

Average convective-pore velocity of carbon dioxide gas through grain bulks

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¹Department of Biosystems Engineering and ³Department of Mechanical and Industrial Engineering, University of Manitoba, Winnipeg, MB, Canada R3T 5V6; and ²Agriculture and Agri-Food Canada, Research Centre, 195 Dafoe Road, Winnipeg, MB, Canada R3T 2M9. Received 16 August 1994; accepted 16 February 1996.

Bundas, C.L., Jayas, D.S., Muir, W.E., White, D.D.G. and Ruth, D. 1996. Average convective-pore velocity of carbon dioxide gas through grain bulks. *Can. Agric. Eng.* 38:091-098. Experiments were conducted to observe the movement of carbon dioxide (CO₂) gas through a variety of grain bulks subjected to controlled temperature differences. The CO₂ concentration, as it varied with time, was used in a finite difference, diffusion-convection model to determine an average convective-pore velocity of CO₂ through grain bulks. The average convective-pore velocity increased as the temperature difference increased when the CO₂ was introduced into the grain bulk from the bottom surface (P<0.05). The average convective pore-velocity was not affected by the temperature difference when the CO₂ was introduced into the grain bulk from the top surface (P>0.05). The average convective-pore velocity was smaller for canola than for two cereal grains (barley and wheat) and lentils when the CO₂ was introduced into the grain bulk from the top and bottom surfaces (P<0.05). The lowest average convective-pore velocity was 4.30×10^{-6} m/s for canola at a temperature difference of 20°C when CO₂ was introduced into the grain bulk from the bottom surface. The largest average convective-pore velocity was 2.42×10^{-3} m/s for wheat at a temperature difference of 40°C when CO₂ was introduced into the grain bulk from the top surface. Keywords: pore velocity, controlled atmosphere, modified atmosphere, storage, natural convection, bulk movement, mathematical model

Des expériences ont été menées afin d'observer les mouvements de dioxyde de carbone (CO₂) à travers des masses de grains soumises à des écarts de températures contrôlés. On s'est servi des concentrations de CO₂, selon les variations dans le temps, dans un modèle de diffusion-convection utilisant la méthode des différences finies, pour déterminer la vitesse interstitielle de convection moyenne du CO₂ à travers les masses de grains. Lorsque le CO₂ était introduit par le dessous de la masse de grains, la vitesse interstitielle de convection moyenne augmentait quand l'écart de température augmentait (P<0.05). Lorsque le CO₂ était introduit par le dessus de la masse de grains, les écarts de température n'avaient pas d'influence sur la vitesse interstitielle de convection moyenne (P>0.05). La vitesse interstitielle de convection moyenne était plus faible pour le canola que pour l'orge, le blé et les lentilles, que le CO₂ soit introduit par le dessous ou le dessus de la masse de grains (P<0.05). La plus petite vitesse interstitielle de convection moyenne mesurée était de 4.30×10^{-6} m/s pour le canola, à un écart de température de 20°C, alors que le CO₂ était introduit par le dessous de la masse. La plus grande vitesse interstitielle de convection moyenne mesurée était de 2.42×10^{-3} m/s pour le blé, à un écart de température de 40°C, alors que le CO₂ était introduit par le dessus de la masse. Mots-clés: vitesse interstitielle, atmosphère contrôlée, atmosphère modifiée, entreposage, convection naturelle, mouvement de masse, modèle mathématique

INTRODUCTION

An increase in the carbon dioxide (CO₂) concentration in the intergranular space of a grain bulk caused by respiration of grain, insects, mites, and microflora can be used as an indicator of incipient spoilage (Muir et al. 1985). Modified or controlled atmospheres (CA) of elevated CO₂ and depleted oxygen (O₂) can be used effectively for controlling insects and mites in stored grain (Jayas et al. 1991). For successful detection of incipient spoilage or for successful control of insects and mites, knowledge of the distribution of generated or introduced CO₂ throughout the grain bulk is essential.

The phenomena that affect transport of CO₂ include: natural convection, diffusion, sorption (adsorption and absorption) or desorption, and forced distribution (Banks 1990). These phenomena are influenced by many factors including external environmental factors, properties of the grain through which the gas is moving, and properties of the gases introduced into the storage. Interactions that are complex and not yet fully understood occur among these phenomena.

A mathematical model used for predicting the gas flow rates, due to natural transport phenomena, must incorporate the contributions made by each individual transport process involved. Alagusundaram et al. (1991) developed a three-dimensional diffusion model for CO₂ in grain bins. This model predicted lower concentrations of CO₂ than the concentrations measured in experimental bins. The non-inclusion of the movement of interstitial air due to convection currents within the grain bulk or leaks in the storage structure might have caused these deviations. Cofie-Agblor et al. (1993) showed how sorption and desorption affect the concentration of CO₂ in stored wheat.

