DYNAMIC CONTROL OF STORAGE ATMOSPHERES

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Summary

The storage conditions required for the retention of quality in fresh fruit and vegetables differ between species and cultivars. The present experimental procedure for determining optimum storage conditions is slow and tedious. This paper explores the possibility of automatically establishing and dynamically maintaining optimum storage conditons in both experimental and commercial stores. The control system seeks conditions that will cause the produce to respire at the lowest possible rate, without causing physiological disorders. The control procedure of such a system is discussed, and areas of uncertainty requiring further work are identified. The purpose of the paper is to draw comment and criticism of the proposal.

Introduction

Controlled atmosphere (CA) storage reduces the respiration rate of the stored produce. This is achieved by reducing both the temperature and oxygen levels and increasing the carbon dioxide level. The storage life of the produce is generally inversely proportional to the rate of respiration. Consequently, if the respiration rate is lowered the storage life is increased.

The respiration rate of many fruit and vegetables declines with decreasing oxygen levels until a minimum is reached. The rate then increases as anaerobic respiration predominates (figure 1). This response, commonly known as the 'Pasteur effect' (2) has been observed in the results of a number of authors (8,3). It is also possible that the respiration response of produce to other variables, such as temperature and carbon dioxide levels, may be characterised by a curve with a minimum. It can be argued that conditions that enable storage at the minimum of the respiration curve should also correspond to those achieving maximum storage life, provided that these conditions do not cause physiological injury.

for a single variable can be located quickly. The response to more than one variable may need to be optimized, for instance for temperature and oxygen and carbon dioxide levels. To quickly seek the optimum response to a number of variables it is necessary to use more sophisticated experimental designs such as the single-factor procedure or the method of steepest ascent (1).

A failing of this procedure to determine the optimum storage conditions is that the nature of the produce may change with time or injury may take time to appear. Therefore the storage trial must be performed for the full storage life of the produce. The sequential approach advocated then becomes much slower than the simultaneous designs used at present (ie random or factorial designs (1). The solution is to dynamically change the conditions of storage for the life of the produce. Thus the storage trial is a continuous series of sequential experiments performed on the produce to ensure that it is stored at the point of minimum respiation. While this procedure could be performed manually for experimental trials, it is very tedious and time consuming. A better solution would be to automate the procedure.

Automatic determination of the respiration minimum

An automatic computer based control system is being developed for commercial CA stores (10). It consists of a central computer that controls the plant in order to achieve the desired CA levels. The plant that may be controlled include catalytic burners to remove excess oxygen, activated charcoal scrubbers to remove excess carbon dioxide and ventilation fans to increase oxygen levels. The other parts of the control system include automatic gas analysers for both carbon dioxide and oxygen and a system of automatic valves for routing the store atmospheres between the stores and the plant. The plant recycles the gases back to the store after treatment. In parallel with this, a laboratory scale system is being developed using the same control procedure but with bottled gases to change the gas levels rather than mechanical plant.

Both systems use the conventional control procedure of maintaining constant conditions within the stores. However, the control program or algorithm collects the rates of change in gas levels for the various operations that occur in a CA store, i.e., respiration, ventilation and removal of carbon dioxide or oxygen. These rates are used to calculate the time of operation of the plant to restore the conditions within the stores to their desired levels (9). The rate of change of carbon dioxide within the store can be used by a dynamic control algorithm to find the respiration minimum. Therefore the automatic control program could be modified to seek the respiration minimum rather than merely maintaining static conditions.

In determining the optimum oxygen level the operation of the automatic control system would be to progressively lower the oxygen level, waiting each time for the system to stabilise, until the respiration rate increased rather than decreased for a decrease in the oxygen level. The control system would then hold the atmosphere at the oxygen level that gave the lowest respiration rate. The control system would continue to check the change in respiration rate for small changes in the oxygen level around the minimum. This will enable the control system to track the minimum if it moves with time. Minimum seeking is an established control algorithm and is known as 'hill climbing' (7).

Finding the initial minimum can be tackled a number of ways. If the position of the minimum was not approximately known, the minimum seeking algorithm could use a binary search to find it. Initially the oxygen level is reduced to half ambient. If this reduces the respiration rate, the level is halved again and again until the respiration rate increases. When the rate increases, the next level to be used is half way between the level that caused the increase and the preceding level. The whole process is repeated until the next change in oxygen is within the controller deadband (the zone around the set point in which the level can vary without causing control action). It is possible to find a minimum to within ± 0.2% in seven attempts, using a binary search. A binary search could be used when the atmosphere is established with nitrogen or respiration. It may be difficult to perform using catalytic burners, because of the necessity to stop the burner while conditions stabilized before restarting it for further reductions in the oxygen level.

