On-Line Estimation of Respiration and Fermentation Rates in Controlled Atmosphere Facilities

H.R. Timmer, J. Budding, H.H.J. van Ooijen and L.J.S. Lukasse
Agrotechnological Research Institute (ATO)
PO-Box 17
6700 AA Wageningen
The Netherlands

Keywords: O_2-uptake, CO_2-production, measurement, monitoring, fruits, vegetables

Abstract:

This paper presents an algorithm for estimation of respiration and fermentation rates in CA-stores under normal operation, which can be used for:

- **Monitoring the product state**
- **Control of respiration and fermentation rates**
- **Detection of anaerobic conditions**

All published estimation methods require either a steady state flow-through or a batch respiration chamber. For implementation in full-scale storage facilities the estimator must be able to handle both situations and especially the more difficult non-steady state flow-through condition. To our knowledge, the only attention for monitoring respiration rate in full-scale storage facilities is a proposal by Janssens *et al.* (1995). In this study a Kalman Filter is designed to estimate the respiration and fermentation rates recursively. The results are compared to calculated respiration and fermentation rates. The rates of respiration and fermentation estimated from the O_2 and CO_2-balances converge to their calculated values. Experiments are currently carried out and results will come available in the oncoming months.

INTRODUCTION

It is generally known that the respiration and fermentation rates are related to growth and decay rates of living organisms. Therefore estimation of respiration and fermentation rates has received a tremendous attention in largely different domains over the last decades. For example in wastewater treatment plants (Lukasse et al., 2000), plant respirometry (Berard et al., 1990) and animal respirometry (Aguilera et al., 1986). In fruit storage lowering temperature and oxygen concentration reduces the respiration and fermentation rates. On-line monitoring of respiration and fermentation rates can be used for:

- On-line control of respiration and fermentation rates
- Monitoring the product state
- Detection of increased fermentation due to anaerobic conditions

Estimation methods for respiration rates in fruits and vegetables are presented in e.g. Bower et al., (1998) and Wareham et al., (1999). To our knowledge, the only attention for monitoring respiration rate in full-scale storage facilities is a proposal by Janssens et al. (1995).

All published estimation methods based on O_2 and CO_2 measurements require either a steady state flow-through or a batch respiration chamber. For implementation in full-scale storage facilities the estimator must be able to handle both situations and especially the more difficult non-steady state flow-through condition. This paper focuses on the development of an algorithm for estimation of respiration and fermentation rates in a Controlled Atmosphere (CA) container that does not require a specific experimental condition. The strategy is currently being tested in a 70 dm^3 pilot scale facility. In a next stage the strategy is intended to be tested on a full-scale refrigerated 40-ft. high cube seagoing container. It is stressed that there's principle difference with land-based CA-storage facilities.

THEORY

Respiration and Fermentation

In fruits stored under low temperature and low oxygen there are two biochemical processes relevant to quality evolution that affect the O_2 and CO_2 concentrations of the storage facility. These two processes are aerobic respiration and anaerobic fermentation:

$$C_6H_{12}O_6 + 6O_2 \longrightarrow 6CO_2 + 6H_2O \qquad \text{respiration} \tag{1}$$

$$C_6H_{12}O_6 \longrightarrow 2CO_2 + 2C_2H_5OH \qquad \text{fermentation} \tag{2}$$

The reaction rates for respiration and fermentation (r_r and r_f respectively) depend on n_{O2} according to the well known Michaelis Menten kinetics (Peppelenbos *et al.*, 1996), while dependence on n_{CO2} is negligible. See figure 1 for a graphical illustration for this relation. See table 1 for the meaning of all variables in this paper.

$$r_r = r_{r,\max}\frac{n_{O2}}{k_r + n_{O2}} \quad \text{and} \quad r_f = r_{f,\max}\frac{k_f}{k_f + n_{O2}} \tag{3}$$

On Line Estimation

The main challenge in *recursive* on-line parameter estimation in general is to minimise the trade-off at each sampling instant k between the available estimates based on measurements acquired up to time k-1, and the new measurements acquired at time k. A powerful, and commonly used, tool for optimising this trade-off is the so-called Kalman filter (see e.g. Young, 1984). At each sampling instant k the Kalman filter updates the estimated parameter vector in a way that the trade-off is optimal.

METHODS

An estimation procedure is accomplished for recursive estimation of r_r and r_f. There are two important gas balances over a perfectly mixed container (eqns. 4-5).

$$\frac{dn_{O2}}{dt} = \frac{F_{in}}{V_{air}} \cdot n_{O2,in} - \frac{F_{out}}{V_{air}} \cdot n_{O2} - r_r + \frac{F_l}{V_{air}} \cdot (n_{O2,amb} - n_{O2}) \tag{4}$$

$$\frac{dn_{CO2}}{dt} = \frac{F_{in}}{V_{air}} \cdot n_{CO2,in} - \frac{F_{out}}{V_{air}} \cdot n_{CO2} + r_r + r_f + \frac{F_l}{V_{air}} \cdot (n_{CO2,amb} - n_{CO2}) \tag{5}$$

with:

$$F_{out} = F_{in} + V_{air} \cdot r_f \cdot V_m \tag{6}$$

First, the theoretical recursive identifiablility is investigated by using the concept of observability (Kwakernaak *et al.*, 1972). Secondly the Kalman Filter is designed and tuned. The performance of the Kalman Filter has been compared by first generating data by simulating the n_{O2}- and n_{CO2}-balances using the Michaelis Menten kinetic models (eqns. 3-6) and subsequently applying the Kalman Filter to the simulated data.