More research is required to understand the nature of the movement of CO₂ resulting from natural convection during CA storage. Therefore, the effects of temperature difference, grain type, and location of introducing CO₂ into a grain bulk, on the convective-pore velocity of CO₂ through a grain bulk were investigated.

MATERIALS AND METHODS

Experimental apparatus

An apparatus was designed to simulate the expected circulation of gas in a typical stored-grain bulk caused by natural convection. One vertical column was used to represent the

hot region of the grain bulk and the other to represent the cold region of the grain bulk (Fig. 1). These vertical grain columns were connected at the top and bottom by gas chambers. The gas chambers allowed confined, free passage of air between the two columns and were used as locations for introducing CO₂ into the grain bulk. Sliding-gate valves were installed at each end of the vertical columns. The valves were used to control the movement of interstitial gas between the grain columns. This was done by having any combination of the sliding-gate valves opened or closed at any given time. Perforated flooring (1 mm x 5 mm openings) was installed at the bottom of each vertical column to prevent the grain from entering the bottom gas chamber.

The grain columns and gas chambers were constructed from 1-mm-thick sheet metal. The vertical grain columns were 1778 mm long and were rolled and welded to a diameter of 305 mm. Water jackets made of the sheet metal were permanently fixed to each grain column. The top and bottom gas chambers were bent to form rectangular chambers that were 330 mm square and 1245 mm long. Acrylic sheets, 9-mm-thick, were used to construct the sliding-gate valves in the gas chambers and the view ports in each gas chamber. The view ports were used for visual inspection of dry ice sublimation. Access ports were made in both gas chambers so that dry ice, the source of the CO₂ gas used in the experiments, could be readily placed in each chamber. Joints and access ports were sealed with silicone caulking. The experimental apparatus was then tested for air-tightness to ensure that no detectable leaks existed.

The temperature of the grain bulk in each column was adjusted by circulating water at constant temperature through

the water jackets. Copper-constantan (T-type) thermocouples were used to measure the temperature of the grain bulk. Thermocouples were placed along the length of each grain column at evenly spaced locations and at the top, centre, and bottom cross-sections of each column (Fig. 1). Temperatures measured by thermocouples were monitored using three data acquisition boards (Model KS102, Taurus, Ottawa, ON) and a personal computer (PC-XT IBM Compatible) or monitored manually using a multi-switch junction box, connected to a temperature indicator (Microprocessor Thermometer, Model HH23, Omega, Stamford, CT). Thermocouples were also used to monitor the temperature of the laboratory and to control the water temperature of the hot water circulator. The temperature at a given location was also used to convert the measured CO₂ concentrations to densities (mass concentrations) using the ideal gas law.

The CO₂ concentrations were monitored at various locations in the grain bulk of each grain column. Polyvinyl chloride (PVC) tubing was threaded through holes in the wall of the grain column and was attached with wire to the desired sampling locations (Fig. 1). The holes and wires were also used to install thermocouples at the designated locations in the grain columns. The ends of the PVC tubes were fitted with 3.2 mm rubber septa which were fixed to the end of each tube by means of silicone caulking. A needled syringe was used to extract gas samples from the grain bulk. The gas samples were analysed using a gas chromatograph (Model-HP 5895A GC Workstation, Hewlett Packard, Mississauga, ON). The gas chromatograph had a thermal conductivity detector. The carrier gas used was helium at a flow rate of 40 mL/min.

Experimental design

The parameters investigated included temperature difference between the hot and cold grain columns, grain type, and locations of introducing CO₂ into the grain bulk. The temperature difference considered was the average difference in temperature measured by the thermocouples in each of the two vertical grain columns. This average excluded the temperature measurements in the upper and lower 50 mm of each vertical grain column because large temperature gradients existed in these regions. The temperature differences investigated were 20, 40, and 56°C which are typical in stored grain bulks on the Canadian Prairies. For a temperature difference of 20°C, the cold column was maintained at 10°C while the hot column was maintained at 30°C. For temperature differences of 40 and 56°C, the hot column temperatures were maintained at 45 and 61°C, respectively, and the cold column temperature was maintained at 5°C. The grain types investigated were barley, canola, lentils, and wheat. The CO₂ was introduced into the grain bulk from the top or bottom gas chambers.