If the position of the minimum is approximately known, the oxygen level could be reduced to that level and a binary search used to find the exact location. For instance, with apples, the oxygen level could be reduced to 3% (the lower limit for operation of catalytic burners), before the minimum seeking algorithm was used. Respiration would be used in conjunction with ventilation to obtain further step changes.

Once the minimum has been found, it can be tracked in time without introducing deliberate steps by using the normal fluctuations in the store atmosphere within the deadband. For instance, when controlling the oxygen level in a tightly sealed CA room, the oxygen level is nominally kept at say 2% ± 0.25%. The oxygen level can drop to 1.75% before the store will be ventilated, or rise to 2.25% before some of the oxygen is removed. The control system could use this movement around the set point to determine which way it should change the oxygen level in order to obtain the respiration minimum. If the respiration rate at 1.75% was lower than the respiration rate at 2.25% the set point could be lowered to 1.75% ± 0.25%. If the respiration rate at 1.5% was lower than at 1.75% or 2.0% the set point would be lowered further to 1.5% ± 0.25%. If the respiration rate at 1.25% and 1.75% were both higher than at 1.5%, the set point would remain at 1.5% and the system would continue to cycle within this deadband until the minimum moved.

Discussion

It is suspected that the minima do move. At the start of a season, Granny Smith apples can tolerate zero oxygen for the first couple of weeks. After months of normal CA storage, the apples can no longer tolerate the zero oxygen conditions and the oxygen level must be raised to avoid oxygen stress disorders. This either means that the respiration minimum moves up with time, or alternatively, the response of the apples to zero oxygen is slow and it takes a couple of weeks for oxygen stress to observed. The latter explanation is unlikely if apples have a similar response time to sweet potato. Solomos (8) showed that sweet potatoes began responding to the change in atmospheres within hours and achieved a stable equilibrium response within a day.

If the minimum does move the dynamic controller can follow it. It should be possible for the controller to provide zero initial oxygen to start with, if the minimum is at zero oxygen, and to increase the oxygen level as the minimum moves away from zero oxygen.

It is possible that other factors affecting respiration may also have minima in their response curves. Increasing carbon dioxide for some varieties of apples reduces the respiration rate and extends the storage life. It is possible, although unverified that the respiration rate may increase with the onset of CO_2 induced disorders. If this were so, the dynamic controller could then seek the minimum caused by the joint action of oxygen and carbon dioxide. This creates a complex control theory problem, but it could be solved using the steepest descent approach (5). If there is no minimum in the CO_2 respiration curve, then it would be necessary to experimentally determine the CO_2 level that gives the longest storage life without any CO_2 induced injuries.

There is limited amount of data to suggest that there may be a minimum in the temperature/respiration curve that moves with time. Fidler and North (3) presented a series of curves showing the respiration response to various temperatures over time. Initially the respiration rate was lowest for the lowest temperature (0^oC), however with time, the rate rose above those for higher temperatures, presumably due to the onset of damage caused by cold injury. With a dynamic controller it would be possible to increase the temperature to ensure that the respiration rate was minimised. Initially the produce would be stored at very low temperatures (0^oC). The temperature would be increased with the onset of cold injury at the lower temperatures. This is in effect what happens with the intermittent warming of stone fruit. Although in this case the stone fruit can be returned to temperatures that would cause cold injury with sustained storage, after the warm period. If the onset of cold injury is marked by an increase in the respiration rate, a dynamic controller may be able to automatically follow the cooling/warming cycles.

The use of a dynamic controller would ensure that the produce was stored under optimum conditions. Variables such as maturity, cultural practices or climate could be accomodated automatically. There would be no risk of subjecting over mature fruit, for example, to initial oxygen stress, a treatment that would be harmful to it. There are limits to what the system could do. Like all storage systems, it cannot improve on the initial quality of the produce, only retard its deterioration.

There are a number of assumptions that need to be proved if dynamic control is to work for some or all of the control variables. These include:-

a) Minimizing respiration maximizes storage life.

b) The respiration response to oxygen, carbon dioxide and temperature are characterized by a curve with a minimum.

c) Small excursions for short periods into storage conditions that cause damage, such as oxygen stress or cold injury are reversible and do not cause long-term damage.

d) The onset of disorders due to improper CA conditions are reflected in the respiration rate and there are no disorders if produce is held at the respiration minimum.