RESULTS AND DISCUSSION

From the observability test it occurred that it is theoretically possible to identify r_r and r_f recursively from n_{O2} and n_{CO2} measurements provided that F_l=0 or known. The with KF estimated r_r and r_f can hardly be distinguished from the simulated r_r and r_f. The results of the simulation do not take any leakage into account (F_l=0 in eqns 4-5). Unknown leakage of ambient air into the container gives an offset in the estimation of the respiration and fermentation rate.

CONCLUSIONS

In simulation it is possible to estimate the rates of respiration and fermentation recursively from the O_2 and CO_2-balances, resulting in unbiased estimates. Nevertheless, it is impossible to identify oxygen uptake, CO_2 production and leak rate from gas concentration measurements only. The practical interpretation is that if leakage is unknown and significant, the estimates of O_2-uptake and CO_2-production contain significant offset.

Litertuare Cited

Aguilera, J.F. and C. Prieto (1986). "Description and function of an open-circuit respiration plant for pigs and small ruminants and the techniques used to measure energy metabolism". Archives of Animal Nutrition 36(11): 1009-1018.

Berard, R.G. and G.W. Thurtell (1990). "Respiration measurements of maize plants using a whole-plant enclosure system." Agronomy Journal 82(3): 641-643.

Bower J.H., J.J. Jobling, B.D. Patterson and D.J. Ryan (1998). "A method for measuring the respiration rate and respiratory quotient of detached plant tissues." Postharvest Biology and Technology 13: 263-270.

Janssens, M., A. Thompson, et al. (1995). Practical determination of the respiration rate in controlled atmosphere (CA) stores, DG XIII-A, Commission of the European Communities; Luxembourg.

Kwakernaak, H. and R. Silvan (1972). "Linear optimal control systems." John Wiley and Sons, New York, pp367.

Lukasse L.J.S., Keesman K.J., Spanjers H. and Bloemen M. (2000). Diagnosis and identification of respirometer dynamics and sludge kinetics in continuous-flow respirometers. Water Environment Research, 72(3), pp. 340-347.

Peppelenbos, H.W. and Rabbinge, R. (1996). Respiratory characteristics and calculated ATP production of apple fruit in relation to tolerance of low O-2. Journal-of-Horticultural-Science 71(6); pp. 985-993.

Wareham P.D. and Persaud, K.C. (1999). On-line analysis of sample atmospheres using membrane inlet mass spectrometry as a method of monitoring vegetable respiration rate. Analytica-Chimica-Acta 394(1), pp. 43-54.

Young, P. (1984). "Recursive estimation and time-series analysis, an introduction," Springer Verlag, Berlin.

Tables

Table 1. list of symbols

Symbol	Description	Unit
F_{in}	flow gas in	m^3/h
F_{out}	flow gas out	m^3/h
F_l	flow leakage	m^3/h
V_{air}	air volume in container	m^3
V_m	molair volume gas	m^3/mole
n_x	molar concentration of component x	mole/m^3
$n_{x,in}$	molar concentration of component x in influent flow	mole/m^3
$n_{x,amb}$	ambient molar concentration of component x	mole/m^3
r_r	respiration rate (O_2-uptake)	mole O_2/m^3air.h
r_f	fermentation rate	mole CO_2/m^3air.h
$r_{r,max}$	maximal respiration rate	mole O_2/m^3air.h
$r_{r,max}$	maximal fermentation rate	mole CO_2/m^3air.h
k_r	Michaelis Menten constant respiration	mole/m^3
k_f	Michaelis Menten constant fermentation	mole/m^3

Figures

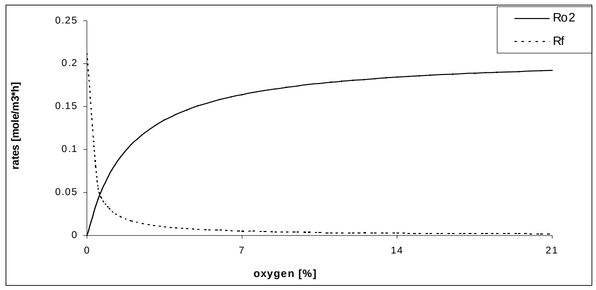

Fig. 1. Respiration and fermentation rate in relation to the oxygen concentration (Peppelenbos et al., 1996).

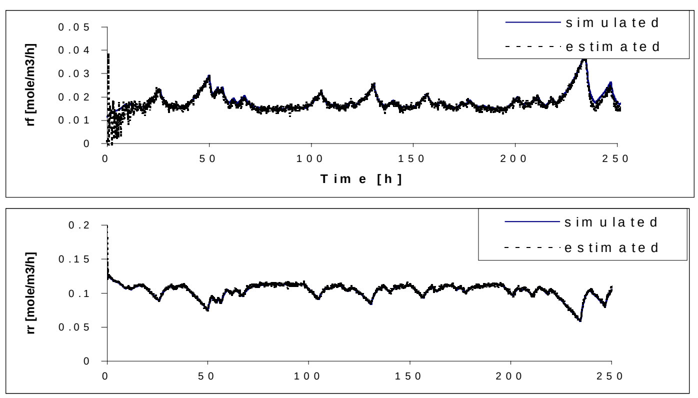

Fig. 2. Simulated and estimated r_r and r_f.