Procedures

Prior to each replicate or set of experiments, the top gas chamber was removed and the vertical grain columns were filled with grain using two sections of PVC pipe (50 mm in diameter) of different lengths (one 1830 mm; the other 914 mm). The long pipe was used to fill the bottom half of the column and the short pipe was used to fill the top half of the

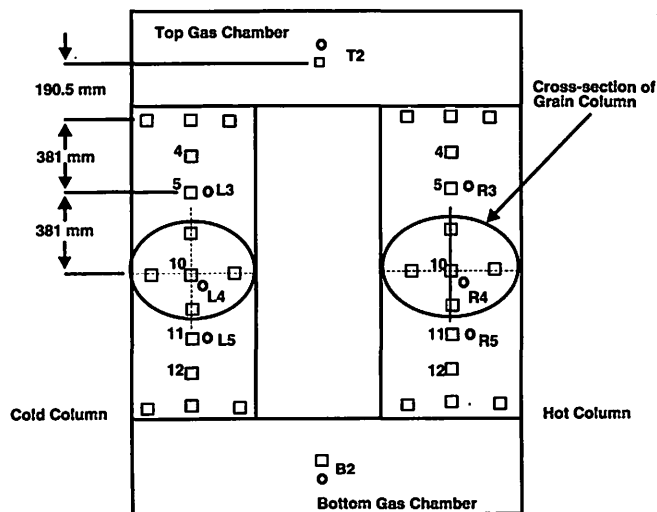


Fig. 1. Thermocouple and gas sampling locations. Thermocouple locations that are not numbered were not used to calculate the temperature difference between grain columns. The drawing is not to scale. O Gas sampling locations (numbers preceded by letters); □ Thermocouple locations.

column. The PVC pipes had 90 elbows at their ends. As the pipes were filled, a small amount of grain would exit the bottom of the pipe until it was blocked by the formation of a small pile of grain at the end of the pipe. When the pipe was full, it was elevated a small amount and the grain exited the bottom of the pipe as if it was dropped from a zero height. This was done to ensure that the porosity would be as uniform as possible throughout the entire length of each grain column. After filling was complete, the grain bulk settled to a height 12 mm below the top of the column. This settling was taken into account when the geometric parameters used in later analyses were determined and in the calculation of the porosity. The mass of the grain was measured and recorded prior to filling each column.

After the vertical grain columns were filled for each replicate, a minimum period of 12 h was allowed for the grain temperature to become uniform at the desired value. Dry ice pellets (315 to 320 g) were then placed into either the top or bottom gas chambers through access ports and allowed to sublimate at atmospheric pressure. This resulted in no pressure gradient when the gate valves were opened. This also reduced the leakage through the sliding-gate valves. Sublimation occurred with all sliding-gate valves in the "closed" position. This was done to ensure that at time zero, when the sliding-gate valves were opened, the interstitial air in the grain bulk would contain ambient levels of CO₂. The sublimation period ended when it was determined by visual inspection through the view ports of the gas chambers that no more dry ice was present in the gas chambers. The access port was then closed and sealed.

The concentrations of CO₂ in the interstitial gas at various locations in the apparatus were monitored at 10-20 min intervals during the first hour and at 1 h intervals for the next 5 h or until the concentration of CO₂ became uniform in the grain columns. A "no-flow test" and a "bulk-flow test" were done for each location of introducing CO₂ and for each temperature difference.

In the no-flow test, the sliding-gate valves, in the gas chamber where the dry ice was placed, were moved to the "open" position after initial samples of interstitial gas in the grain bulk and air in the gas chambers were taken. The sliding-gate valves in the other gas chamber remained closed (i.e. the loop remained closed). Therefore, the flow between the grain columns caused by natural convection was eliminated.

In the bulk-flow test, the combined effects of no-flow ("diffusion") and natural convection were investigated. After initial samples of interstitial gas were taken, all of the sliding-gate valves were moved to the "open" position. This allowed for an open circuit through which interstitial gas could circulate. The air exiting the top or bottom of a column was allowed to move into the second column and return to its starting point.

A sample set consisted of one sample from each of the seven gas sampling locations. The intervals at which interstitial gas samples were taken were chosen so that trends in CO₂ movement could be easily deduced but also allow enough time to analyse samples between sample sets. A sample set was always taken prior to opening any of the sliding-gate valves to give the initial concentration of CO₂ in the vertical

grain columns.

On completion of the test, all sliding-gate valves were placed in the "open position" (if they were not already) and the access ports to the gas chambers were opened for 9-10 h to allow the interstitial gas to reach the ambient levels. The grain bulk was allowed to equilibrate 8-9 h with the temperature of the water jackets prior to the start of the next experiment.

