Respiration rate of potatoes (*Solanum tuberosum L.*) measured in a two-bin research scale storage facility, using heat and moisture balance and gas analysis techniques

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Fennir, M.A., Landry, J.A. and Raghavan, G.S.V. 2003. **Respiration rate of potatoes (*Solanum tuberosum L.*) measured in a two-bin research scale storage facility, using heat and moisture balance and gas analysis techniques.** Canadian Biosystems Engineering/Le génie des biosystèmes au Canada **45**: 4.1-4.9. Heat and moisture balance, in-store gas analysis, and mass loss methods were applied for quantifying respiration rates and moisture losses of potatoes stored in a two-bin research scale storage facility that was specially built and instrumented for long term storage of potatoes. The heat and moisture balances were applied on data collected for two months, and in-store gas analysis also was performed during a 40-day period. Net heating rate produced by potatoes was quantified and converted into respiration rates as CO_2 (mL kg^{-1} h^{-1}). The daily in-store gas analysis was also used for quantifying respiration rate as CO_2 produced. Respiration rates obtained by the heat and moisture balance were found to be in agreement with ranges reported in the literature. However, they were higher than rates obtained by in-store gas analysis and by closed system gas analysis. Mass losses were quantified using the mass balance and mass loss analysis performed over the entire storage period. Results showed agreements among the two measurements and losses estimated were also in agreement with those reported in the literature. The study demonstrated the feasibility of using the heat and moisture balances and mass loss methods for in-store determination of respiration rates, and their use as indicators for changes in physiological and health status of stored perishables. **Keywords:** Heat, moisture, balance, storage, respiration, CO_2, gas analysis, potatoes.

Des bilans de chaleur et d'humidité, des analyses de gaz produits et des méthodes de perte de masse ont été appliqués pour quantifier les taux de respiration et de perte d'humidité chez des pommes de terre entreposées dans deux compartiments d'entreposage d'échelle expérimentale qui ont été construits et instrumentés pour l'entreposage de pommes de terre à long terme. Les bilans de chaleur et d'eau ont été vérifiés à l'aide des données prises durant deux mois et l'analyse des gaz produits a été réalisée sur une période de 40 jours. Le taux net de production de chaleur par les pommes de terre a été quantifié et converti en taux de respiration en termes de CO_2 (mL kg^{-1} h^{-1}). L'analyse quotidienne des gaz produits a aussi été utilisée pour quantifier le taux de respiration produit sous forme de CO_2. Les taux de respiration obtenus par les bilans de chaleur et d'humidité sont en accord avec les valeurs rapportées dans la littérature. Toutefois, ils étaient supérieurs aux taux obtenus par les méthodes d'analyse des gaz produits et d'analyse des gaz en système clos. Les pertes massiques ont été mesurées en utilisant le bilan de masse et l'analyse de perte massique performée sur toute la période d'entreposage. Les résultats obtenus montrent que les deux types de mesures donnent des résultats similaires et que ces résultats sont comparables aux valeurs rapportées dans la littérature. Cette étude a démontré qu'il est possible d'utiliser les bilans de chaleur et d'humidité et les méthodes de perte de masse pour l'estimation en entreposage des taux de respiration et comme indicateurs des changements physiologiques et de statut sanitaire de produits périssables entreposés. **Mots clés**: chaleur, eau, bilan, entreposage, respiration, CO_2, analyse de gaz, pommes de terre.

INTRODUCTION

Respiration is the major physiological process which continues after a produce is detached from its parent plant. Under proper storage conditions, respiration proceeds at relatively low and stable rates throughout the storage period. However, respiration may increase or decrease based upon changes in storage conditions and physiological status of the produce (Kader 1992). Additionally, respiration reflects the physiological activity of stored produce; thus, its increase may indicate changes in the stored produce.

For potato storage systems, from a practical stand point, there are very few existing methods for knowing the physiological and health status of the stored produce. Although attempts to quantify respiration rate under commercial storage conditions have been made (Schaper and Varns 1978; Hunter 1985, 1986), they were not aimed at determining the condition of the stored produce.

Apart from respiration, several studies on establishing early disease detection methods have been reported (de Lacy Costello et al. 1999, 2000; Lyew et al. 1999, 2001; Ratti et al. 1995). They were aiming at the determination of specific volatiles that are associated with some postharvest diseases. Although promising results have been achieved at the experimental stage, their practical application under larger scale storage conditions has not been reported.

