Evaluation of a computer-controlled ventilation system for a potato storage facility

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[1]Department of Biosystems Engineering, 438 Engineering Building, University of Manitoba, Winnipeg, Manitoba, Canada R3T 5V6; and [2]Agriculture and Agri-Food Canada, Pacific Agri-Food Research Centre, Summerland, British Columbia, Canada V0H 1Z0.

Jayas, D.S., Irvine, D.A., Mazza, G. and Jeyamkondan, S. 2001. **Evaluation of a computer-controlled ventilation system for a potato storage facility**. Canadian Biosystems Engineering/Le génie des biosystèmes au Canada. **43**: 5.5 - 5.12. A microcomputer-based monitoring and control system was designed, assembled, and field-tested as a ventilation controller in a commercial multi-bin potato storage in Southern Manitoba. The system was integrated with an automatic temperature controller to control the fresh air inlet and used CO_2 and temperature as parameters for control of the fan operation in one of two 650 t bins monitored. Carbon dioxide was measured by the infrared method. The air sample retrieval system was designed for RH and CO_2 measurements in remote locations. When the fans in all bins were 'off' for 8-10 h continuously, CO_2 concentrations in the test bin increased rapidly to warrant CO_2 set-point control to turn a fan 'on'. However, when the fans in the adjacent bins were 'on', the fan in the test bin was 'off' for an extended period due to continuous dilution from air infiltration. Therefore, CO_2 alone was inadequate as a criterion for ventilation control. A preset minimum differential temperature between the upper and lower elevations of the potato pile was added as another criterion. Higher CO_2 concentrations were found at higher elevations in the bin than at lower elevations. Thus, for control purposes, air can be sampled at the top of the potato pile. Monitoring of temperature, RH, and CO_2 within the potato bin was successful. However, frequent interferences by the potato storage manager affected the evaluation of the computer control system and resulting energy savings. An expert system would be suitable for control of ventilation in potato storage bins. **Keywords**: reduced ventilation, potato storage, computer control, air sample retrieval.

Un système informatisé de suivi et de contrôle de la ventilation a été conçu, assemblé et testé dans un entrepôt commercial de pommes de terre à cellules multiples du sud du Manitoba. Un régulateur automatique de la température a été intégré au système pour contrôler l'entrée d'air frais. Les paramètres utilisés pour contrôler le ventilateur d'une des deux chambres expérimentales étaient le CO_2 et la température. Le taux de dioxyde de carbone était mesuré par la méthode de l'infrarouge. Un système d'échantillonnage de l'air permettait de mesurer l'humidité relative et la concentration de CO_2 dans les endroits éloignés. Lorsque les ventilateurs cessaient de fonctionner pour une période de 8 à 10 heures en continu, les concentrations de CO_2 dans la cellule augmentaient rapidement jusqu'à ce que le point de contrôle soit atteint, déclenchant ainsi le ventilateur. Cependant, lorsque les ventilateurs des cellules adjacentes fonctionnaient, ceux de la cellule expérimentale ne fonctionnaient pas pour une longue période à cause de la dilution occasionnée par l'infiltration d'air. La concentration de CO_2 , seule, n'est donc pas un critère satisfaisant pour le contrôle de la ventilation. Un différentiel de température minimal entre le dessus et le dessous du tas de pommes de terre a été ajouté comme critère. Les concentrations de CO_2 mesurées dans le haut de la cellule étaient plus élevées. Donc, pour ce qui est du contrôle, l'air devrait être échantillonné sur le dessus de la pile de pommes de terre. Le suivi de la température, de l'humidité relative et de la concentration de CO_2 dans la cellule de pommes de terre s'est bien déroulé. Cependant, l'évaluation du système de contrôle informatisé et des économies énergétiques qui en résultent a été perturbée par le travail du responsable de l'entrepôt. La ventilation des cellules d'un entrepôt de pommes de terre pourrait être contrôlée par un système expert. **Mots clé:** réduction de la ventilation, entreposage des pommes de terre, contrôle informatisé, échantillonnage d'air.

INTRODUCTION

Storage of potatoes in bulk commercial bins up to 10 months is necessary to make them available for consumption and processing from one harvest to the next. To remain viable and competitive, processors demand high quality potatoes from producers. Therefore, the producers must provide a storage atmosphere that can maintain high tuber quality throughout the storage period. A potato storage manager must minimize the loss of mass resulting from dehydration (moisture loss) and respiration (dry matter loss). At the same time, the storage manager must minimize accumulation of reducing sugars in potatoes that can lead to non-enzymatic browning (an undesirable browning of the chip colour) during frying (Mazza 1983).