After a replicate was completed, samples of the grain from both columns were collected and the moisture content measured to check if moisture migration occurred within the grain columns during a replicate. The initial and final moisture contents of each grain type were measured using ASAE Standard S352.2 (ASAE 1993). The particle densities were measured using an air comparison pycnometer (Model 930, Beckman Instruments Inc., Fullerton, CA).

ANALYSIS OF DATA

The following transport equation for unsteady, one-dimensional movement of a given chemical species through a porous medium (Ebach and White 1958; Fried and Combarous 1971; Hensley and Schofield 1991) was solved using the finite difference method (Bundus 1994):

$$\frac{\partial(\phi c)}{\partial t} + \frac{\partial(\phi c v_p)}{\partial y} = \frac{\partial}{\partial y} \left[\phi \Gamma \frac{\partial c}{\partial y} \right] + S \quad (1)$$

where:

- ϕ = porosity of the porous media,
- c = chemical species concentration in the pore volume (kg/m³),
- v_p = average (laminar) velocity of the pore fluid phase (convective-pore velocity) (m/s),
- y = length in the vertical direction (m),
- Γ = no-flow coefficient (m²/s), and
- S = net rate of internal production of the chemical species mass per unit volume (kg • m⁻³ • s⁻¹).

The net rate of internal production of the chemical species is the difference between the rate of internal production of the chemical species and the rate of the chemical species transfer from the fluid to the solid phase (sorption-desorption). The sorption-desorption effects in this study were assumed to be negligible.

The predicted CO₂ concentrations for given values of the no-flow coefficient and the convective-pore velocity were compared at three gas sampling locations with the measured CO₂ concentrations. These parameters were varied individually at each gas sampling location to obtain a minimum average-absolute difference between predicted and measured CO₂ concentrations. The values of the parameters that gave the lowest differences for each location were averaged and were considered to best describe the processes that occurred during the experiments (Tarantola 1987; Osman and Beck 1988; Anger 1990; Flach and Özisik 1992; Bundus 1994).

RESULTS AND DISCUSSION

Experimental CO₂ concentrations

The properties of the grain bulks used in this study are

summarized in Table I. For both no-flow and bulk-flow tests, when CO₂ was introduced from the top gas chamber, major movement of CO₂ occurred in the cold column and when CO₂ was introduced from the bottom gas chamber, major movement of CO₂ occurred in the hot column. For the no-flow tests, the CO₂ concentrations increased at a fast rate at the beginning of the experiment and after this initial movement the rate of increase in concentration gradually slowed as the experiment progressed.

When the CO₂ was introduced into the grain bulk from the bottom gas chamber, it rose through the hot column, entered the top gas chamber, and then moved downward through the cold grain column. For temperature differences of 40 and 56°C, the CO₂ had sufficient time during a 6-h experiment to circulate within the apparatus and create a uniform concentration throughout the grain bulk. For a 20°C temperature difference, CO₂ concentrations did not become uniform during a 6-h period. The direction of movement of CO₂ was the same when the CO₂ was introduced from the top gas chamber. In this case, however, it took much less time (< 3 h) for CO₂ concentrations to become uniform. Even for a temperature difference of 20°C, a uniform concentration was reached.

For bulk-flow tests, the CO₂ concentration at a gas sampling location increased to a peak value and then decreased to a level that was equal for all sampling locations (i.e. uniform concentration). The peak value of CO₂ concentration decreased as the distance from the source of the CO₂, in the direction of movement, increased and as the temperature difference decreased. As an example, for wheat having a temperature difference of 56°C, the peak CO₂ concentration was 0.8517 kg/m³ for gas sampling location R5, 0.8197 kg/m³ for gas sampling location R4, and 0.7627 kg/m³ for gas sampling location R3 when CO₂ was introduced from the bottom gas chamber. For wheat having a temperature difference of 20°C, the peak CO₂ concentration was 0.3860 kg/m³

for gas sampling location R5 when CO₂ was introduced from the bottom gas chamber.

Moisture migration in grain bulks is believed in part to be the result of natural convection. The moisture contents taken at the end of each replicate indicate that some moisture migration may have occurred. The moisture content of the grain increased by as much as 6 percentage points (wb) in the upper levels of the hot grain column and increased 2 percentage points (wb) in the upper levels of the cold grain column for wheat and barley. As the warm interstitial air rose through the grain bulk, it contacted the cooler air in the top gas chamber. Some of the moisture in the air was adsorbed by the grain in the upper levels of both grain columns. The presence of moisture on the interior walls of the top gas chamber confirmed that some condensation had occurred. The lentil and canola tests did not exhibit this moisture migration, possibly due to their lower porosity and thus lower convective-pore velocity than wheat or barley or because of different equilibrium relative humidities.