Since respiration rate indicates the physiological activity of produce, its in-storage measurement could serve as a monitoring tool, and its increase can be used as an indication of sudden

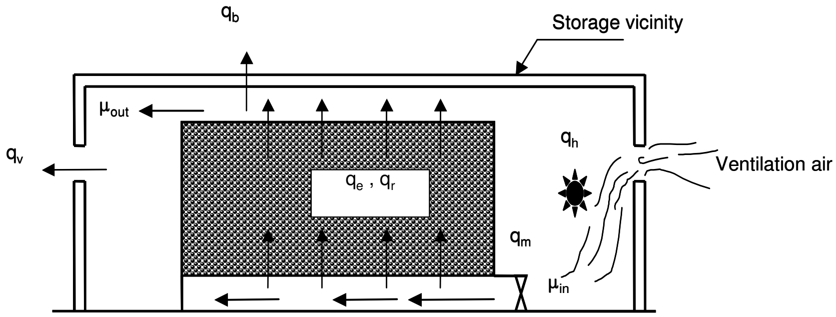

Fig. 1. Layout of the heat and moisture balance of a potato storage. Parameters are listed in Eqs. 1 to 12.

changes in the status of the stored produce. However, before such application is attempted, quantifying respiration rate under commercial storage conditions has to be performed as a base for carrying on further investigations.

This work reports the quantification of respiration rate of potatoes by monitoring the heat and moisture balance, in-store gas analysis, and mass loss analysis in a research-scale storage facility. The facility was designed, built, instrumented, and tested to provide storage conditions that normally exist in air-cooled potato storage systems.

HEAT and MOISTURE BALANCE APPROACH

A heat and mass balance is based on the principles of heat and moisture gains and losses. Figure 1 shows a schematic representation of both the heat and moisture balance applied to a storage room.

Heat balance

Application of the heat balance is performed based on the measurements of temperature, relative humidity, and ventilation flow rate. The measured variables are applied in the heat and moisture balance equations as:

$$q_r + q_m + q_h = q_b + q_v + q_e \tag{1}$$

where:

q_r = vital heat from potatoes (W),
q_m = rate of heat produced by fans, lights, and other mechanical devices (W),
q_h = supplemental rate of heat from heaters (W),
q_b = rate of heat loss through bin structure walls (W),
q_v = rate of sensible heat gained by ventilation air (W), and
q_e = rate of latent heat of evaporation of water measured as a difference between inlet and outlet air water contents (W).

Since the heat produced by the commodity per unit time (q_r) is to be determined, Eq. 1 can be rearranged as:

$$q_r = q_v + q_b + q_e - q_m - q_h \tag{2}$$

Equations 3-8 are used to calculate the components of the heat balance equation.

Sensible heat rate gained by ventilation and infiltration (q_v)

Ventilation

Heat gained from or lost to ventilation air is the amount of heat added to or removed from the system with the introduction of an air mass at a temperature lower or higher than the system.

$$q_v = M_a C_p \left(T_{out} - T_{in} \right) \tag{3}$$

where:

M_a = rate of ventilation air (kg/s),
C_p = specific heat of air (J kg^{-1} °C^{-1}),
T_{in} = incoming air temperature (°C), and
T_{out} = outgoing air temperatures (°C).

Infiltration

Air infiltration in this study was considered due to the temperature difference between the bins and their surroundings. The air flow was calculated based on an equation from ASHRAE (1997):

$$Q = C_D A \sqrt{2 g \Delta H_{NPL} \left(T_{bin} - T_{surr} \right) / T_{bin}} \tag{4}$$

where:

Q = airflow rate (m^3/s),
C_D = discharge coefficient for openings (dimensionless),
A = area of estimated openings at the bin shell (m^2),
g = gravitational constant (9.81 m/s),
ΔH_{NPL} = height from midpoint of lower opening to neutral pressure level (NPL),
T_{bin} = bin average temperature (˚C), and
T_{surr} = average surrounding temperature (˚C).

The discharge coefficient of openings was determined as:

$$C_D = 0.40 + 0.0045 \left| T_{bin} - T_{surr} \right| \tag{5}$$

Structural heat rate loss (q_b) The structural heat loss was determined from:

$$q_b = \sum_{p=1}^{n} \frac{A_p}{R_p} \left(T_{bin} - T_{amb} \right) \tag{6}$$

where:

A_p = surface area of each of n partitions (m^2),
R_p = total resistance to heat flow of each partition (m^2 °C W^{-1}), and
$T_{amb.}$ = temperature of the outside of each partition (°C).

Heat rate used for evaporating water (q_e) The heat rate used for evaporating water was determined from:

$$q_e = \Delta \mu M_a h_{fg} \tag{7}$$

where:

$\Delta\mu$ = humidity ratio difference between incoming and outgoing air (kg water per kg dry air),
M_a = ventilation rate (kg/s),

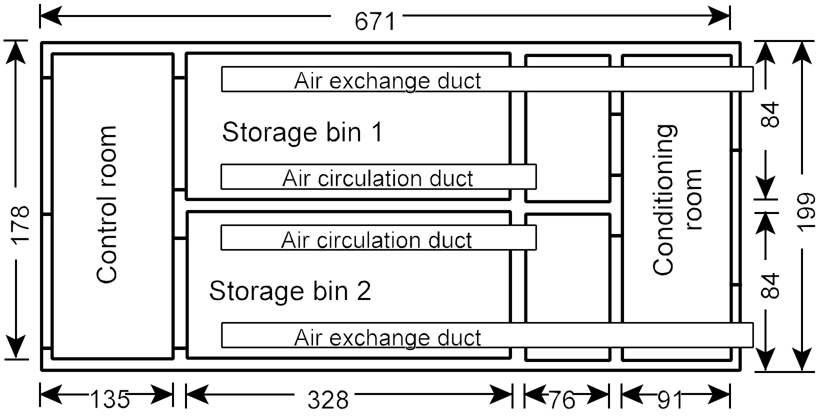

Fig. 2. Plan view of the storage facility. All dimensions in centimeters. Wall thickness is 10.2 cm.