Heat, water, and carbon dioxide (CO_2) are products of potato respiration. Respiration of potatoes is continuous throughout all storage phases but not constant. Respiration rates have been reported from 1.0 mg CO_2 kg^{-1} h^{-1} for mature, dormant tubers at 7.5°C (Schippers 1977b) to 83 mg CO_2 kg^{-1} h^{-1} after harvest of immature, intact Norchip potatoes (Shamaila 1985).

Sugars accumulate less at storage temperatures of 7 to 12°C than at temperatures of 0 to 5°C. Higher temperatures result in higher moisture loss. Therefore, the storage manager has to compromise between quality and moisture loss. Potatoes should be stored at 90 to 95% relative humidity (RH) to minimise moisture loss (ASAE 1991). An exception is when potatoes are brought into storage wet, in which case they must be immediately dried to prevent soft rot (*Erwinia carotovora)* (Rastovski and van Es 1981). A reduction of RH may be necessary if late blight (*Phytophthora infestans*), leak (*Pythium* spp.), or frozen potatoes are present (ASAE 1991). Carbon dioxide concentrations of 0.2 to 0.3% are common in ventilated potato bins (ASAE 1991). After an application of sprout inhibitor isopropyl-N-(3-chloro-phenyl) carbamate, commonly

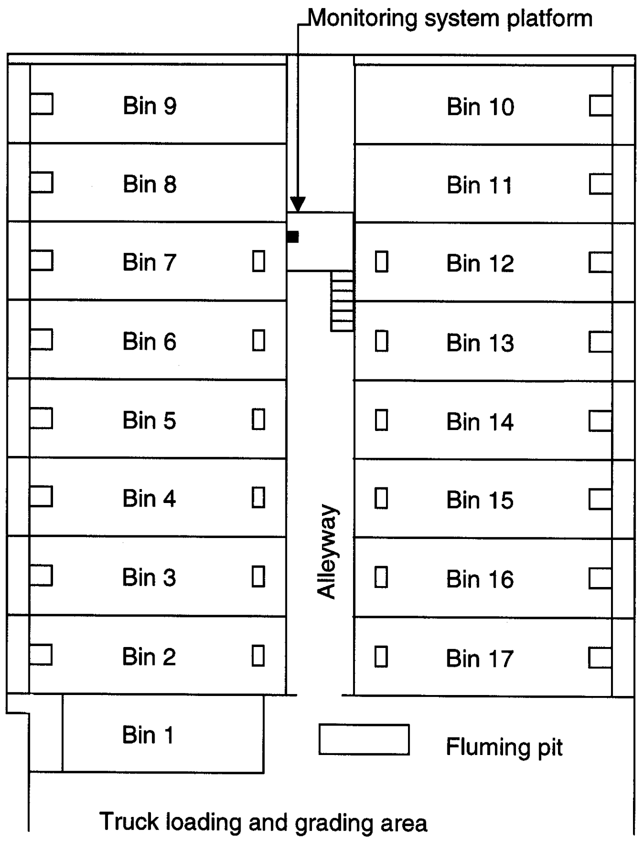

Fig. 1. Layout of a potato storage facility in Southern Manitoba showing locations of monitored bins 12 and 13.

known as CIPC, CO_2 accumulated to 3.2% in less than 48 h in a sealed Manitoba commercial storage (Mazza and Siemens 1990). Above normal rises in CO_2 are correlated to increased reducing sugar concentrations in potatoes (Mazza and Siemens 1990) which causes brown colour in processed chips making them unacceptable to consumers.

Ambient temperature often drops to sub-zero temperatures for more than 4 months during winter in Manitoba. Many storage managers try to reduce the loss of respiratory heat generated by potatoes by minimizing ventilation and re-circulation of air in a bin during cold months with intermittent fan operation. This reduced ventilation saves a considerable amount of energy. Potato storage facilities are subjected to an additional demand charge in December, January, and February if they consume more energy than allotted, because not only is it expensive to generate energy in these months but also energy demand is high. Also, during these months, bins are emptied to supply the processor and potatoes are prepared for shipment by warming them with air in the grading area. Therefore, energy consumption in the grading area cannot be reduced by any significant amount during this time. Usually storage facilities exceed their necessary peak demand power consumption by 75% during December to February and are penalized (Unpublished 1992 data, Manitoba Hydro Load Research Section, 820 Taylor Ave., Winnipeg, MB). Energy could be saved if reduced ventilation was employed. However, care must be taken not to affect potato quality.

Reliable, accurate, and inexpensive measurement of temperature in potato storage bins is available. Consistent high RH and contaminated environment in the bins make accurate, reliable, and inexpensive RH measurement difficult. It is difficult to measure RH at remote locations inside the potato bulk. Carbon dioxide is not usually monitored continuously in potato storages (Brook et al. 1995; Irvine 1997; Landry and Norris 1995).