Assessment of procedure for data analysis

The measured CO₂ concentrations along with predicted CO₂ concentrations obtained using the no-flow coefficients that gave the least mean absolute errors at the different sampling locations are given in Fig. 2. By averaging three no-flow coefficients from three different sampling locations, the mean no-flow coefficient for a particular test was calculated. The predicted concentrations that were obtained by using the mean no-flow coefficient were almost identical to the concentrations that were obtained by using individual coefficients. The agreement between the measured and predicted concentrations shows that the obtained no-flow coefficients describe the process of CO₂ "diffusion" well. Also, the no-flow coefficient did not depend on the sampling location.

Similar graphs for convective-pore velocity are given in Figs. 3 and 4. The agreement between the measured and predicted CO₂ concentrations based on individual velocities is moderate (Fig. 3) but that based on mean velocity is poor (Fig. 4). The calculated velocity decreased as the distance in the direction of CO₂ movement increased, i.e. the velocity based on sampling location R5 was greater than the velocity based on location R4 and velocity based on sampling location R4 was greater than the velocity based on location R3 (Fig. 3). When mean velocity was used, the velocity based on location R5 dominated the mean and predicted concentrations were in poor agreement (Fig. 4). In plug-flow situations, the velocity is not expected to vary along the length of a column; therefore, mean velocities were calculated and reported. Any movement of CO₂ in the horizontal direction would decrease the vertical component of the velocity as CO₂ moves upward. The decrease in velocity indicates that some horizontal movement

Table I: Description and physical properties of the types of grain studied

Crop	Cultivar	Statutory grade	Initial moisture content (% wb)	Porosity (ϕ)	Particle density (kg/m ³)
Barley	Bonanza	Canada certified No. 1 seed	11.8	0.51	1381.4
Canola	A C Excel	Canada certified No. 1 seed	6.2	0.38	1118.5
Lentils	Eston	Canada certified No. 1 seed	11.2	0.40	1374.6
Wheat	Katepwa	Canada certified No. 1 seed	13.3	0.43	1412.2

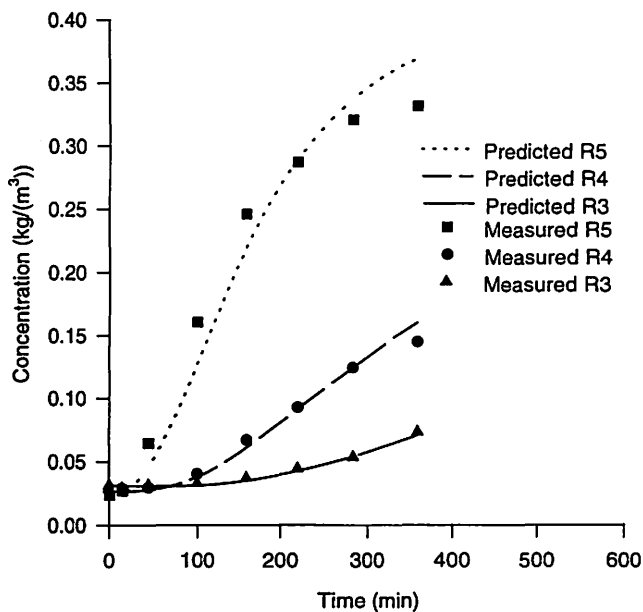


Fig. 2. Comparison of predicted and measured CO₂ concentrations at the three sampling locations for a typical no-flow test (wheat replicate #3; temperature difference = 40°C; CO₂ introduced into the grain bulk from the bottom gas chamber). The predicted curves are for different values of no-flow coefficients determined by minimization at each sampling location (no-flow coefficient at R5 = 8.4×10^{-6} , R4 = 8.5×10^{-6} , R3 = 8.7×10^{-6} m²/s).

may have occurred, i.e. the assumption that the flow is one dimensional may not be valid. Large temperature gradients existed at the ends of each column which might have affected the predictions of the model. Also, the effects of sorption-desorption were neglected in the diffusion-convection model and might have had an effect on the results. Further studies designed to measure all three components of the velocity may assist in explanation of these results. The individual velocities obtained for each sampling location are given elsewhere (Bundus 1994). Only the mean velocities are reported here because (i) only trends in changes in velocity with parameters are discussed and (ii) the movement in horizontal direction is only a speculation at this time.

