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Research Paper

A mathematical model of commodity wet-bulb temperature (CWBT) for grain storage applications

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Commodity wet-bulb temperature (CWBT), which is the value of wet-bulb temperature of the interstitial air within a grain bulk, is an important insect control term in grain storage applications. However, due to difficulties in its measurement and also the need for iterative calculations, its application for aeration control has been limited in commercial grain industries throughout the world. In the present study, a remedy to these difficulties is introduced. A straightforward model was developed by applying dimensional analysis methods to the CWBT data obtained from iterative solutions of the original wet-bulb temperature equation. This model is capable of determining non-iteratively CWBT as a function of dry-bulb temperature and relative humidity inside the grain bulk. The values of coefficient of determination (R^2), mean bias error (MBE), standard error (SE) and root mean square error (RMSE) for obtained CWBT model were 0.999, 4.71%, 0.015 °C and 0.319 °C, respectively, when compared with original data, which reflect accurate predictions. The model predictions were compared with available data from valid psychrometric charts. The mean relative deviation (MRD) was less than 1.85%. The model was further applied to determine the errors in calculation of CWBT as affected by uncertainties in dry-bulb temperature and relative humidity measurements. This enhanced the capability of the model to be applied in CWBT aeration controllers.

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1. Introduction

Wet-bulb temperature is a well-established means to determine the quality of cooling air. It is usually measured by using a wet-bulb thermometer with a wet wick slipped over its bulb. To ensure the accuracy of measurement, an airflow of 5 m s^{-1} should flow past the thermometer bulb (Noyes & Navarro, 2002).

For grain storage applications, the wet-bulb temperature is very important especially in terms of controlling insect populations. As reported by Griffiths (1967), the wet-bulb temperature is more satisfactory for controlling stored grain aeration systems than dry-bulb temperature. Wilson and Desmarchelier (1994) developed the control term of Seed Wet-Bulb Temperature (SWBT) when developing a stored grain aeration system to control insect populations. To give a wider meaning to SWBT for all types of grains including seeds, Noyes and Navarro (2002) applied the term Commodity Wet-Bulb Temperature (CWBT) instead. CWBT is the value of wet-bulb temperature of the intergranular air. It could be

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Nomenclature

a_w^*	Limiting water activity, Pa Pa^{-1}
C_{pa}	Specific heat capacity of dry air, kJ kg^{-1} °C^{-1}
C_{pw}	Specific heat capacity of liquid water, kJ kg^{-1} °C^{-1}
$E_{T_{wb}}$	Absolute error in CWBT calculations, °C
I_a	Air enthalpy, kJ kg^{-1}
I_v	Vapour enthalpy, kJ kg^{-1}
k	Rate coefficient, °C^{-1} week^{-1}
N_0	Insects initial population
N_t	Insect population at time t
P	Atmospheric pressure, Pa
P_s	Saturation vapour pressure, Pa
r	Insect intrinsic rate of growth, week^{-1}
RH	Relative humidity,%, Pa Pa^{-1}
t	Time, weeks
T	Dry-bulb temperature, °C
T_0	Threshold CWBT for preventing insects population growth, °C
T_m	CWBT at which the insect population growth is a maximum, °C
T_{wb}	CWBT, °C
w	Absolute humidity of air, d.b., kg kg^{-1}
w_I	Absolute humidity of air at constant enthalpy line, d.b., kg kg^{-1}
w_s	Absolute humidity of air at saturation curve, d.b., kg kg^{-1}
δRH	Absolute error in relative humidity measurement,%, Pa Pa^{-1}
δT	Absolute error in dry-bulb measurement, °C
$\Delta T_{wb_{res}}$	Residual of prediction of CWBT, °C

Subscripts

0	At time $t = 0$
const	Constant enthalpy
Iter	Related to iterative approach
psy	Related to psychrometric chart
res	Residual
t	At time t
targ	Target
wb	Wet-bulb

applied as a management tool in insect control. The insect population growth rate can be estimated from CWBT. According to Desmarchelier (1988) there is a threshold CWBT which prevents insect population growth, so that at or below this threshold CWBT, the insect population growth rates are zero and above that the populations increase exponentially. So any combinations of dry-bulb temperature and relative humidity which provide the threshold CWBT and above should be avoided. Desmarchelier provided CWBT related data for several grain-infesting insect species.

Engineers in several fields such as air conditioning, ventilation, and meteorology might need to measure wet-bulb temperature if dry bulb temperature, relative humidity and pressure are known. To measure CWBT, the intergranular air should be blown across a wet-bulb thermometer at 5 m s^{-1}. There are developed tools which are available and can be used to achieve this goal. However, the application of such tools inside grain bulks is not simple. Measuring CWBT is usually difficult since it is necessary to extract an air sample from within the grain bulk. So it is usually estimated by solving the CWBT equation using some known properties such as grain type, available data of dry bulb temperature and moisture content. For this purpose, instead of using sensors that measure CWBT directly inside grain bulks, two sensors of dry-bulb temperature and relative humidity can be applied at the same place within the bulk. The data obtained from these sensors is further processed and applied to estimate CWBT. Although application of relative humidity sensors might be costly, reaching a safe and secure storage condition may justify their applications for stored grain protection. To solve the CWBT equation from data of dry-bulb temperature and relative humidity, an iterative procedure like Newton–Raphson method (Thorpe, 1994) or Brent's method (Brent, 1973) has regularly been applied. However, the application of such iterative procedures is not simple and the difficulties in calculation have been a barrier to adoption of CWBT as a control index for commercial stored grain aeration systems. To remedy this problem Noyes and Navarro (2002) provided some valuable figures which help ready determination of CWBT for nine types of stored grains.

Another useful and more applicable remedy for this problem would be to develop a straightforward model of CWBT using dimensional analysis methods. This model directly calculates CWBT from available data of dry-bulb temperature and relative humidity within the grain bulk. Development of such a model might overcome the barriers that hinder the applications of CWBT as a control index in stored grain aeration systems. When the data from dry-bulb thermometers and relative humidity sensors are used to calculate CWBT, it is important to consider how the errors in measurements of dry-bulb temperature and relative humidity propagate to the error in calculation of CWBT.

The objectives of this paper are (1) development and evaluation of a straightforward model for CWBT by applying dimensional analysis methods to the data obtained from iterative solutions of the wet-bulb temperature equation (Noyes & Navarro, 2002), (2) evaluation of absolute errors in calculation of CWBT as affected by uncertainties in dry-bulb temperature and relative humidity measurements, and (3) application of CWBT model in stored-grains insect control.

2. Materials and methods

2.1. *Commodity wet-bulb temperature calculation procedure*

To calculate CWBT data the method reported by Noyes and Navarro (2002) was applied. During aeration, the air velocity inside grain bulks is slow enough to maintain the intergranular air and grains near moisture equilibrium. So in this procedure, the interstitial air was considered to be in moisture equilibrium with stored grains. This assumption requires users to experimentally validate the obtained models for near equilibrium conditions for aeration of different grain types. Therefore, for a specific condition of a stored product including its type, dry-bulb temperature and moisture

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