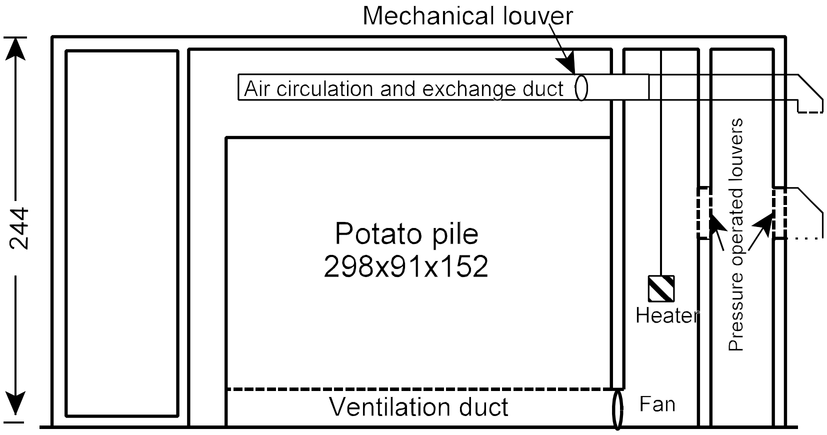

Fig. 3. Section of the storage facility showing internal details of the storage bins.

h_{fg} = latent heat of evaporation of water (J/kg) and determined by:

$$h_{fg} = 2{,}502{,}535.259 - 2385.76 T_{bin} \tag{8}$$

Heat rate produced by mechanical means Heat rate produced by mechanical means such as fans, heaters, and lights has known values that are considered in the balance.

Moisture Balance

Calculation of air psychrometric properties, at dry bulb temperature T, is performed using psychrometric equations based on the measured dry bulb temperatures and relative humidity of the air entering and leaving the potato pile. Equations 9-11 are adapted from ASAE (1999) and used for the calculation of ventilation air properties.

$$\ln\left(\frac{P_s}{R}\right) = \frac{a + bT_a + cT_a^2 + dT_a^3 + eT_a^4}{fT_a + gT_a^2} \tag{9}$$

$$P_a = P_s RH \tag{10}$$

$$\mu = \frac{0.6219 P_a}{P_{atm} - P_a} \tag{11}$$

where:

T_a = T + 273.16,
P_s = saturated water vapour pressure at temperature (T) within a range of 0 to 40°C (Pa),
P_a = actual water vapour pressure at temperature T (Pa),
P_{atm} = atmospheric pressure (Pa),
μ = humidity ratio of the air entering and leaving the bin (kg/kg),
RH = relative humidity of air (%),
R = 22,105,649.25,
a = -27,405.526,
b = 97.5413,
c = -0.146244,
d = 0.12558×10^{-3},
e = -0.48502×10^{-7},
f = 4.34903, and
g = -0.39381×10^{-2}.

Evaporation rate is evaluated based on the psychrometric calculations. Equations 9-11 are used for determining the amount of water evaporated at humidity ratio difference between incoming and outgoing air (Eq. 12).

$$ER = \Delta\mu M_{air} \tag{12}$$

where:

ER = evaporation rate (kg/s),
$\Delta\mu$ = change in humidity ratio between air entering and leaving the pile (kg/kg), and
M_{air} = mass of air ventilation rate (kg/s).

Equations 3-12 were programmed to calculate the heat and moisture balance that was applied on a research scale storage facility. The components of heat and moisture balances were calculated based on measurements of temperature, relative humidity, and air flow rate collected from a storage operation.

MATERIALS and METHODS

The storage facility

A research scale storage facility with external dimensions of 6.71 × 1.83 × 2.44 m was built. It was partitioned into control room, two storage bins, two air mixing rooms, and a conditioning room. Figures 2 and 3 show plan and sectional views of the facility, respectively. The two bins were built to be identical in size and large enough to simulate real storage conditions. Both bins were equipped with identical air handling systems and equipped with similar instrumentation.