The objective of this study was to design, implement, and evaluate a microcomputer-based monitoring and control system for reduced ventilation in a commercial potato storage facility.

METHODS and MATERIALS

Storage facility and bins

A commercial multi-bin potato storage in Winkler, Manitoba was the location for this study. Each of 17 bins was filled with approximately 650 t of freshly harvested potatoes in the fall. Several bins in the facility contained table stock potatoes and were emptied as the storage season progressed. Bins for this study contained 'Russet Burbank' potatoes, a cultivar used for french fry processing. These bins were usually kept full until June or July of the following year due to the availability of refrigeration for spring holding.

The layout of the facility is shown in Fig. 1 with the location of the monitoring system and bins 12 (test bin) and 13, which were monitored in this study. Dimensions, ventilation ducts, and sampling locations of the monitored bin are shown in Fig. 2. The two monitored bins had identical dimensions, fans, and distribution ducts. Ventilation was provided by a 3.7 kW, two-speed fan in each bin. The fans were always operated ‘on’ low setting at about 1.8 - 2.0 kW, giving volumetric flow rates of approximately 15 m^3 h^{-1} t^{-1}. All bins had insulated, wooden construction with galvanized steel panelling on both inside and outside. Each bin had a set of swing type plywood sheeted and insulated doors of size 4.9 x 4.9 m. Floors were concrete with cast-in-place water flumes connected to a central water flume that led to a central collection pit. The central collection pit serviced a large and regularly active grading and loading area. The water flumes were covered by wooden slats with unguarded slots and were used for a portion of the potato bin ventilation. The primary ventilation to the bins was distributed by two round, corrugated, and galvanized steel ducts with 32 mm perforations spaced at 200 mm centre to centre on each side in a row located 45° down from the horizontal centre line of the duct.

Monitoring system

A microcomputer-based monitoring system was designed and installed for two consecutive storage seasons. In 1991/92, the system was only used to evaluate the equipment for its suitability to monitor the environment in a full-size bin and some changes, described below, were made in the installation of the sensors. In 1992/93, the system monitored bin environments and fan status and controlled the fan in bin 12. Only data obtained in the second season (October 1992 - March 1993) are presented and discussed.

The microcomputer-based monitoring and control system was located on a platform in the alleyway (Fig. 1). The microcomputer was an IBM compatible 286 AT with a 1.0 Mb RAM.

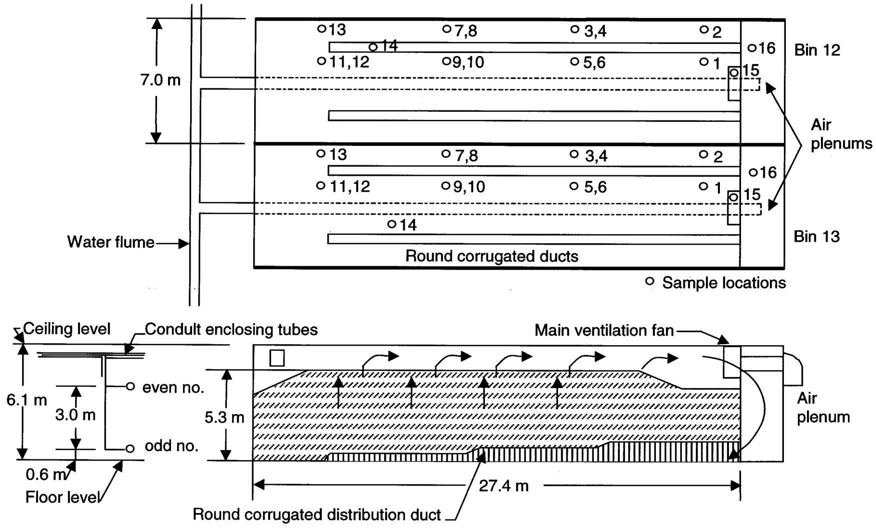

Fig. 2. Test bin plans and section showing sampling locations.

Data acquisition and control were performed using two analog cards with 16 bit resolution (Analog Connection ACPC-16-16, Strawberry Tree Inc., Sunnyvale, CA). Four compatible 'T11' terminal panels, each having eight analog input, digital input, and digital output terminals provided connections for all instruments, sensors, and controlled equipment (Fig. 3). The analog cards came with associated software which could be custom programmed with calibration factors, timed or set-point control settings, data logging options, and other various input or output options. The two analog cards provided the system with 32 analog and 32 digital channels. All analog input terminals were on aluminum isothermal plates and had built-in cold junction compensation for thermocouples.

