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Dedicated to Prof. Antonius Kettrup on the occasion of his 60th birthday

USE OF TEMPERATURE- AND HUMIDITY-DATALOGGERS IN FOOD ENGINEERING

L. O. Figura and Ch. Borchert

Hochschule Bremerhaven, D–27568 Bremerhaven, Germany

Abstract

The use of dataloggers in food engineering is discussed in two examples. The first example describes the measurement of temperature and humidity in a bulk tank car during transport and unloading. In the case of wheat flour the relative humidity in the air raises from about 80% r.h. to values near 100% r.h. at the air compressors for pneumatical unloading start working. The second example shows the use of the datalogger in education on heat transfer. The device was fixed in an ice cream sample which was placed in a store at –25°C. The measured hardeningtime agrees well to theoretical heat transfer calculation.

Keywords: humidity, ice cream, temperature datalogger, wheat fluor

Introduction

Engineering, transport and storage of food is strongly affected by the water activity (a_W) of the food material. The a_w-value gives the mean degree of the force of the bonding of water molecules to the food material. So "free" water has $a_W=1$, absolute strictly bounded water has $a_W=0$. The water activity of real foods ranges from 0.02 to 1.0. Spoilage of food is dependent on the water activity of the material. By decreasing the water activity accompanying the growth rate of bacteria, yeasts and moulds tend to zero (Table 1).

The water activity of food materials is a function of its temperature, of the water content and the pre-treatment of the material [1]. The relation between water content and water activity is the water sorption isotherm. To avoid spoilage during transport and storage of food materials the knowledge of water activity and its dependence on temperature is necessary [2]. The water activity can be measured by sensing the relative humidity of air which is in equilibrium with the food material.

Frozen food materials have to be produced and stored under conditions which eliminate the growth of large ice crystals. Growth of microscopic ice crystals

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Table 1 On decreasing the water activity spoilage reactions in food may be stopped successive (simplified)

a_w	activity stop of
1.0	
0.9	
0.8	bacteria
0.75	yeasts
0.7	moulds
0.6	
0.5	
0.4	enzymes
0.3	fat oxidation (minimum)
0.2	Maillard-reactions
0.1	
0.0	

may damage biological cells. Local freeze thaw processes can damage cells by osmotic effects. The cooling rate and the temperature fluctuations during storage have to be known and to be optimized by the food engineer. Thermoanalytical measurements on food are performed mainly by DSC and DTG [3]. Water sorption isotherms can also be measured with a modified BET-apparatus [4]. Macroscopic measurement of humidity and temperature typically are performed with cable connected sensors and recorders. A very simple and robust technique to get temperature and humidity data out of big samples are small dataloggers which even can be immersed in the food material. The work with dataloggers shall be illustrated by two examples of the food engineering sector.

Experimental

The dataloggers used (Regeltron, Germany) consist mainly of one ore more sensors with a housed semiconductor memory with battery. A datalogger measures about 180×70×70 mm (L×W×H) and has a mass of about 250 g. The data transfer with a personal computer is performed by optical coupling with infrared diodes. During data transfer and programming the datalogger is powered contactless by electromagnetic induction from the computer interface to save battery power. Choosing appropriate data recording rates enable measuring periods from some hours to some years. Two different types of dataloggers were used:

Type A: One built-in temperature sensor. The datalogger is completely closed without any switches or plug connectors. By this it can be immersed in liquids, bulk goods and powders up to a hydrostatic pressure of few bars.

Type B: One mounted temperature-humidity sensor and one cable-connected temperature sensor. Due to the sensor plug connector this datalogger must not be immersed in liquids. With a suitable filter on the humidity sensor the datalogger can be used in dry bulk goods and powders.

Measurements were made in the following manner:

1) Programming the datalogger via computer interface (measuring range, data aquisition rate, etc.);

2) Placing the datalogger at the measuring location for 5 to 30 h;

3) Recovering the datalogger, data reading out via optoelectronic interface and evaluation by software.