External walls and internal partitions were built from 50.8 × 101.6 mm wood studs spaced at 406 mm. Between the studs, mineral wool sheets with a thermal resistance (R) of 1.76 °C m^2 W^{-1} were installed and covered with a vapour barrier on the internal side of the walls. The internal and external sides of the walls were covered with 12.7 mm thick treated plywood sheets. The overall thermal resistance (R) value of the walls was

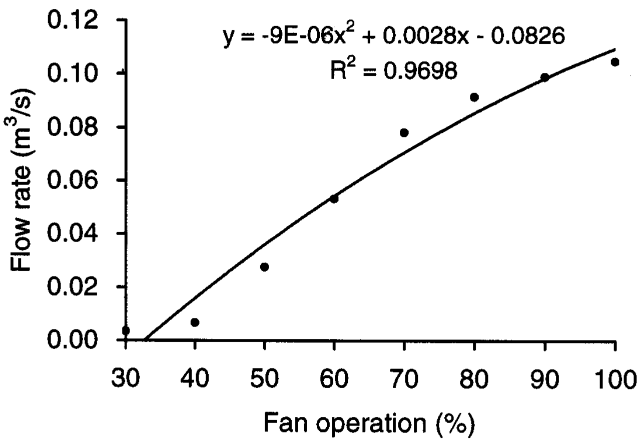

Fig. 4. Fan calibration curve.

determined to be 2.05 °C m^2 W^{-1} and of the roof was determined to be 2.1 °C m^2 W^{-1}. It is to be noted that the facility was built inside an existing unheated building, therefore lower R values were required.

Storage bins The heart of the facility was two identical and independent storage bins, each with internal dimensions of 3.28 × 0.84 × 2.44 m and a storage capacity of about three metric tons. To support the horizontal pressure of the potatoes, sidewalls were joined using four pairs of 12.6 mm diameter threaded steel rods positioned at equal distances above and below the potato pile. To reduce infiltration, corners and joints were filled with silicon and airtight doors were installed. The produce was cooled using a slotted floor type ventilation system. A rectangular ventilation duct with dimensions 0.305 × 0.305 × 3.28 m was built beneath the pile. Corners of the duct were also sealed to prevent air leakage. The duct was covered with sections of 50.8 × 203.2 mm treated wood spaced at an adequate slot spacing to facilitate uniform air distribution. At the entrance of the duct and on the bottom of the wall separating the bin from the mixing room, a variable speed centrifugal fan (Model AXC 150A, AEROFLO, Mississauga, ON) was installed. The fan delivered a flow rate of 0.076 m^3/s against 125 Pa pressure head. Air flow delivered by the fan was controlled via a custom built variable-speed drive interface connected to the control system. Prior to storage, ducts were tested for air distribution uniformity and fans were also calibrated.

Above the pile, each bin was equipped with two 280 mm diameter circular galvanized steel ducts for air exchange and circulation. The air exchange duct was extended to the outside, while the air mixing duct delivered air to the mixing room. Both ducts were opened and closed using a mechanical louver operated by an electrical motor that was activated by the control system.

Air mixing and conditioning rooms Each storage bin was attached to an air mixing room with internal dimensions of 0.762 ×0.84×2.44 m. Mixing rooms were separated from each other to assure independency of their ventilation systems and to facilitate the application of different conditions to each bin. On the door of each mixing room, a 0.305 × 0.305 m pressure operated louver was installed. In each room, a portable bench heater with a 500 W heating capacity and a water supply system were installed. The water supply system consisted of an automatic in-line balanced diaphragm control valve (WaterMaster, Model 57103, ORBIT Irrigation products, Inc., Bountiful, UT) and a mist nozzle. The valve was activated by a 24 V source and its operational pressure could be adjusted to the desired nozzle pressure. The nozzle was installed in the ventilation duct facing the fan and operated at a pressure range of 6.4-18.9 kPa.

Air exchange was made based on pressure variation between the bin and the outside, and air circulation was based on pressure variation between the bin and the mixing room. During air exchange, the louver in the air exchange duct was opened and the one in the circulation duct was closed, the fan was operated, pushing air through the pile to the outside through the open exchange duct. Thus, pressure inside the bin became lower than that of outside, and cold air entered the mixing room through the pressure-operated louver. When air circulation between the mixing room and the bin was required, the louver in the air circulation duct was opened and the one in the air exchange duct was closed. The fan then pushed air through the potato pile to the mixing room, and no outside air entered the mixing room since the pressure difference was only between the bin and the mixing room. Also, partial mixing could be performed by partially opening both louvers allowing both air circulation and exchange.

Since outside air can be cooler and drier than that of the storage environment, adding moisture and/or heat to the system was based on measured air temperature, relative humidity, and their comparison to their respective set-point.

Instrumentation

Temperature Temperature was measured using of 59 type (T) thermocouples (FF-T-24-TWSH-SEL 500, OMEGA Eng. Inc., Laval, QC). The temperatures recorded were used for both the control process and the application of heat and moisture balance. Thermocouples were distributed as follows: 12 through each pile, 2 in each ventilation duct, 2 in each of the air exchange and air circulation ducts, 2 in each pile's head space, 8 distributed around the storage facility, 3 in each mixing room, 3 in the conditioning room, and 2 for the outside air. All thermocouples were calibrated using a mercury thermometer as a reference. Several readings were taken starting with an ice bath, and warm water was added gradually until the water temperature exceeded 50°C. A linear regression analysis was made for each thermocouple, and temperature measurements were corrected.