Temperature measurement

Temperatures were measured at several locations (Fig. 2) with 24 gauge, type T, copper-constantan thermocouples (Thermo Electric Canada Ltd., Brampton, ON). The thermocouple wires in the bin ranged from 18 to 55 m in length. Because of the difficulty in installing thermocouples due to their tendency to tangle with themselves and with other wires or get caught on wood splinters or any other protrusion, thermocouple wires were taped to the plastic tubing used for retrieving air samples from within the pile. This prevented stretching and tearing of the wires. All thermocouples had their tips coated with clear nail polish to protect them from corrosion and were calibrated before installation. In the bins, thermocouples were protected from direct contact with potatoes by securing each tip inside a hollow 40 mm diameter, plastic, spherical ball with 6 mm diameter perforations around its surface.

RH measurement

Over-specification of accuracy in RH measurements can be expensive. In general, the accuracy of RH measurements is ±3% in clean air and ±5% in unclean air (White and Ross 1991). Also, RH instrumentation requires regular maintenance and drifts over time. RH instruments need frequent re-calibration (White and Ross 1991). Because RH sensors require regular maintenance, it is difficult to measure RH in situ in potato bins. The measurement is further complicated by the contaminated environment and consistent high RH values found in the storage bins. Therefore, an air retrieval system was designed to pump the air from different sampling locations to the sensor.

Air samples were pumped by 115 VAC vibratory type pumps built into each CO_2 monitor (Model 421P, Nova Analytical Systems Inc., Hamilton, ON). Flow rates of samples varied between CO_2 monitor pumps but were always between 1.5 and 4 L/min. A sample was pumped from a location through sampling tubes (Nylo-Seal 44-SN, Imperial Eastman, Chicago, IL) having an inner diameter of 4.7 mm, when a corresponding, normally closed, 2-way solenoid valve (Deltrol Fluid Products, Bellwood, IL) was turned 'on' (Fig. 3). The air samples were pumped through the tubing and the solenoid valve, past an encapsuled RH sensor, and then through a CO_2 monitor for 4.5 min before switching to another location.

RH was measured in pumped air streams (Fig. 3) with an RH sensor/transmitter unit which uses a bulk polymer resistance sensor (Model RH-2, General Eastern Instruments Ltd., Watertown, MA). The RH units were factory calibrated to ±2% in the range of 20-95% RH. Operating range was 0-99% RH, non-condensing. More reliable RH readings are achieved when the RH is below 90%. However, the normal range of RH found in potato storages is 90-100%. To correct this problem, a known amount of sensible heat (adding heat without adding or removing moisture) was added

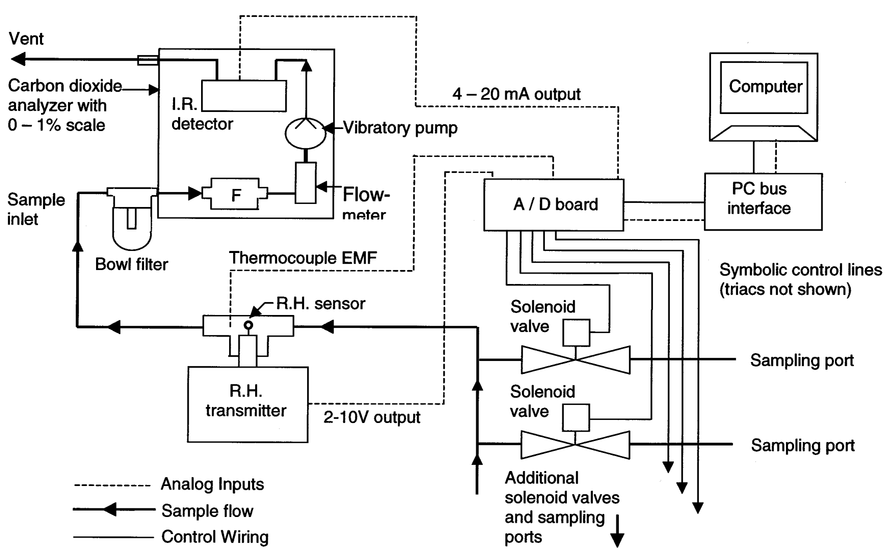

Fig. 3. Schematic of partial monitoring system.

