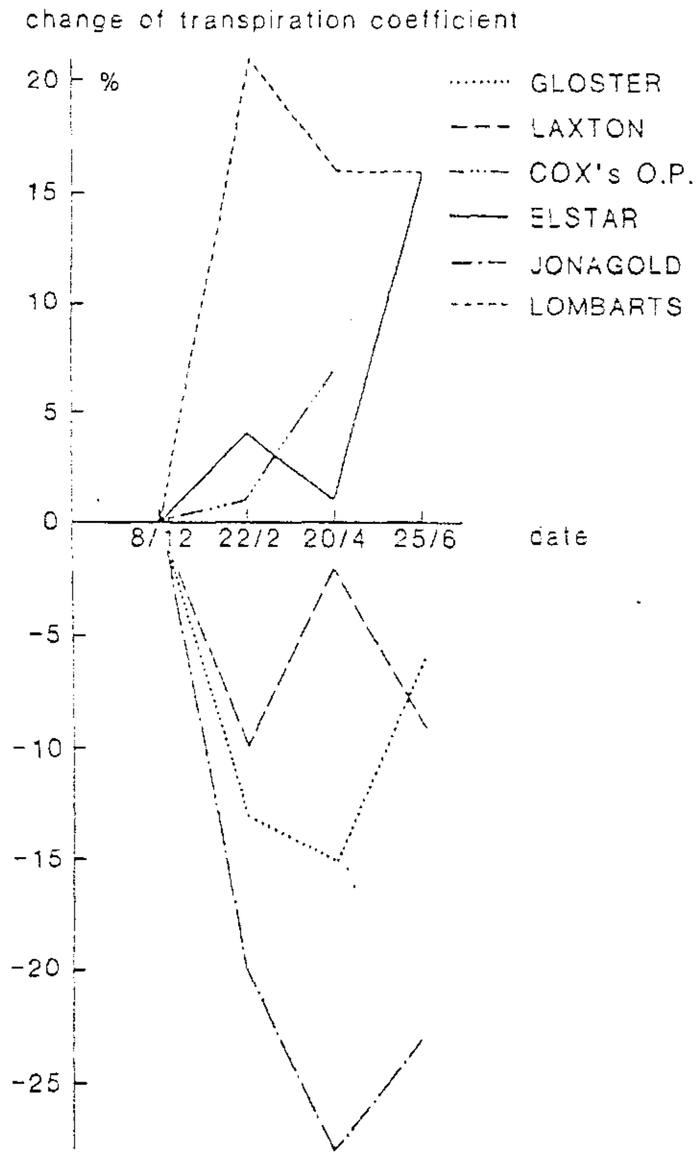

Fig. 4: Change of transpiration coefficient of apples during one season

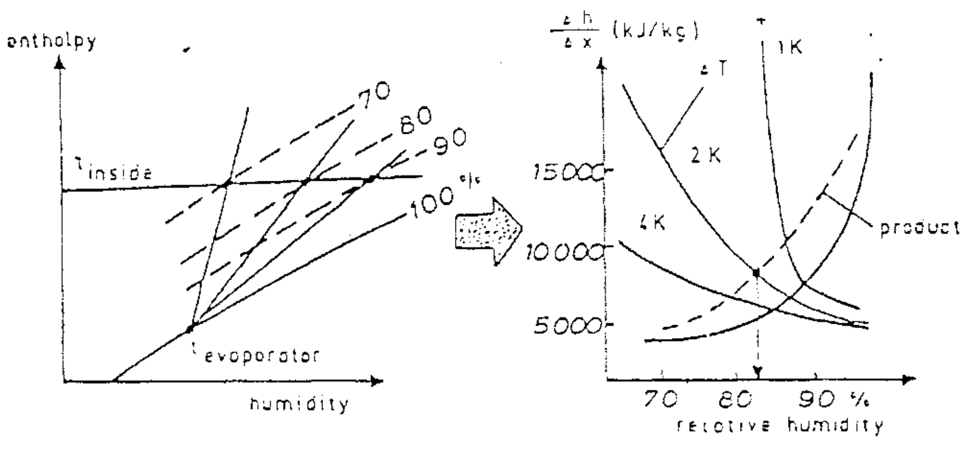

Fig. 5: Prediction of the relative humidity in a cold room