Relative humidity Relative humidities were measured for outside air, at the mixing room, and above the pile using RH transducers (model HU-224-2VAC, Mamac Systems, Minneapolis, MN). Sensors were calibrated by the manufacturer and have a maximum error of 2% within a measurement range of 0 to 100%.

Flow rate Air flow rates provided by fans were calibrated at several fan speeds. At every measurement, the air exchange louver was opened, and air flow rate was measured at several points along the cross section of the duct using a hot wire anemometer (model 37000.60, Tri-Sense air velocity transducer, Cole-Parmer Instrument Co., Vernon Hills, IL). A mathematical relationship for flow rate versus fan operation percentage was developed and used for the determination of the flow rate at corresponding fan speed as shown in Fig. 4.

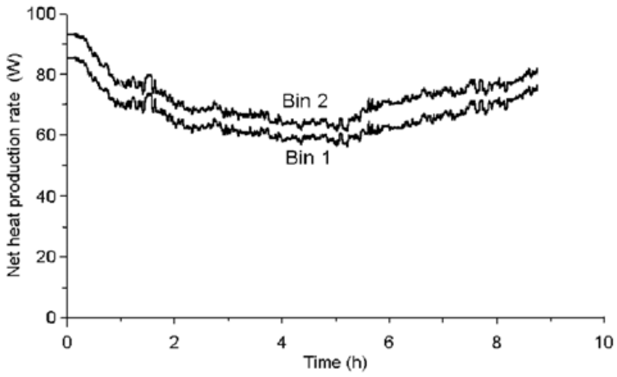

Fig. 5. Net heat produced by potatoes in the two storage bins on January 14, 2001.

Computer hardware and software Measurement and control processes were performed using an IBM Compatible PC equipped with several OMEGA products interface and data boards (OMEGA Eng. Inc., Laval, QC). The control of the facility operations and data collection were performed using an object oriented computer program specially developed for potato storage operations as described by Markarian and Landry (1999). The software facilitated full automation of the facility as well as data collection. Measured temperature, relative humidity, and flow rate were used for the control purposes. Temperature and relative humidity measurements and the status of the heaters, water sprayers, louvers, and fan speed operational percentage were recorded every 10 seconds throughout the storage period. Data were saved in three main files, Bin1, Bin2, and a file in which temperatures measured by the 59 thermocouples were recorded. Data collected on a daily basis were transferred from the control computer and used for the application of heat and moisture balances.

Potatoes

Potatoes cv. Chieftain were grown in the Quebec city region. The potatoes were surface dried, suberized, treated with a sprout inhibitor, and kept at 5°C at the producer's storage facility. The unwashed potatoes were packed into 22.2 kg bags and transferred to the research facility in a refrigerated truck on December 6, 2000. Growing conditions were unknown, but the physical appearance of the tubers was excellent.

Upon receiving the produce, the two storage bins were filled to about 2 m in depth by emptying the bags. A total mass of 2.5 t (110 bags) was bulk stored in each bin. Tubers maintained a stable temperature throughout the filling and handling operations, and when the filling of the two bins was completed the mean temperature of both bins was 5°C. Data were taken between January 14 and February 28, 2002 for calculating the respiration rate using the heat balance method.

Experimental procedure

The control system was set to provide the desired storage temperature and a relative humidity of 95%. Several temperature set points were applied throughout the storage duration, within the range of 4 to 10°C. For most of the storage period, low temperature set point was applied to provide relatively stable conditions and to keep the produce for a longer period and minimize losses.

Although the control system provided automated operations of heaters, louvers, water sprayers, and fans, for specific periods the system was operated manually to obtain stable conditions at which data used for the heat and moisture balances were gathered. For a two month period, the system was periodically adjusted to a minimal fan speed, heaters and water sprayers were turned off, and data were collected for periods exceeding 8 hours per day.

Several assumptions were made including: (1) heat losses from the bin structure were due to conduction; (2) heat gained by the ventilation air was due to convection in one-dimensional flow; (3) heat gain and loss due to irradiation was negligible; (4) condensation inside the bins had minimal effect and thus was neglected; and (5) air infiltration was entirely due to thermal forces (air temperature difference between the storage bins and their surroundings).

Heat gained per unit time by ventilation air from the potatoes' bulk (q_v) was calculated using temperatures measured before the air reached the produce (in the bottom ventilation duct) and above the pile (at the bin head space). Heat introduced by the heaters and fans was eliminated from the heat balance calculations by applying the balance between the ventilation duct and the air space, and considering the mixing rooms as separate entities that underwent heat exchange with the storage bins.