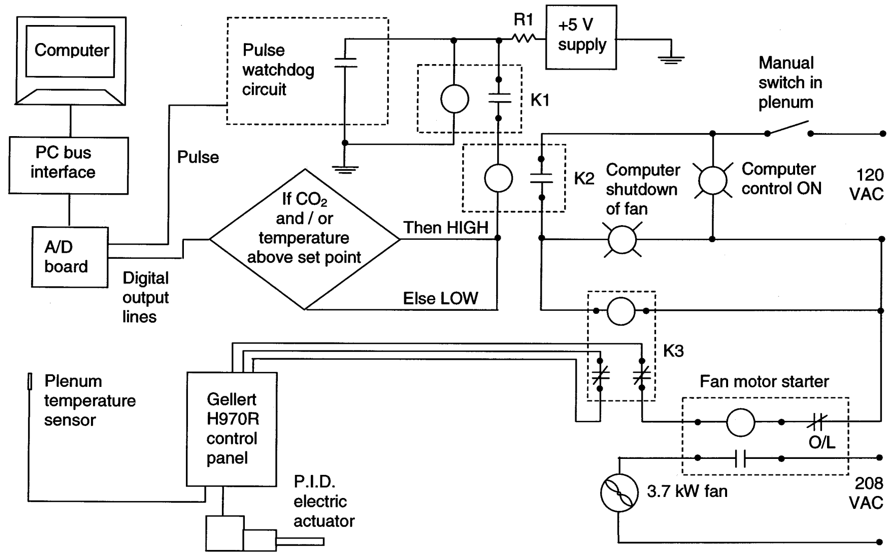

Fig. 4. Schematic of the integrated microcomputer based control system and the conventional temperature controller.

to the known amount of air sample and the RH was measured. The air temperatures were measured at each sample tube inlet in the bin using the thermocouples as previously described. The RH in the bin was then calculated using standard psychrometric equations by incorporating the bin temperature at the tube inlet, the temperature at the sensor, and the measured RH at the sensor. To help ensure sensible heating, the sample tubes were enclosed in PVC conduit from the monitoring system cabinet to the points where the tubing branched into the pile of potatoes. A 1500 W air heater was placed in a small enclosure with a small blower connected to the PVC conduit to provide warm forced air into the conduit. Under normal circumstances the sensor would, due to sensible heating, be measuring relative humidities between 50 and 85%.

The advantages of measuring the RH of sensibly heated air withdrawn from a potato pile were:

1. A single RH sensor was used to measure the RH from numerous locations. The use of a single sensor offered two advantages: the cost of measuring RH at several locations was reduced and all measurements were relative to each other in the sense that there was no calibration differences between different RH sensors.
2. The sensor was accessible for calibration or replacement.
3. Air samples measured by the sensor had a lower RH, thus problems associated with measuring relative humidities in the range of 90-100% were eliminated.
4. The air from the contaminated environment was first filtered before reaching the sensors, thereby improving the accuracy and life of the sensors.

The disadvantages of this technique were:

1. The accuracy of the measurement depends upon the accuracy of three measurements: two temperatures and the RH.
2. A leak proof sampling system is necessary as is a reliable pump, though for this study they were a prerequisite for CO_2 sampling.
3. Calculations must be performed to determine the RH at the sample origin; however, this was not a problem as a computer was used to receive and process data.
4. A continuous output was not possible. A certain length of time was required for a sensor to equilibrate to relative humidities of the air pumped from consecutive locations. Considering that RH is seldom actually measured in many potato storages, even periodic data accessible by automatic printout or through a data file were a great improvement.

The RH sensor was calibrated regularly using a General Eastern Hygro-M1 Optical Dew Point Monitor and 1111H sensor (General Eastern Instruments, Watertown, MA).

Carbon dioxide measurement

Carbon dioxide was measured using the "non-dispersive infra red method" by Nova model 421P CO_2 monitors (Nova Analytical Systems Inc., Hamilton, ON). These monitors give continuous 4-20 mA output proportional to CO_2 content of an airstream. One monitor was a non-linear output type and the other was a linear output type. Vibratory pumps, built into the monitors, moved a continuous airstream through the sensor. These pumps were found sufficient to retrieve air samples from the sampling locations in the bin through the tubing. Both units were wall mounted, had a visible meter on the front panel for direct reading, and were equipped with water and dust traps at their inlets. Calibrations of the CO_2 monitors were made using an infrared gas analyzer (Model 865, Beckman Instruments Inc., Fullerton, CA) as the standard. A CO_2 scrubber tube was supplied with each analyzer to provide a means of checking zero. These checks were performed every 2-3 weeks.

Ventilation control system

The function of the control system (Fig. 4) was primarily to maintain either temperature or CO_2 within a preset range in the bin by turning ‘on’ the ventilation fan at the upper set-point and ‘off’ at a lower set-point. When the fan did run, a fresh/return air blending door was operated by a raw product ventilation control panel (Model H970R Series, The Gellert Company, Boise, ID) to maintain a uniform temperature in the plenum. All the normal safety limits were built into the control panel such as low temperature limit in the plenum and high outside air temperature limit.