The final assumption, if incorrect, can be overcome if there are other ways of detecting the on-set of injury. One possible way to do this is to calculate the respiratory quotient (RQ). If there is substantial departure of the RQ from unity, abnormal respiration due to anaerobis or cold injury would be indicated. However the RQ can be as high as 1.5 for safe storage. This is because anaerobic respiration starts at very low rates prior to the "extinction point" in the response to oxygen. The levels of alcohol produced at oxygen levels above this point are below those detectable by taste (6). The use of RQ would only be possible in the tightly sealed laboratory system, as its calculation requires the measurement of absolute gas levels. Respiration is a suitable indicator for commercial stores as the control system uses relative changes. Air leaks in commercial stores would interfere with absolute but not relative measurements of the carbon dioxide level.

There are a number of problems that could be encountered with attempting to store produce at the minimum respiration rate.

1 The respiration rate may be difficult to measure sufficiently accurately. In the control system respiration would be measured by the rate of increase of carbon dioxide in the store atmosphere between two sampling periods using an infra-red gas analyser. Provided the sampling periods are separated by a time sufficient to give an increase many times greater than the error of the analyser, this technique should work.

2 There may be local minima. The controller could find a local minimum rather than the absolute minimum. To verify that the minimum was not local, the controller would need to initiate a substantial change in the control variable in both directions. If it were a local minimum the jump would allow the controller to move away from its influence and continue seeking the absolute minimum. (see figure 5.2). If the minimum were not local, the jump would simply cause the set-point to move away away from the minimum and then move back again. There are well established techniques such as the conjugate gradient method for seeking absolute minima (4).

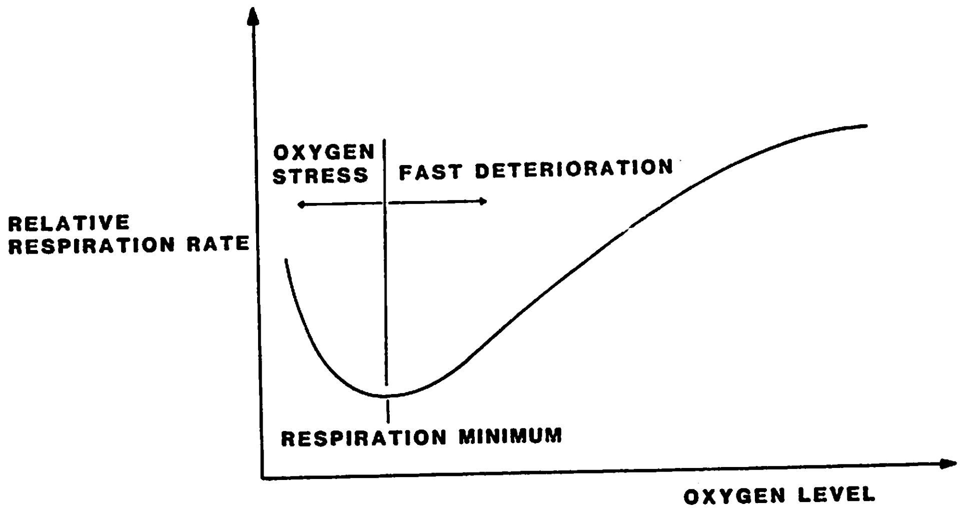

Fig 5.1 Idealized response of respiration to oxygen showing respiration minimum (Pasteur effect).

Conventionally, the ideal storage conditions, in terms of temperature and gas levels are determined by storing produce in a number of chambers each with individual conditions. At the end of the storage period, the produce is removed and some measure of quality made. For apples this comprises a firmness test and observations for yellowing and disorders. The conditions maintaining the best quality produce are then recommended for commercial use.

Sequential trials to determine optimum storage conditions

An alternative to experimenting with fixed atmospheres may be to alter the conditions of storage, in particular the oxygen level, during the storage period to obtain the minimum respiration rate. From ambient gas levels the oxygen level would be reduced stepwise until any further reduction in the oxygen level resulted in an increase in the respiration rate. Solomos (8) demonstrated this with sweet potato roots. The oxygen level was reduced in a series of steps. After each step change the system was allowed to stabilise. It took about one day before the respiration rate reached equilibrium after each change. The minimum respiration rate occurred at 4.25% oxygen. Decreasing the oxygen level to 1.75% or zero increased the respiration rate. This experiment demonstrates that the Pasteur effect exists for sweet potato roots, but more importantly that the response time to changes is finite and repeatable.