Mass loss determination

At the beginning of the storage period, four samples of tubers were weighed, placed in mesh bags, and distributed in the pile. At the end of the 5-month storage operation, bags were weighed again and mass loss determined. Two bags from each bin were weighed on a daily basis for an extended period and their mass loss determined on a daily basis.

Measurement of CO_2 level in the bins

A portable infrared gas analyzer (Model 309BT; NOVA Analytical Systems Inc., Hamilton, ON) was used for determining CO_2 level. Air circulation and exchange were halted for a period of 8 hours. The air exchange louvers were closed and the air circulation duct ends at the mixing rooms were wrapped with plastic sheets and taped. After the designated time, the air exchange louver was opened, the fan was operated at 40% capacity, and air was sampled in four replicates of one minute each. The sampling was carried out without opening the bins, and was performed for Bin1 followed by Bin 2.

RESULTS and DISCUSSIONS

Heat balance

Figures 5 and 6 show the net heat rate produced by potatoes inside the two storage bins, and Table 1 shows means of pile temperature, rate of heat produced by potatoes (W), and respiration rates (mL kg^{-1} h^{-1}) over the selected periods for the two storage bins.

Temperature and the vital heat production rate in both bins studied were fairly stable. The average of heat rates produced by the potatoes over the storage period were 50 and 59 W for Bins 1 and 2, respectively. There was no significant difference between the net heat rates produced in the two bins. Mean respiration rates were 3.74 and 4.08 mL kg^{-1} h^{-1} for potatoes in

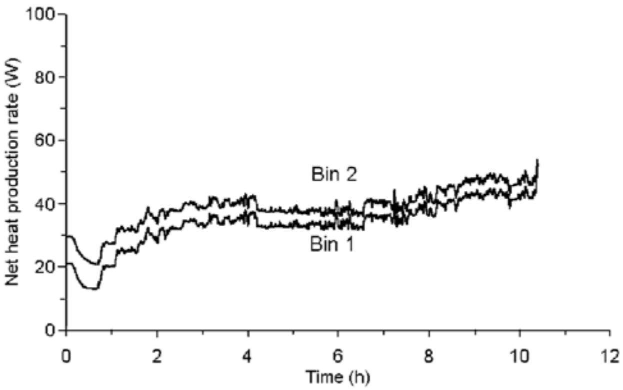

Fig. 6. Net heat produced by potatoes in the two storage bins on February 2, 2001.

Bins 1 and 2, respectively. Trends in net heat rates and corresponding respiration rates were similar among potatoes within each bin.

Respiration rates measured using heat and moisture balances were compared with those reported in the literature. Among the large number of potato cultivars tested, respiration rates for the cultivar used in this study (Chieftain) have not been reported. Using a closed system gas analysis method, the respiration rate of Chieftain in our study was determined to range from 1.44 to 1.89 mL kg^{-1} h^{-1} at 5°C.

Respiration rates, as CO_2 produced, by other potato cultivars at temperatures near 5°C have been reported. Hardenburg et al. (1990) reported respiration rates for mature potatoes in the range of 1.5-4.5 mL kg^{-1} h^{-1}. Dennis (1983) presented respiration rates gathered from the literature ranging from 1.38-4.4 mL kg^{-1} h^{-1}. Peterson et al. (1981) reported respiration rates in the range of 0.76-1.3 mL $kg^{-1}h^{-1}$ for mature Russet Burbank potatoes. Schaper and Varns (1978) reported respiration rates for several cultivars, measured using gas analysis methods, ranging from 0.76-1.11 mL kg^{-1} h^{-1}. Dwelle and Stallknecht (1978) reported the respiration rate as CO_2 production of 2.3 to 4.3 mL kg^{-1} h^{-1} for two cultivars of potatoes at approximately 5 ºC and 95% relative humidity. The respiration rates obtained using the heat and moisture balance method in this study fall within the ranges reported in the literature. One must also consider that variation in respiration rates are attributable to factors such as cultivar, growing conditions, experimental conditions, and physiological status of the tubers.

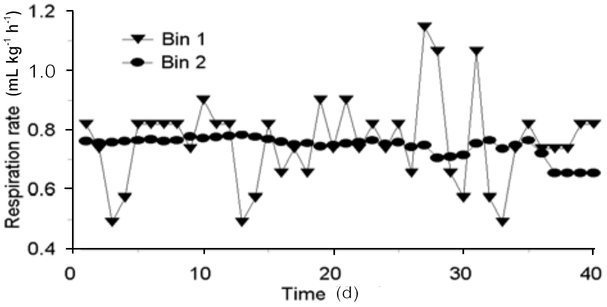

Fig. 7. Respiration rates measured in the two bins.