Control was set up to allow the storage manager to turn ‘off’ computer control with a manual toggle switch installed in the H970R control panel (Fig. 4). Panel lights were installed to indicate if the computer had shut ‘off’ the fan and if the computer system had control of the fan or not. The H970R panel provided the operator with all other indicator lights required to know the status of the system. The H970R control panel was operated in continuous ventilation mode for the duration of the experiment. Without manual or computer control intervention, the control panel could only shut ‘off’ the fan if the air in the

Table 1. Means and standard deviations of CO_2 concentrations (%) at sampling locations for four different ventilation conditions in bin 12 between November 30, 1992 and January 21, 1993.

Bin 12 location	All fans in facility On			Fan in bin 12-On Others† Off			Fan in bin 12- Off Others† On			All fans in facility Off		
	Mean	S.D.§	n‡	Mean	S.D.§	n‡	Mean	S.D.§	n‡	Mean	S.D.§	n‡
1*	-	-	-	-	-	-	-	-	-	-	-	-
2	0.09	0.09	459	0.11	0.10	58	0.18	0.09	700	0.24	0.12	262
3	0.09	0.08	450	0.11	0.09	59	0.17	0.09	705	0.25	0.12	258
4	0.10	0.10	471	0.14	0.12	69	0.19	0.09	675	0.27	0.11	257
5	0.10	0.09	458	0.12	0.10	64	0.18	0.10	703	0.25	0.13	253
6	0.10	0.09	456	0.11	0.10	56	0.22	0.10	697	0.29	0.13	238
7	0.10	0.09	462	0.10	0.08	60	0.17	0.09	691	0.25	0.12	244
8	0.14	0.11	579	0.18	0.11	105	0.17	0.09	545	0.26	0.12	188
9	0.13	0.11	568	0.17	0.12	106	0.15	0.09	556	0.24	0.13	190
10	0.13	0.11	567	0.16	0.10	97	0.20	0.09	567	0.29	0.12	209
11	0.13	0.11	543	0.16	0.10	96	0.17	0.09	591	0.24	0.11	210
12	0.13	0.11	542	0.17	0.10	96	0.19	0.11	578	0.28	0.10	208
13	0.12	0.11	526	0.16	0.10	91	0.20	0.11	558	0.28	0.13	196
14	0.11	0.10	498	0.13	0.08	88	0.16	0.09	627	0.24	0.12	217
15	0.12	0.11	512	0.13	0.08	90	0.18	0.09	612	0.25	0.12	232
16	0.10	0.09	460	0.14	0.14	67	0.17	0.09	704	0.24	0.12	282

† "Others" refers to other fans in the facility.
§ S.D. = Standard deviation
‡ n = sample size
* Data missing due to failed solenoid in sample stream

plenum was too cold. Also, if the 4-20 mA analog signal from the CO_2 analyzer to the data acquisition system dropped below a preset lower set-point, the digital output to relay K2 dropped to a low voltage to energize solid state relay K2. Relay K3 coil was then energized by the 120 VAC line, its contacts opened, and the fan stopped. The watchdog circuit (Fig. 4) was constructed to prevent the computer from turning or holding the fan 'off' if the program did not or could not maintain a regular digital output pulse. Irregular output could be caused by program malfunction, an exit from the program control mode, or an exit from the program itself.

RESULTS

Monitoring system

Heavier and more manageable thermocouple wires would be a worthwhile investment if monitoring was to be done year after year. Coating the thermocouple ends was effective in preventing corrosion. All ends recovered stayed in the perforated balls throughout the test and were well protected. This technique ensured that the temperature measured was the temperature of the air entering the tubing which also had its open end inserted in the perforated ball.

The RH sensor held its calibration during the first season. During the second storage season there was a slight drift in the calibration. Under normal circumstances the sensor would, due to sensible heating, be measuring relative humidities between 50 and 85%. At 50% RH, the difference in calibrations between September and May of the second storage season was only 0.23% RH but at 85% the difference was 1.65% RH. When high accuracy in RH measurement is desired in a contaminated environment, it is inevitable that the sensor has to be re-calibrated at least once every year to account for drift. Response of the sensors was fast enough for 4 min sampling times. Condensation occurred once in the sampling tubes during suberization, a period after harvest when temperature and RH are high. The calculated RH of samples soon became greater than 100% as the moisture left in the tubing was absorbed by subsequent samples. Other than this incidence, RH monitoring was successful.