This sequential procedure can be used to rapidly determine the optimum storage conditions for any produce, provided the conditions causing the respiration minimum also give maximum storage life. A number of sequential experiments, starting at a randomly selected initial value and then testing values either side of the initial value, are performed. The level that reduces the respiration rate is further changed in the same direction until the respiration rate increases, or until an absolute barrier is reached, such as the produce freezing (if varying temperature). Thus the respiratory minimum

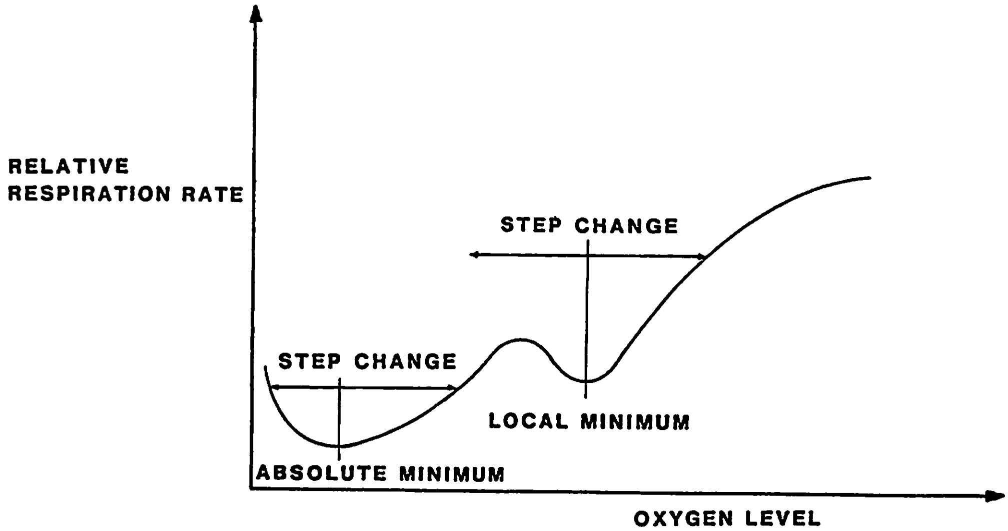

Figure 5.2 A jump either side will help determine a local minimum from the true minimum.

3 There may be excessive or unpredictable time responses. The respiration rate of the produce must respond within a few hours and do so repeatedly if the normal cycling about the set-point is to be used. If the responses were long in terms of the total storage life of the product or unpredictable it would still be possible to use the dynamic controller, but the control theory to do so would be complex.

4 Changes in the store atmosphere due to external or uncontrolled sources may cause errors in operation. The principle influence would be leaks in and out of the store caused by changes in ambient atmospheric pressure. This effect could be minimized by the use of a breather bag. Constant leaks would not be a problem as the controller is only looking at changes in the respiration rate,not its absolute value.

Conclusion

Potentially, the concept of a minimum seeking controller would be a major change in CA technology. On the lab scale, it would simplify the experimental procedure for determining optimum storage conditions. On the commercial scale it would ensure the stored produce was always kept at optimum conditions.

References

1 Ackoff, R.L, Gupta, S.V. and Minas, J.S. (1962) Scientific Method- optimizing applied research decisions John Wiley & Sons Inc New York.

2 Bleasdale, J.K.A. (1976) Plant Physiology in relation to horticulture. Pub. Macmillan Press London.

3 Fidler, J.C. and North, C.J. (1967) 'The effect of conditions of storage on the respiration of apples, I. The effects of temperature and concentrations of carbon dioxide and oxygen on the production of carbon dioxide and uptake of oxygen.' J. Hort. Sci. 42, 189-206.

4 Fletcher, R. and Reeves, C.M. (1964) 'Functional minimization by conjugate gradient.' The Computer Journal 7(2) 149-154.

5 Kirk, D.E. (1970) 'Minimization of functionals by steepest descent' Ch 6 Optimal Control Theory. Prentice Hall New York.

6 Lalaguna, F. and Thorne, S. (1982) 'Gas exchange between atmospheres of different oxygen concentrations and "Cox's Orange Pippen" apples." Proc. Third National Controlled Atmosphere Research Conference, Oregon, 155-160 Pub. Timber Press, Oregon.

7 Roberts, J.D. (1965) 'Extremum or hill-climbing regulation: a statistical theory, involving lags, disturbances and noise' Proc. IEE 112 137-150.

8 Solomos, T. (1982) 'Effects of low oxygen concentration on fruit respiration : nature of respiratory diminution.' Proc. Third National Controlled Atmosphere Research Conference, Oregon, p. 161-170. Pub. Timber Press, Oregon.

9 Wollin, A.S. (1984) 'Computer controlled atmosphere storage of horticultural produce.' M. Eng. Sci. Thesis, University of Melbourne Aust.

10 Wollin, A.S., Lee, V., Lee, J. (1984) 'Hardware for computer controlled atmosphere of horticultural produce.' Proc. Conf. on Agric. Eng. Bundaburg Queensland. 195-199 Institution of Engineers Aust. Barton