Although the respiration rates reported in Table 1 fall within the ranges reported in the literature, they are higher than those obtained using the gas analysis method (1.44 - 1.89 mL kg^{-1} h^{-1}). However, it should be noted that the two methods of respiration rate estimation were carried out under different conditions. Respiration measurements using heat and moisture balances were taken under large-scale storage conditions, whereas the gas analysis measurements were carried out in a closed system and hence were much more stable. Also, sources of measurement error such as temperature, relative humidity, flow rate calibration, and the determination of the structural resistance to heat flow (R) and other storage conditions, all may have their effects in one way or another on respiration rate itself and its measurement. Nonetheless, the heat and moisture balance was aimed at assessing respiration ranges rather than obtaining absolute values as is done under laboratory conditions using precise and well tested methods such as gas analysis.

Table 1. Means of pile temperature, heat generated inside the two bins, and their corresponding respiration rates.

Month/ day	Bin 1			Bin 2		
	Temperature (°C)	Heat rate (W)	CO_2 (mL kg^{-1} h^{-1})	Temperature (°C)	Heat rate (W)	CO_2 (mL kg^{-1} h^{-1})
01/14	4.8	66	4.5	5.9	72	5.0
01/18	6.4	54	3.7	7.3	80	5.5
01/22	6.8	51	3.5	7.5	58	4.0
01/25	7.0	60	4.1	7.1	67	4.6
01/28	5.7	55	3.8	6.2	64	4.4
02/02	4.0	34	2.3	4.8	39	2.7
02/07	3.8	53	3.7	4.8	49	3.3
02/16	3.9	53	3.7	4.8	56	4.0
02/23	4.0	30	2.1	4.7	58	3.9
02/28	3.9	44	3.1	4.2	49	3.4
Mean	5.03	50.0	3.74	5.73	59.2	4.08
SE*	0.125	1.05	0.072	0.117	1.14	0.079

*SE = standard error of the mean

The relative humidity during the whole storage period was maintained at above 95%.

Gas analysis

Figure 7 shows respiration rates of the potatoes in the two bins over a 40 day period measured by in-store gas analysis. While the

Table 2. Means of monthly evaporation rates and their standard deviations in potatoes at 4-10°C and 95% relative humidity.

Month	Evaporation rate (g kg^{-1}h $^{-1}$)	
	Bin 1	Bin 2
Month 1	0.0211±0.041	0.0257±0.0434
Month 2	0.0144±0.0238	0.00276±0.014

respiration rate calculated for Bin 1 fluctuated significantly, that for Bin 2 was fairly steady. Mean respiration rates were 0.76 and 0.75 mL kg^{-1} h^{-1} for Bins 1 and 2, respectively. The fluctuation in Bin 1 may have been caused by lack of tightness of the bin. Nonetheless, apart from the fluctuating rates of Bin 1, respiration rates of the two bins were quite similar. When such values were compared with those obtained by the heat and moisture balance and the laboratory gas analysis, respiration rates calculated based on CO_2 measurements in the bins were underestimated. This might be attributable to the lack of complete airtightness that caused air movement to dilute the CO_2. Even after considering 13% for infiltration suggested by Schaper and Varns (1978), the results obtained using the in-storage gas analysis are still lower than those obtained by the laboratory gas analysis method.

Jayas et al. (2001) reported a CO_2 percentage of about 0.2%, similar to the results obtained in the current study. However, Jayas et al. (2001) did not use CO_2 percentages to estimate respiration rates, rather they used the values as an operational parameter for the ventilation system. Schaper and Varns (1978) reported 2-4% CO_2 in a storage during suberization of several potato cultivars. Their storage bin was specially modified for such an operation, and thus higher CO_2 percentages were reported. Another reason might be due to the higher temperature (10-15 °C) used during the suberization.

Moisture balance

Humidity ratios were calculated based on temperature and relative humidity measurements in the mixing rooms and storage bins. Change in humidity ratio difference ($\Delta\mu$) was used to determine the latent heat of evaporation (q_e) and applied in the heat balance. For the moisture balance, the humidity ratio difference was averaged every four hours. A positive $\Delta\mu$ represented water evaporation, while a negative $\Delta\mu$ represented condensation on produce surfaces that could be evaporated after attaining a positive $\Delta\mu$.

The net 4-hour mean $\Delta\mu$ was used to calculate water evaporation rate. However, evaporation rates do not practically represent transpiration rate, since a transpiration rate measurement requires the determination of vapour pressure at the surface of the produce surface and of its surrounding air. Alternatively, water evaporation rate was measured and compared with mass loss measurements.

Table 2 shows means of water evaporation rates. In some instances, bins exhibited very low evaporation rates, attributable to the higher relative humidity applied at the mixing rooms. Relative humidities at the mixing rooms were maintained higher than that in the bins themselves.

One must consider the difficulties in measuring evaporation rates and accordingly the transpiration rates even under controlled environment and the difficulties in maintaining a steady air flow at a stable relative humidity. It is expected that under commercial storage conditions such measurements are likely to be quite unstable.