Carbon dioxide monitors worked well throughout all tests. There were no malfunctions, no loss in response time, and the monitors held their calibration well. The sample tubes remained free from plugging throughout the storage season in spite of condensation. Typically the analyzer responded to changes in concentration of CO_2 from different bin locations in 30 s. The 4 min sampling time from each location was more than enough to obtain a reliable reading from a location. Slight drift from zero with these monitors was not uncommon but never more than 0.05% deviation of CO_2 from zero occurred in either direction of the 0-1% range monitors. For potato storages, CO_2 concentrations less than 1% are desired.

Carbon dioxide accumulation and decay

When all the fans were 'off' during the holding period (November 1, 1992 to January 21, 1993) of the second season, the average rate of CO_2 accumulation at all locations in bin 12 was 0.016% CO_2/h (S.D: 0.003% CO_2/h), while in bin 13, CO_2 accumulations was 0.017% CO_2/h (S.D: 0.003% CO_2/h) (Irvine 1997). This average accumulation of CO_2 calculation for the storage period excluded two periods during which rapid

Table 2. Means and standard deviations of CO_2 concentrations (%) at sampling locations for four different ventilation conditions in bin 13 between November 30, 1992 and January 21, 1993.

Bin 13 location	All fans in facility On Mean	S.D.§	n‡	Fan in bin 12-On Others† Off Mean	S.D.§	n‡	Fan in bin 12- Off Others† On Mean	S.D.§	n‡	All fans in facility Off Mean	S.D.§	n‡
1	0.15	0.08	457	0.19	0.15	64	0.25	0.11	690	0.28	0.12	266
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15	0.17	0.09	512	0.26	0.11	90	0.24	0.10	612	0.37	0.12	232
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† "Others" refers to other fans in the facility.
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accumulations were noted, namely suberization and following the application of CIPC. The rate of accumulation was similar at all locations throughout the bin. However, CO_2 concentrations at higher elevations were consistently higher by approximately 0.05% than at lower elevations (Irvine 1997). Average concentrations of CO_2 in bin 12, for various locations and fan status within the facility during the holding period, are shown in Table 1 and for bin 13 in Table 2. Table 1 clearly shows that the fan status in adjacent bins affected the CO_2 concentration in the test bin. The CO_2 accumulation rates (%CO_2/h) can be converted to respiration rate (g of CO_2 t^{-1} h^{-1}) by using the volume of air present in the bin (27 000 moles) and mass of potatoes in the bin (650 t). The average respiration rate was calculated to be 0.3 g CO_2 t^{-1} h^{-1}.

Ventilation control

The fan in the test bin was controlled primarily based on CO_2 concentrations. Ventilation control began in October, but was frequently turned 'off' by the store manager to allow suberization. On November 6, the fans were activated to maintain a CO_2 concentration between 0.20 and 0.25%. On November 14, another criterion for stopping the fan when the temperature in location 1 of the test bin dropped below 7.7°C was added based on the advise of the storage manager. On November 11, CIPC was applied to neighbouring bins 14 and 15, which resulted in an increase in CO_2 concentration in bins 12 and 13 due to leakage. Simultaneous rapid removal of CO_2 by the fan and high infiltration of CO_2 from adjacent bins resulted in frequent on/off status of the fan for a day. On November 25, the storage manager requested a change in the desired CO_2 range to 0.15-0.20% to increase the fan 'on' periods and the control was accordingly adjusted. On November 26, CIPC was applied to bins 12 and 13 and all fans were manually turned 'off'. The next day, the computer control was resumed with a change in criterion of CO_2 concentration range. Because CIPC was applied, we expected higher CO_2 concentrations and therefore we changed the desired range to 0.35 - 0.40% so the control program was again adjusted. During this period, the fans in the adjacent bins were 'on' and this resulted in lower CO_2 concentration in the test bin. Rapid removal of CO_2 by the fans in both the test bin and the adjacent bins and simultaneous high production rates of CO_2 by the potatoes caused frequent on/off of the fan status. The storage manager did not like this frequent cycling of the fan and therefore the fan was manually held 'on' from November 28 to December 4. On December 4, the automatic control was resumed. During this period, the energy consumption was high due to the high demand for energy in the grading area. To reduce the peak demand of power, the storage manager manually turned 'off' the power during the day from December 4 - 10. The temperature differences between upper and lower levels in the bin increased to about 1.6°C on December 9 and the storage manager manually turned the fan 'on'. On December 10, the automatic control was resumed and the lower CO_2 limit was achieved on the same day and thereafter the fan was 'off' by the computer until December 15. There was some on/off cycling on December 15. The storage manager then turned 'on' the fan manually between December 16 and 24. On December 24, the automatic control was resumed, but the fan was held 'off' as the CO_2 concentrations were below the critical level. During this period, the air temperature in the plenum became cold enough to trigger the cold temperature shut-down built into the H970R control panel, which was set at 4.4°C. The storage manager then turned 'on' the fan manually from December 28 to January 5. From January 6 onwards, intermittent ventilation was followed. Fans were either operated continuously with a low airflow or for only 6 to 12 h/d with higher airflow rates during the holding period, as recommended by Schaper and Preston (1989).