Results

Example 1: wheat flour transport

During bulk transport of wheat flour in tank cars condensation of water vapour was observed by workers. Liquid water droplets in the wheat flour must be avoided due to possible spoilage reactions (Table 1) and because of flow problems by powder lumping and sticking. A datalogger (type B) was placed in the headspace of the tank (Fig. 1) to record the conditions and reasons for water condensation. The datalogger measured the temperature and relative humidity during transport and unloading of the flour. After about 20 h the data were read out. Figure 2 shows the result. It can be seen that the air temperature in the tank during overnight transport falls to 7.5°C. Due to the long contact with the wheat the relative humidity of the air is in the range of 80% r.h. before unloading. When unloading is started the relative humidity in the headspace of the tank rises to values up to 100% r.h. Because unloading is performed pneumatically after compression the tank headspace air from the pressure $p_1 \cong 1$ bar to $p_2 \cong 2$ bar simultaneous to the rise in humidity an increase of the air temperature of about 5 K can be seen. By this experiment it could be verified that the start of pneumatic unloading is

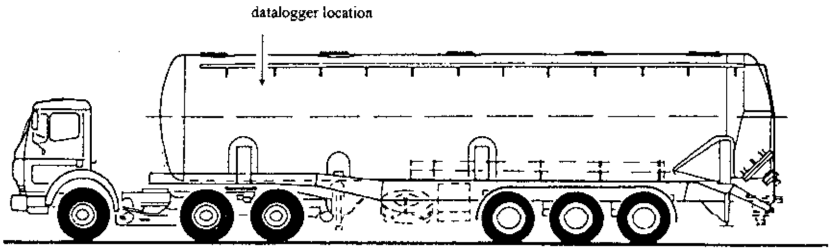

Fig. 1 Dry bulk tank for transportation of wheat flour

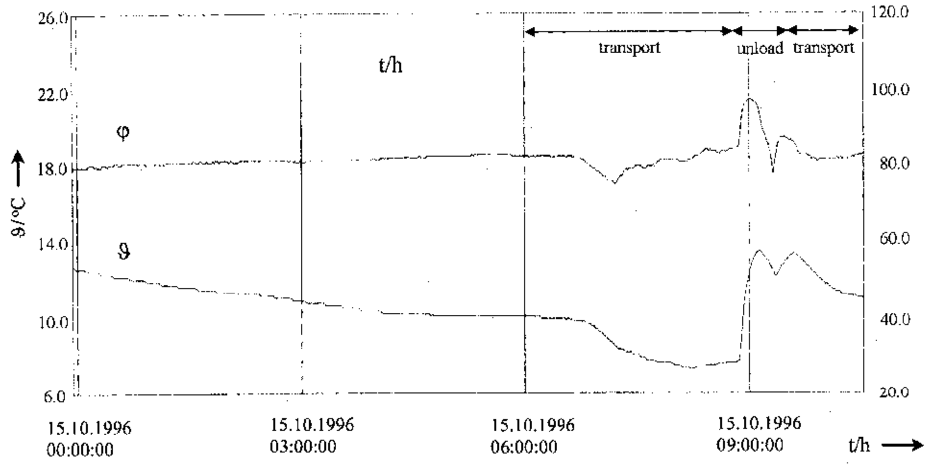

Fig. 2 Temperature and humidity plot during transport and unloading of wheat flour

the critical moment in which water condensation can occur. Because of the high water content of the tank air after transport the pressure rise due to the compressor action results in relative humidity values near 100% r.h. Calculation of these effects is difficult because of missing material data.

Assuming polytropic compression, the temperature T_2 at pressure p_2 after compressing air with T_1, p_1 is

$$p_1^{1-n}T_1^n = p_2^{1-n}T_2^n$$

so

$$T_2 = T_1\left(\frac{p_1}{p_2}\right)^{(1-n)/n}$$

The polytropic exponent n is known for the isothermal case (n=1) and also for the isentropic case (n=isentropic coefficient) but unknown for the given case of a big non isolated tank partly filled with wheat flour. Also is the case of with the pressure–humidity function which can be calculated for gaseous phases is not known for the non isotherm system "wheat flour – air". Simply based on the experimental curve it can be concluded that if the unloading procedure shall be maintained unchanged then air drying before unloading would be advisable.

