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COMPUTER SIMULATION OF GAS CONCENTRATION IN THE INTERSTITIAL ATMOSPHERE OF A WHEAT SILO-BAG FOR TYPICAL AGRICULTURAL AREAS OF ARGENTINA

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ABSTRACT

A validated mathematical model was used to determine the change in concentration of CO_2 in a silo-bag holding wheat from summer to winter for a typical productive region in the North (Saenz Peña, Chaco Province), Center (Pergamino, Buenos Aires Province) and South (Balcarce, Buenos Aires Province) of Argentina. Initial moisture content of grain was set to 12, 14 and 16% w.b. and bagging temperatures to 25ºC and 40ºC. For standard conditions (12% w.b., 25ºC) CO_2 level increased to 4% V/V and O_2 decreased to 15.5% V/V in Balcarce while to 6% V/V and 13.9% V/V in Saenz Peña. For moist grain (16% w.b., 25ºC and 40ºC), O_2 depleted to less than 1% at the three locations. Evolution of grain mean temperature in combination with CO_2 and O_2 levels achieved in the silo-bags demonstrate that for the climatic conditions of Argentina insect activity is controlled in airtight silo-bags.

Keywords: grain storage, hermetic storage, wheat, silo-bags, atmosphere composition, modeling

INTRODUCTION

In 2010 more than 40 million tonnes of grains were stored in hermetic systems (silo-bags) in Argentina. This technique, originally used for grain silage, consists in storing dry grain in hermetically sealed plastic bags. The respiration process of the biological agents in the grain ecosystem (grain, insects, mites and microorganisms) increases carbon dioxide (CO_2) and reduces oxygen (O_2) concentrations, promoting a suitable environment for grain conservation.

Gas concentration in grain bags depends on the balance between respiration of the ecosystem, the entrance of external O_2 to the system, and the loss of CO_2 to the ambient air. The transfer of gases depends on the gas partial pressure differential and the effective permeability of the plastic cover (openings and natural permeability of the plastic layer to gases). Grain type and condition, moisture content (m.c.), temperature, storage time and O_2 and CO_2 concentrations affect the grain respiration rate.

A novel technology for monitoring grain storability in silo-bags based on CO_2 detection was implemented by The National Institute of Agricultural Technologies of Argentina (INTA), Balcarce Experimental Station (EEA) (Bartosik et al., 2008; Cardoso et al., 2008). The procedure consists of comparing the measured CO_2 concentration at some locations in the silo-bag (local concentration value) with a referential value which represents adequate storage conditions. Additionally, it was observed that this referential value can change according to the season and climatic condition of a particular agricultural area. However, setting experimental field tests to cover the wide range of possible storage conditions is time consuming and costly.

The authors developed a 2D heat and mass transfer model which predicts grain storage temperature and m.c., O_2 and CO_2 concentrations as function of weather conditions, taking into account simultaneous O_2 consumption, CO_2 generation, and permeability to gas transfer of the plastic bag. The model was validated by comparison of predicted temperature, grain moisture content, mean O_2 and CO_2 concentrations with measured values in field tests (Gastón et al., 2009; Abalone et al., 2011a; b; c).

In the present work, the model was used to determine the referential mean O_2 and CO_2 concentration that corresponds to three productive region in the North (Saenz Peña, Chaco Province), Center (Pergamino, Buenos Aires Province) and South (Balcarce, Buenos Aires Province) of Argentina. The evolution of O_2 and CO_2 concentration during six months was simulated in silo-bags holding wheat. The effect of initial m.c. and bagging temperatures was investigated.

MATERIAL AND METHODS

Silo-bags

Silo-bags are 60 m long, 2.70 m diameter and 230 - 250 microns thick. The bags are made of a three-layer plastic, black in the inner side and white in the outer side with UV stabilizers. The plastic layers are a mixture of high density (HDPE) and low density polyethylene (LDPE). Approximately 200 tonnes of grains (wheat, corn and soybean) can be held in a bag; farmers usually store their production in bags during six to eight months.