No-flow coefficients

For a given grain type, the no-flow coefficients were not affected by the temperature difference between the columns when the CO₂ was introduced into the top gas chamber (Table II). This is reasonable since the no-flow coefficient was determined using data from the cold grain column. The average temperature of this column was 5°C for 40 and 56°C temperature differences and was increased to 10°C for the temperature difference of 20°C. When the CO₂ was introduced from the bottom gas chamber (Table III), the no-flow coefficients increased significantly with increases in temperature difference. This is also reasonable because the temperature of the hot column was increased each time the

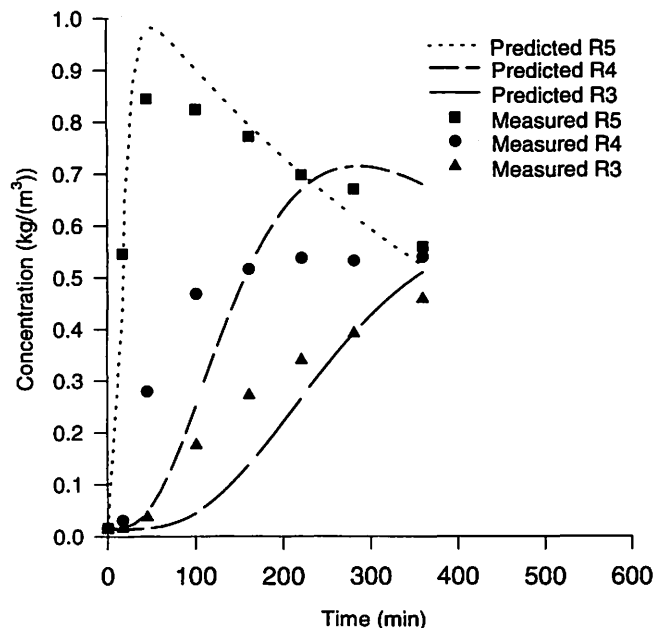


Fig. 3. Comparison of predicted and measured CO₂ concentrations at the three sampling locations for a typical bulk-flow test (wheat replicate #3; temperature difference = 40°C; CO₂ introduced into the grain bulk from the bottom gas chamber; average no-flow coefficient = 8.5×10^{-6} m²/s). The predicted curves are for different convective-pore velocities determined by minimization at each gas sampling location (convective-pore velocity at R5 = 6.297×10^{-4} , R4 = 0.987×10^{-4} , R3 = 0.628×10^{-4} m/s).

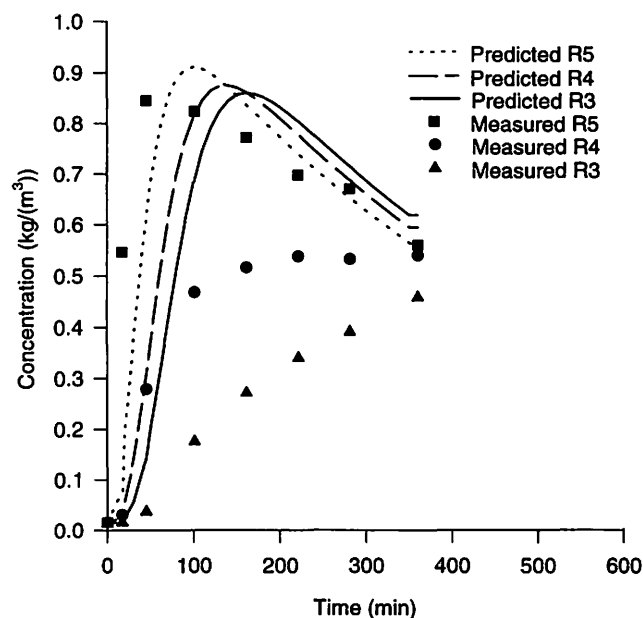


Fig. 4. Comparison of predicted and measured CO₂ concentrations at the three sampling locations for the bulk-flow test in Fig. 3. The mean average convective-pore velocity (2.637×10^{-4} m/s) was used to generate the predicted curves.

Table II: No-flow coefficient when CO₂ was introduced from the top gas chamber

Crop type	Temperature difference (°C)	No-flow coefficient (10 ⁻⁴ m ² /s)		
		Mean	SD*	CV**
Wheat	20	1.96 _{ax}	0.67	34
	40	2.44 _{ax}	1.27	52
	56	2.40 _{ax}	0.87	36
Barley	20	2.31 _{acxy}	0.31	14
	40	1.30 _{by}	0.15	12
	56	2.93 _{bcxy}	1.05	36
Lentils	20	2.63 _{ay}	0.38	15
	40	2.99 _{ax}	0.35	12
	56	3.15 _{ay}	0.22	7
Canola	20	0.40 _{az}	0.09	23
	40	0.66 _{bz}	0.09	13
	56	0.76 _{bz}	0.21	27

* SD = Standard deviation, based on n=3 except for wheat n=9.