Example 2: education

On industrial scale ice cream is produced first by freezing to a temperature of about –4°C and then – after packaging – hardened in tunnels with flowing cold air. Fast heat transfer is necessary to avoid growing of water crystals which could be detected by sensory test. As the material data are known the heat transfer and the hardening time can be calculated roughly:

Assuming a core temperature in a plate shaped ice cream sample of $\Theta_{t=0}$=–10°C, a temperature of the cooling air of Θ_u =–25°C, the hardening time (here defined as the time period to reach Θ_M=–24°C in the core of the sample) results from:

$$\frac{\Theta_u - \Theta_M}{\Theta_u - \Theta_{t=0}} = \frac{-25^\circ\text{C} - (-24^\circ\text{C})}{-25^\circ\text{C} - (-10^\circ\text{C})} = 0.07$$

$$\text{Bi} = \frac{\alpha x}{\lambda} = \frac{40\ \text{W K}^{-1}\ \text{m}^{-2}\ 0.015\ \text{m}}{0.3\ \text{W K}^{-1}\ \text{m}^{-1}} = 2$$

$$\text{Fo} = \frac{at}{x^2} = \frac{\lambda t}{\rho c_p x^2}$$

from diagram $\frac{\Theta_u - \Theta_M}{\Theta_u - \Theta_{t=0}}$ over Fourier-number (Fo) for an infinitesimal plate (Fig. 3) with the thickness $d=2x$ and for $\frac{1}{\text{Bi}}$=0.5, it can be read: Fo=2.7.

So:

$$t = \text{Fo}\frac{x^2 c_p \rho}{\lambda}$$

$$t = 2.7\frac{0.015^2\ \text{m}^2\ 11500\ \text{J K}^{-1}\ \text{kg}^{-1}\ 550\ \text{kg m}^{-3}}{0.3\ \text{W K}^{-1}\ \text{m}^{-1}} = 12808\ \text{s}$$

$$t = 3{:}33\ \text{h}$$

whereas

Θ_u	temperature of cooling air
$\Theta_{t=0}$	sample core temperature at $t=0$
Θ_M	sample core temperature at time t
x	heat penetration depth ($x=d/2$)
d	sample thickness, here: d=3 cm
c_p	heat capacity at p=const., here: c_p=11500 J K^{-1} kg^{-1} from [5]
α	heat transfer coefficient, here: α=40 W K^{-1} m^{-2} (typical value for slow flowing air)
Bi	Biot-number
Fo	Fourier-number
a	temperature conductivity
λ	heat conductivity, here: λ=0.3 W K^{-1} m^{-1} from [5]
ρ	density, here: ρ=550 kg m^{-3} from [5]

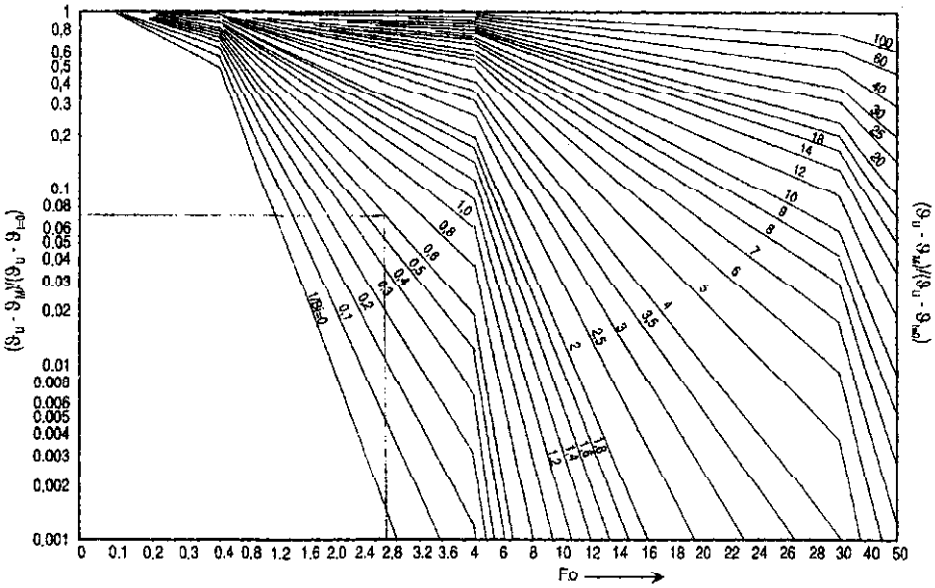

Fig. 3 Relative temperature difference over Fourier-number for an even plate (from [5])