Mathematical modelling

Stating the energy and mass balances for the grain and air phases in a control volume, a coupled system in terms of temperature T, grain moisture content W, oxygen O_2 and carbon dioxide CO_2 concentrations are derived. The balances take into account heat, water vapor, oxygen consumed and carbon dioxide released by respiration of the grain ecosystem, which is modeled by the complete combustion of a typical carbohydrate. Boundary conditions considered the interaction between the soil and the bottom layer of the silo-bag, solar radiation and convection to the surroundings. It was assumed that the silo-bag was impermeable to moisture transfer. Gas transfer through the plastic layer was modeled by defining an equivalent permeability of the plastic to O_2 and CO_2. This value is calculated by use of a resistance series model as the silo-bag is a mixture of high density (HDPE) and low density polyethylene (LDPE). A detailed description of the model is presented elsewhere (Gastón et al., 2009; Abalone et al., 2011a; b; c). The mathematical model was implemented using *COMSOL Multiphysics 4.2a* and solved numerically by the finite element method. Figure 1 shows the calculation domain, which represents a cross section of the silo-bag.

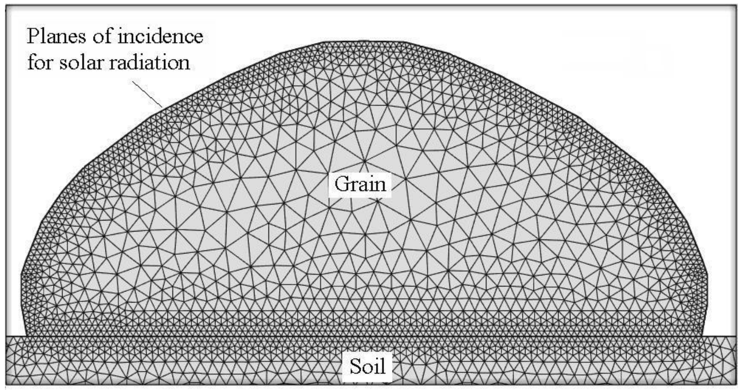

Fig. 1- Cross section of the silo-bag and discretization domain

RESULTS AND DISCUSSION

The model was applied to analyze the storage of wheat in a silo-bag from January to June (six months). Initial grain m.c. was set to 12, 14 and 16% w.b. and initial bagging temperatures to 25ºC and 40ºC. Climatic data corresponding to (1997-2004) years were considered for Balcarce (37.84S; 58.26W), in the Southwest of Buenos Aires Province; to (2001-2006) years for Pergamino (33.85S; 60.93W), in the North of Buenos Aires Province and to (1999-2006) years for Saenz Peña (26.78S), in Chaco Province.

Dependence of the rate of CO_2 production Y_{CO2} was evaluated by use of the correlation developed by White et al. (1982) which takes into account grain temperature, m.c. and storage time. Equivalent permeability of the plastic layer to O_2 was set equal to 9.75 $10^{-8}m^3md^{-1}m^{-2}at^{-1}$ and to CO_2 equal to 3.22 10^{-7} $m^3md^{-1}m^{-2}at^{-1}$, average plastic thickness L to 240 μm, effective diffusivity to CO_2 and O_2 to 3.97 10^{-6} m^2s^{-1} and 5.22 10^{-6} m^2s^{-1}, respectively, wheat porosity to 0.38 and tortuosity to 1.53.

Figure 2 compares annual mean temperature and solar radiation at the three locations. In summer, mean ambient temperature in Saenz Peña is about 3ºC higher than in Pergamino and 7ºC higher than in Balcarce, while in winter about 6ºC and 8ºC higher, respectively. Solar radiation is comparable in Saenz Peña and Pergamino and about 9% higher than in Balcarce. In autumn irradiance at Saenz Peña is about 13% and 30% higher than in Pergamino and Balcarce.