Mass losses were determined for both bins over the entire storage period and for short periods in which a daily mass loss analysis was undertaken. In general, both measurements were quite similar; the means of daily mass losses were 0.0232 and 0.0190 g kg^{-1} h^{-1} for Bin 1 and Bin 2, respectively. Considering that many factors like variations in temperature, relative humidity, and flow rate may affect the water losses, variations from one month to another are expected. However, when evaporation rates presented in Table 2 are compared with those obtained by mass loss analysis (Tables 3 and 4), the two are quite similar.

Determination of mass losses

Four plastic mesh bags were filled with potatoes and distributed within each storage bin. At the beginning and at the end of the storage period, the bags were weighed. Table 3 shows the samples mass, their mean mass loss, and their percent fresh mass loss. The mass loss over the entire storage period was determined at 0.0187 and 0.0179 g kg^{-1} h^{-1} for Bin1 and Bin 2, respectively.

Table 3. Mass loss determination for the two storage bins during the 5-month storage period at 4-10°C and 95% relative humidity.

	Replicates and their start and ending masses (kg)							
	Replicate 1		Replicate 2		Replicate 3		Replicate 4	
	Start	End	Start	End	Start	End	Start	End
Bin 1	2.148	2.00	2.131	1.99	2.143	2.05	2.055	1.90
Bin 2	2.137	1.96	2.152	2.04	2.162	2.015	2.132	2.015

	Mass loss (%) and their means ± standard deviations				
	R1	R2	R3	R4	Mean
Bin 1	6.9	6.6	4.3	7.3	6.28±1.2
Bin 2	8.3	5.4	6.8	5.5	6.50±1.2

Table 4 shows mean mass losses determined on a daily basis. Both bins exhibited linear mass loss over time with mean rates of 0.0230 and 0.0192 g kg^{-1} h^{-1} for Bins 1 and 2, respectively. Since the two bins were subjected to the same storage conditions, it is evident that they exhibited similar mass loss rates. Losses due to respiration and transpiration were about 1.3% per month.

Monthly mass losses were compared to those reported in the literature. Hunter (1986) reported the mass loss of several cultivars stored at 7°C and 95%

Table 4. Periodical mass loss analysis.

Days	Bin 1		Bin 2	
	Sample average mass (g)	Loss (g $kg^{-1}h^{-1}$)	Sample average mass (g)	Loss (g $kg^{-1}h^{-1}$)
0	2030		2041	
2	2028.5	0.015	1039.5	0.015
4	2027	0.015	2037.5	0.020
6	2024	0.031	2035.5	0.020
8	2021.5	0.026	2034	0.015
10	2018.5	0.031	2032	0.020
12	2016.5	0.021	2029.5	0.026
14	2014.5	0.021	2028.5	0.010
16	2012	0.026	2026.5	0.020
18	2010	0.021	2024.5	0.020
20	2007.5	0.026	2022.5	0.020
Mean		0.023±0.005		0.019±0.004
Monthly mass loss (%)		1.66%		1.25%

Note: The storage temperature was between 4 and 10°C and the relative humidity was above 95%.

relative humidity to be between 0.2 and 0.4% per week, resulting in a mass loss of 1% per month. In the present study, no quality assessment analysis was performed after storage, but tubers maintained good appearance and firmness. Giving considerations to the variability in storage conditions and produce related factors, the mass analysis obtained in the present study agreed with mass losses reported in the literature.

CONCLUSIONS

A research scale storage facility was constructed, instrumented, and used for storing potatoes. Two storage bins were filled with potatoes and their temperatures, relative humidities, ventilation rates, and other operational parameters were recorded for the entire storage duration. Data collected from selected periods were used for the application of heat and moisture balance to determine heat rate produced by the stored potatoes. Mean heat rate produced by potatoes over the selected period was 50 W (equivalent to CO_2 3.74 mL kg^{-1} h^{-1}) for Bin 1 and 59.2 W (equivalent to CO_2 4.08 mL kg^{-1} h^{-1}) for Bin 2. When these means were compared with respiration rates reported in the literature, those obtained by the heat and moisture balance fell within ranges reported in the literature, but were higher than those obtained by closed system gas analysis (1.44-1.89 mL kg^{-1} h^{-1}) and in-store CO_2 analysis (0.75 mL kg^{-1} h^{-1} for Bin 1 and 0.76 mL kg^{-1} h^{-1} for Bin 2).

The moisture balance was also applied on two months of data and mass loss was analyzed for the entire storage duration and on a daily basis. Both were within the generally acceptable losses reported in the literature. Monthly mass loss was estimated at 1.3%, slightly above the losses reported in the literature. Water evaporation rates determined by the moisture balance were generally comparable with those obtained by mass loss analysis. Mean mass loss rate for the two bins, determined by the moisture balance, was 0.0232 g kg^{-1} h^{-1}, while that determined by mass loss throughout the storage period was 0.0178 g kg^{-1} h^{-1}.

The study demonstrated the feasibility of applying heat and moisture balance for monitoring respiration rate under large-scale storage conditions and its use for monitoring the conditions of the stored produce.

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