DISCUSSION

The instruments held their calibrations well and the performance of the monitoring system was good. In particular, the air retrieval system for RH and CO_2 measurements was successful and economical. When all the fans were 'off', the CO_2 concentrations at even numbered locations (those at higher elevations) in the test bin had higher average CO_2 concentrations than those at lower elevations. This contradicts the findings of Schaper and Varns (1978), whose study found higher concentrations close to the floor and away from the fan chamber. They suggested that wind had a diluting effect on the CO_2 concentrations closer to the fan chamber. Away from the fan chamber, they suggested the higher mass of CO_2 molecules than air caused them to settle near the floor. In this study, all fans were 'off' and therefore in natural ventilation and infiltration, wind pressure and thermal buoyancy are the driving mechanisms of CO_2 movement (ASHRAE 1985). This study was conducted primarily while outdoor temperatures were much cooler than the indoor temperatures. Thermal buoyancy in buildings warmer than the outside cause an internal building pressure to be equal to outside pressure against the building at some elevation above the floor while infiltration enters from below this level and exhaust above this level. This phenomenon causing air to flow upward through the building might have been responsible for the larger CO_2 concentration observed at higher elevations in the bins. This tendency makes sampling for control purposes at the top of the pile more appropriate and would make tubing installations easier since they could be installed after the bins are filled rather than during filling.

The fan status in adjacent bins had a considerable impact on the CO_2 concentrations in the test bins (Table 1). Even though all bins in the facility were separated by supposedly sealed walls, it appears that there was significant air movement between them to greatly affect CO_2 concentrations. The average respiration rate was 0.3 g CO_2 t^{-1} h^{-1}, assuming that no leakage or infiltration occurred. This rate is lower than reported in the literature for any condition to which tubers of any cultivar are exposed. As an example, the lowest respiration rate reported by Schippers (1977a, 1977b) for potatoes was 1.0 g CO_2 t^{-1} h^{-1}. The problem with comparing these numbers from a commercial storage as opposed to a laboratory apparatus is in the estimation of air exchange between the test bin, the outside, and adjacent bins and the outside.

Success of ventilation control and resulting energy savings could not be evaluated due to frequent interruptions by the storage manager. The ventilation control was designed purely based on optimum storage conditions for potatoes. However, various practical factors such as optimum use of energy during the period of peak energy demand (December, January, and February), CIPC applications, and infiltration from adjacent bins, are important in commercial situations. Sometimes there was a frequent on/off cycling of the fan due to stringent ventilation control which was not desirable. The storage manager felt that the monitoring system was useful to help visualize the storage conditions at different locations inside the bins and therefore to make better decisions about controlling the ventilation manually rather than by automatic control.

This automatic control system would have been successful if it was tested under laboratory conditions. However, as this study clearly shows, the control decisions are influenced by other practical factors. Therefore, a microcomputer based system must be able to continuously adapt to changing priority criteria. In such real-life situations, a knowledge-based expert system would be suitable.

CONCLUSIONS

The 'non-dispersive infra-red type' monitors used in this study for continuous measurement of CO_2 concentration and the air sample retrieval system for CO_2 and RH measurements were adequate for monitoring and control purposes in commercial storage bins. While the fans were 'off', the measured CO_2 concentrations at the upper levels could be used as a criterion to ventilate because the CO_2 concentrations were higher at higher levels than at lower levels. The accuracy of RH measurements was improved by using sensible heating of air samples before measurements. In multi-bin facilities, a reduced ventilation strategy based on CO_2 concentrations alone is not likely to provide adequate ventilation because CO_2 concentrations can be reduced by fans from other nearby bins due to infiltration and leakages. Other criteria such as lowest temperature point in the lower levels and temperature differentials between the upper and lower levels might be useful. Operating the fans of the adjoining bins intermittently and at different times throughout a storage season in a multi-bin facility would minimize the energy consumption. This will limit the number of bins ventilated simultaneously and reduce the peak energy demand.

The computer control ventilation system and resulting energy savings could not be evaluated due to frequent interruptions by the storage manager. The storage manager changed the criteria for controlling the fan and also manually turned 'off' or 'on' the fan overriding automatic control on several occasions. This study clearly showed that in a commercial storage facility various practical factors influence the control decisions besides actual storage conditions. A knowledge-based expert system which can regulate storage ventilation based on changing criteria should be developed.

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