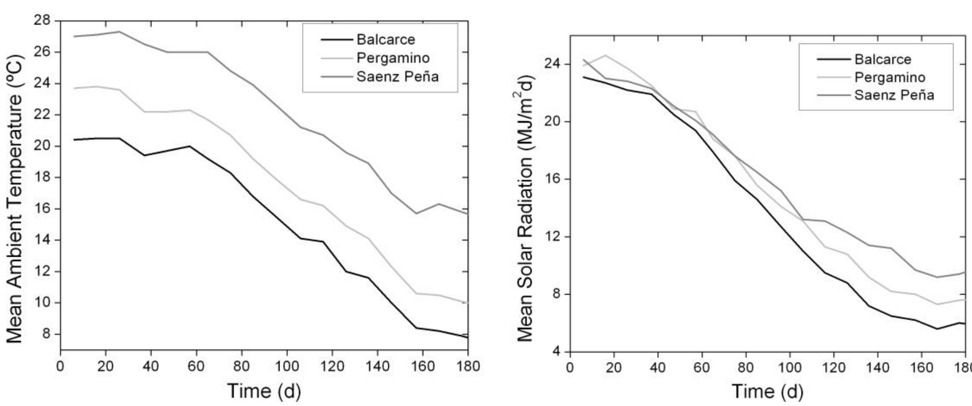

Fig. 2- Comparison of mean ambient temperature and solar radiation of agricultural areas

Results for each bagging condition and location were averaged over the eight years and a 90% confidence intervals for mean temperature, CO_2 and O_2 were constructed by applying a t-Student probability distribution.

Figure 3 shows mean gas concentration at the three locations for 25ºC initial bagging temperature. It can be appreciated that climatic conditions produce significant changes in referential levels after 180 days of storage, especially for 12% and 14% m.c. In Balcarce, CO_2 level increased to (4.03±0.07)%V/V and O_2 decreased to (15.5±0.1)%V/V. An increment of 3ºC in ambient temperature shifts CO_2 and O_2 levels to (4.6±0.1)%V/V and (14.8±0.1)%V/V in Pergamino, and one of 8ºC to (6.0±0.1)%V/V and (13.9±0.2)%V/V in Saenz Peña.