** CV = Coefficient of variation, (CV = (100 x SD)/ Mean).

The values followed by the same letter (a, b, c) for the same grain type were not statistically different (Student's t-Test; P>0.05) for temperature differences. The values followed by the same letter (x, y, z) for the same temperature difference were not statistically different (Student's t-Test; P>0.05) for various grain types.

temperature difference between the columns was increased.

When CO₂ was introduced from the top gas chamber, the no-flow coefficients (Table II) for cereal grain types (barley and wheat) and lentils were significantly higher than those found for canola at all temperature differences. When CO₂ was introduced from the bottom gas chamber, some significant differences between grain types existed for no-flow coefficients (Table III), but it is difficult to conclude any trends that may result from varying the porosity in this case.

Convective-pore velocity

In almost all the cases when the CO₂ was introduced from the top gas chamber, there were no statistical differences among the values at any temperature difference for a given grain type, except for wheat (Table IV). This may be because of gravity having a significant effect on the values of the convective-pore velocity. The gravity effect was not accounted for in the general transport equation. The exception for wheat may also indicate a need for more than a single replicate for the other grain types, but the standard deviation and coefficient of variation for different grain types are lower than those for wheat suggesting that this is not the case.

When CO₂ was introduced from the bottom gas chamber (Table V), the average convective-pore velocity increased with increasing temperature difference. This relationship is based on the fact that significant differences in the average

Table III: No-flow coefficient when CO₂ was introduced from the bottom gas chamber

Crop type	Temperature difference (°C)	No-flow coefficient (10 ⁻⁵ m ² /s)		
		Mean	SD*	CV**
Wheat	20	0.67 _{ax}	0.06	9
	40	1.11 _{bxyz}	0.46	41
	56	4.98 _{bxyz}	6.76	136
Barley	20	0.73 _{ayz}	0.02	3
	40	0.91 _{bxw}	0.02	2
	56	1.31 _{cxw}	0.10	8
Lentils	20	0.62 _{axyz}	0.08	13
	40	0.89 _{byw}	0.03	3
	56	1.66 _{cy}	0.04	2
Canola	20	0.74 _{axyz}	0.08	11
	40	1.04 _{bz}	0.08	8
	56	1.32 _{cwz}	0.08	6

* SD = Standard deviation, based on n=3 except for wheat n=9.

** CV = Coefficient of variation, (CV = (100 x SD)/ Mean).

The values followed by the same letter (a, b, c) for the same grain type were not statistically different (Student's t-Test; P>0.05) for temperature differences. The values followed by the same letter (w, x, y, z) for the same temperature difference were not statistically different (Student's t-Test; P>0.05) for various grain types.

convective-pore velocity occurred between the temperature differences of 20 and 56°C. The lack of significant differences between values for temperature differences of 20 and 40°C and between values for 40 and 56°C may be the result of errors in the method of determining the average convective-pore velocity.

When CO₂ was introduced from the top and bottom gas chambers, the average convective-pore velocities (Tables IV and V) for the two cereal grains and lentils were significantly larger than for canola at all temperature differences. Barley had the highest porosity (0.51) and canola had the lowest porosity (0.38). The low porosity of canola (0.38) and high porosity of barley (0.51), lentils (0.40), and wheat (0.43) suggest that the average convective-pore velocity increases with increasing porosity. This, however, cannot be generalized because the considerably large difference between the porosity of barley and wheat did not give an increase in the average convective-pore velocity. Therefore, it is likely that the shape of the kernels plays a major role in affecting the average convective-pore velocity.

The no-flow coefficients and average convective-pore velocities were greater for CO₂ introduction from the top gas chamber than from the bottom gas chamber. These results suggest that gravity has a large effect on the no-flow coefficient and the convective-pore velocity. For the temperature difference of 20°C, the factor of increase in convective-pore velocity was

Table IV: Average convective-pore velocity when CO₂ was introduced from the top gas chamber

Crop type	Temperature difference (°C)	Average convective-pore velocity (10 ⁻³ m/s)		
		Mean	SD*	CV**
Wheat	20	†0.83 _{ax}	0.40	49
	40	†2.42 _{bw}	1.08	45
	56	2.02 _{bx}	1.36	67
Barley	20	1.33 _{ay}	0.36	27
	40	1.50 _{ax}	0.30	20
	56	1.37 _{ax}	0.51	38
Lentils	20	0.83 _{axy}	0.31	37
	40	1.00 _{axyz}	0.42	42
	56	1.12 _{axz}	0.50	45
Canola	20	0.30 _{az}	0.05	18
	40	0.47 _{bz}	0.10	22
	56	0.48 _{abz}	0.16	33

* SD = Standard deviation, based on n=3 except for wheat n=9.