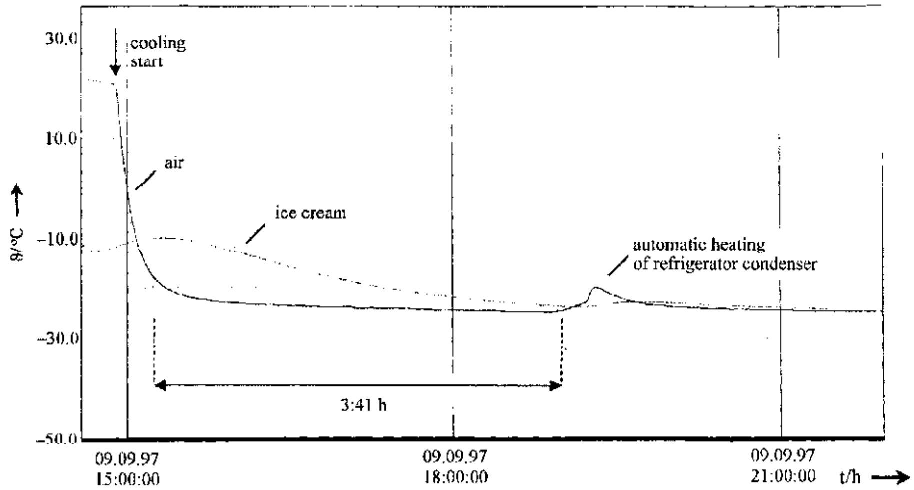

Fig. 4 Temperature in the center of a plate shaped ice cream sample during cooling (hardening) with cold air

To check the mathematical result by experiment a datalogger (type A) was placed in the center of a plate-shaped ice cream sample (about 250×50×30 mm). A second datalogger was fixed outside of the ice cream sample to record the air temperature. The sample with the dataloggers was given to the cold store. The air in the cold store was circulated with slow flow velocity at a temperature of –25°C. After about 10 h the dataloggers were recovered, read out and the temperature–time-curves evaluated. Figure 4 shows the results: Soon after putting the sample into the store (indicated "cooling start") the outer datalogger showed an air temperature of –25°C. The temperature in the center of the sample decreases slowly from $\Theta_{t=0}$=–10°C to Θ_M =–24°C. The temperature peak at about 7:30 p.m. is caused by interruption of the refrigerator activity and electric heating of the condenser. This procedure is automatically performed every 16 h to remove ice from the refrigerator condenser by melting to maintain the condenser activity. From the experimental curve (Fig. 4) the hardening time can be read to t_{exp}=3:41 h. This value is close to the calculted value of t_{calc} = 3:33 h . By comparison of this theoretical and experimental hardening time students in undergraduate course on heat transfer get a feeling where mathematic tools may be helpful or – in other cases – where assumptions made are not valid.

Conclusions

The two examples describe real applications of dataloggers instead of standard laboratory equipment. In the case of condensing water vapour in the wheat flour tank car it can be seen clearly how a rough and not very accurate bulk measurement can assist to solve a technical problem in a fast way. The ice cream hardening experiment shows a simple way to check theoretical assumptions like e.g. assumed heat transfer coefficients. This may be used in the education of engineers and in research and development projects.

Compared to classical TA-sensors the properties of the described dataloggers are nearly opposite and disadvantageous. Temperature-dataloggers are

- relatively large and of high heat capacity
- therefore slow
- upper temperature limit is about 70°C (due to semiconductor function)

On the other hand the described dataloggers have advantages which are useful for work with food samples:

- waterproof
- can be immersed in food material
- no cables, transportable
- can be used in rough environment
- easy to handle
- simultaneous recording of temperature and relative humidity.

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