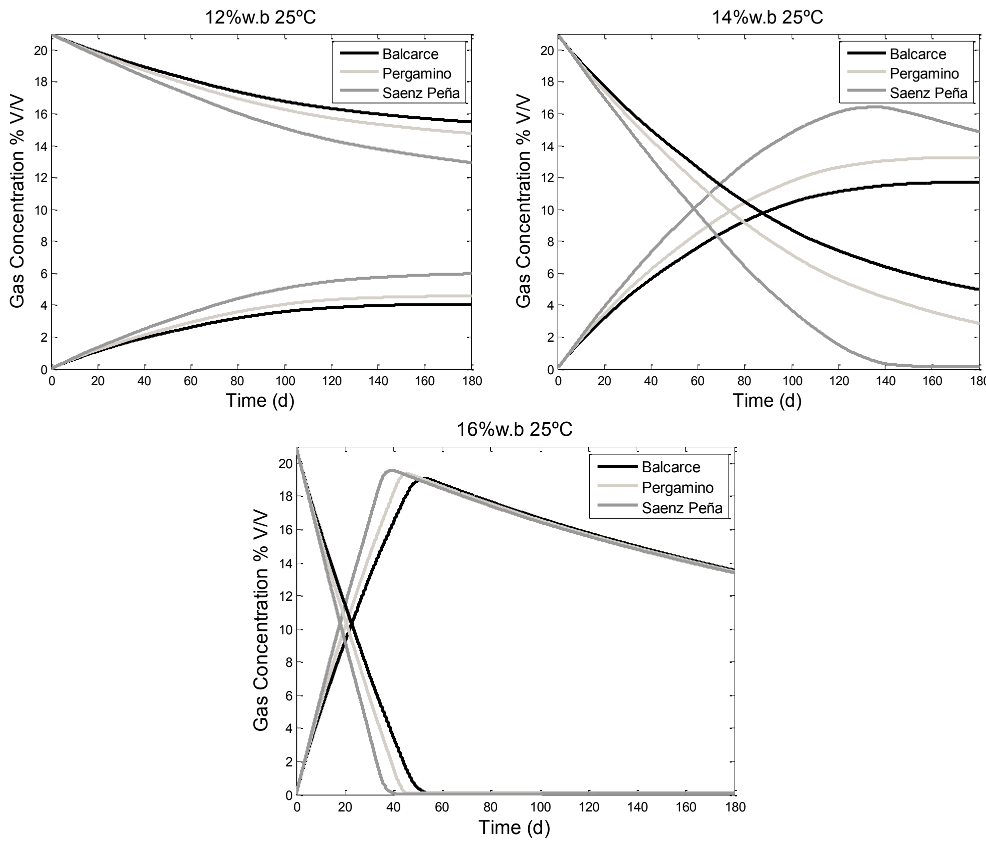

Fig. 3- Gas concentration evolution at Saenz Peña, Pergamino and Balcarce. Initial temperature 25ºC

Differences in concentration levels between summer (40 days) and winter (180 days) remained within 3% points approximately at the three locations. At 14% w.b. mould activity becomes important increasing CO_2 concentration to (11.7±0.2)%V/V and reducing O_2 concentration to (5.0±0.3)%V/V at Balcarce and to (13.2±0.3)%V/V and to (2.9±0.4)%V/V in Pergamino. Differences up 7% points between summer (40 days) and winter (180 days) were found. At Saenz Peña, O_2 is almost consumed after 140 day and remained at zero level thereafter because all O_2 entering through the plastic cover is consumed by respiration. CO_2 reaches 14.9±0.1% V/V and then decays as results of permeation to atmosphere through the plastic layer. For 16% w.b., O_2 depleted to less than 1% within 40 to 50 days (Saenz Peña and Balcarce) and CO_2 evolved as explained before.

Figure 4 shows results for 40ºC initial temperature. For 12% w.b., changes in CO_2 and O_2 are about 1 to 1.5%V/V points increase/decrease with respect to 25ºC. For 14% w.b. O_2 depleted to less than 1%V/V after 90 days in Saenz Peña, 140 days in Pergamino and 180 days in Balcarce while at 16% w.b. this conditions is achieved in about 20 days at the three locations.