** CV = Coefficient of variation, (CV = (100 x SD)/ Mean).

† Mean of eight samples (n=8)

The values followed by the same letter (a, b, c) for the same grain type were not statistically different (Student's t-Test; P>0.05) for temperature differences. The values followed by the same letter (w, x, y, z) for the same temperature difference were not statistically different (Student's t-Test; P>0.05) for various grain types.

much higher than for the temperature difference of 56°C.

Comparison with published results

The previous studies in full size bins suggest that the downward convective velocity should be higher than the upward convective velocity (Dona and Stewart 1988; Yaghoubi et al. 1991). Yaghoubi et al. (1991) predicted that the downward convective velocity was approximately double the velocity of upward convective movement. This, however, may be due to differences in the cross-sectional areas through which the interstitial air was passing in the grain store. The significantly higher average convective-pore velocity when CO₂ was introduced from the top gas chamber than when it was introduced from the bottom gas chamber does support their findings.

For the studies which reported the convective velocities (Smith and Sokhansanj 1990; Nguyen 1986), the convective velocities were all within the range of convective-pore velocities determined in this study. The exception to this was the results of Yaghoubi et al. (1991), where their convective velocities for all the temperatures studied were at least 100 times the convective-pore velocities found in this study. This exception may be indicative of the effect of the height of the grain bulk on the convective velocity because the height of the grain bulk modelled by Yaghoubi et al. (1991) was over

Table V: Average convective-pore velocity when CO₂ was introduced from the bottom gas chamber

Crop type	Temperature difference (°C)	Average Convective-pore velocity (10 ⁻⁵ m/s)		
		Mean	SD*	CV**
Wheat	20	1.68 _{ax}	0.37	22
	40	22.68 _{abx}	24.23	107
	56	75.05 _{bx}	49.14	65
Barley	20	1.85 _{ax}	0.34	18
	40	35.07 _{abxz}	31.57	90
	56	77.71 _{bx}	19.08	25
Lentils	20	1.23 _{ay}	0.19	15
	40	20.80 _{abxy}	28.75	138
	56	61.47 _{bxy}	22.47	37
Canola	20	0.43 _{az}	0.08	19
	40	‡0.94 _{bzy}	0.01	1
	56	11.90 _{baz}	9.62	81

* SD = Standard deviation, based on n=3 except for wheat n=9.

** CV = Coefficient of variation, (CV = (100 x SD)/ Mean).

‡ Predicted result may be unreliable. The minimization algorithm was unable to locate a minimum average-absolute difference in the range of 0.0 to 0.1 m/s for the convective-pore velocity.

The values followed by the same letter (a, b, c) for the same grain type were not statistically different (Student's t-Test; P>0.05) for temperature differences. The values followed by the same letter (x, y, z) for the same temperature difference were not statistically different (Student's t-Test; P>0.05) for various grain types.

25 times the height of the apparatus used in this study.

For a wheat bulk at a temperature difference of 20°C, Berck (1975a, 1975b) reported a convective velocity of interstitial air of 7.5 x 10⁻⁴ m/s. In this study an average convective-pore velocity of CO₂ for the same parameters was 8.24 x 10⁻⁴ m/s when the CO₂ was introduced from the top gas chamber. For wheat bulks having a temperature difference of 45°C, Booy (1985) reported a convective velocity of interstitial air of 3.19 x 10⁻⁴ m/s which is similar to a convective-pore velocity of CO₂ of 2.27 x 10⁻⁴ m/s when the CO₂ was introduced into the bottom gas chamber at a temperature difference of 40°C.

CONCLUSIONS

The following conclusions can be drawn from the results of this study:

1. The CO₂ rises in the hot grain bulk and falls in the cold grain bulk. The temperature difference between the columns, the grain type, and the location of introducing CO₂ into the grain bulk had no effect on the direction of the convective flow of CO₂ through the grain bulk.
2. The average convective-pore velocity increased as the

temperature difference increased for all grain types studied, when the CO₂ was introduced into the grain bulk from the bottom surface (P<0.05).

3. The average-convective pore velocity was greater when CO₂ was introduced from the top surface than when CO₂ was introduced from the bottom surface.
4. The diffusion-convection model performed poorly when used to determine the convective-pore velocities.

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