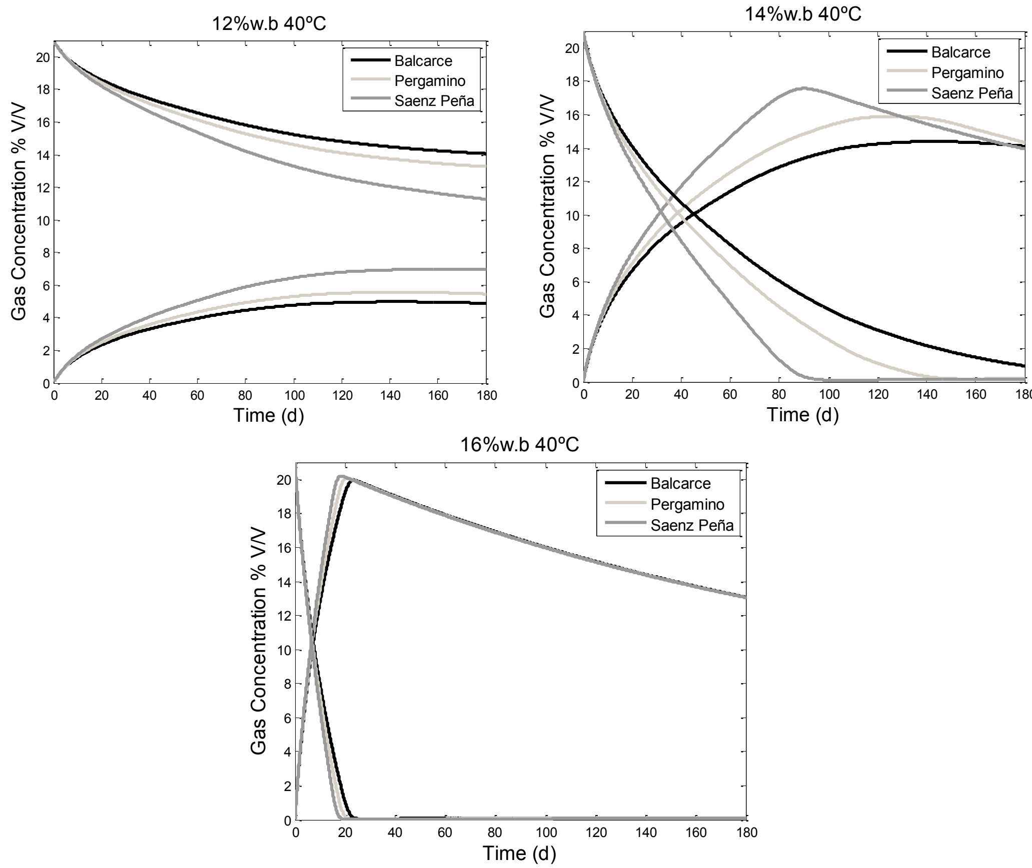

Fig. 4- Gas concentration evolution at Saenz Peña, Pergamino and Balcarce. Initial temperature 40ºC

Figures 5 and 6 illustrate the evolution of the mean temperature of the silo-bags. These results demonstrate that for the climatic conditions of Argentina, insect activity would be limited for dry and moist grain because mean grain temperature decreases below 17ºC during autumn and winter preventing insect infestation. Moreover, even in summer conditions, grain at 14% w.b. or higher, would limit insect activity as result of low O_2 and high CO_2 concentration in the silo-bag, if the silo-bag maintains at high air tightness level.

CONCLUSIONS

The effect of climatic conditions and grain moisture content on the evolution of gas concentration in silo-bags holding wheat was analyzed by use of a validated mathematical model. Referential mean O_2 and CO_2 levels were predicted for a typical productive region in the North (Saenz Peña, Chaco Province), Center (Pergamino, Buenos Aires Province) and South (Balcarce, Buenos Aires Province) of Argentina.

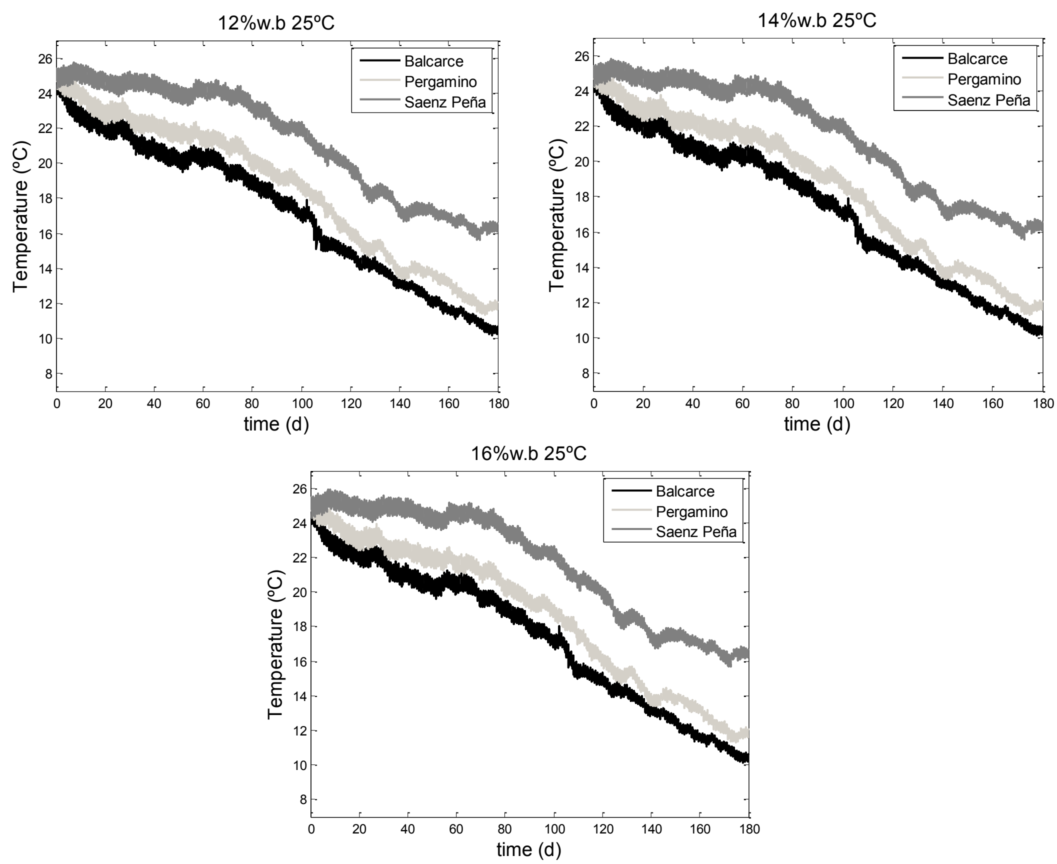

Fig. 5- Grain mean temperature evolution at Saenz Peña, Pergamino and Balcarce. Initial temperature 25ºC

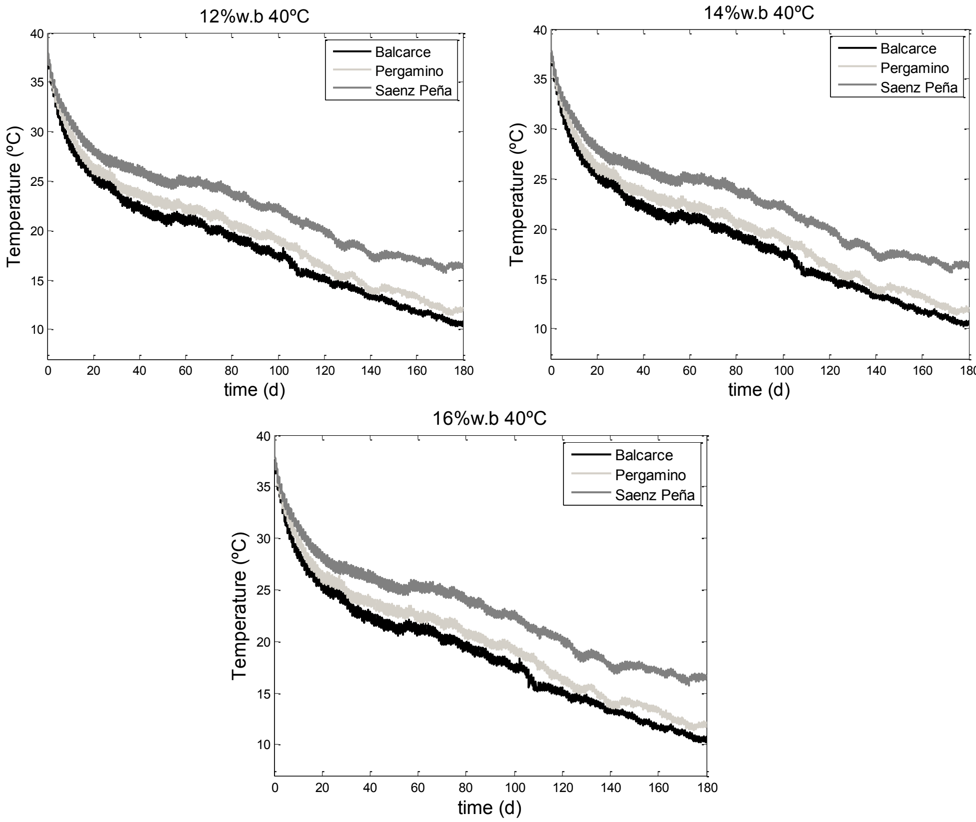

Fig. 6- Grain mean temperature evolution at Saenz Peña, Pergamino and Balcarce. Initial temperature 40ºC

Results showed that referential levels of O_2 and CO_2 strongly depend on initial moisture content and bagging grain temperature. Also, agricultural climatic condition produces significant changes, especially for dry and slightly moist grain. A difference of about 7 to 8ºC in mean ambient temperature between the northern (Saenz Peña) and southern location (Balcarce) shifts referential levels about 2%V/V points for 12% w.b. and about 4% V/V points for 14% w.b. At the three locations, O_2 depleted to less than 1% for 16% w.b.

Evolution of grain mean temperature in combination with CO_2 and O_2 levels achieved in the silo-bags demonstrate that for the climatic conditions of Argentina insect activity would be limited in silo-bags.

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