DEVELOPMENT OF SMART SENSING DEVICES FOR UBIQUITOUS SUPERVISION OF THE COLD CHAIN: APPLICATION TO PERISHABLE COMMODITIES

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Abstract
Wireless sensing technologies allow continuous monitoring of physical parameters that influence the preservation of fruit and vegetables in cold storage, while the smart sensor concept refers to the incorporation of improved prediction capabilities on standard low cost transducers as to enhance quality assurance of stored commodities while reducing in the amount of data to be transmitted. Previous experience of the authors has shown the feasibility of predicting battery shortage due to its effects on measurement oscillations, door opening by means of the instantaneous gradient in temperature and relative humidity, and water loss and condensation on the cargo. In this work, measurements in 3 commercial cold chambers with a variety of horticultural products have been performed, using up to 7 wireless motes from two different manufacturers. The ASABE psychrometric model is used as a base for smart capabilities such as energy consumption estimation is implemented as related to the increase on air enthalpy based on a single Temperature-Relative Humidity sensor. The low cost characteristics of such device encourage the ubiquitous location in the commodities and even the diagnosis of working faults of valves in refrigeration system.

Keywords: wireless sensor networks, ZigBee, cold chain, enthalpy, psychrometry

1. Introduction

The control of temperature throughout the cold chain is essential for conservation in the best possible condition of perishable products. The term "cold chain" describes the series of interdependent equipment and processes employed to ensure the temperature preservation of perishables and other temperature-controlled products from the production to the consumption end in a safe, wholesome, and good quality state (Zhang, 2007). One of the links in this chain is the preservation in cold storage of the collected and stored product until sale to the customer.

The quality of these products might change rapidly, when inadequate temperature and relative humidity conditions during transport and storage occur. Temperature variations are associated with warehousing, handling and transportation. Inadequate temperature is second on the list of factors causing foodborne illness, surpassed only by the initial microflora present in foods (Sánchez López *et al.*, 2008).
At present, fuel prices increase, climate change issues and rising air pollution has prompted governments, businesses and citizens to worry about energy saving. The refrigeration food preservation needs a good deal of energy input in places with hot weather. For example, the cold chambers studied in this work (1,700m^3 and 8 ºC Setpoint Temperature), consume energy of about 3,500Kcal/month in winter, and 7,500Kcal/month in summer. Energy

consumption of the refrigerated chambers is estimated from opening times of the cold glycol valve. Mechanical or electrical failures of these mechanisms lead to measurement and billing errors.
Smart sensors can provide information on malfunctioning of the valves. Thus, we can correlate the air inside the cold storage enthalpy with power consumption, using the psychrometric model on Temperature and Relative Humidity data obtained from sensors. Moreover we can diagnose mechanical or electrical failures in the installation.
Specialized WSN (Wireless Sensor Network) monitoring devices promise to revolutionize the shipping and handling of a wide range of perishable products giving suppliers and distributors continuous and accurate readings throughout the distribution process. In this framework, ZigBee was developed as a very promising protocol for WSN due to its low energy consumption and advanced network capabilities. Its potential for monitoring was proposed by several authors but there were no real experimentation, only theoretical approaches (Qingshan *et al.*, 2004; Jedermann *et al.*, 2006; Wang, 2006).

2. Material and methods

Refrigerate chambers

Experiments were performed in three commercial wholesale refrigerated stores, numbered 11, 29 and 40. Each of which has a volume at of 1,716m^3, 26 · 6 ·11m, with an on/off glycol cooling system and insulated walls built of foam sandwiched between two layers of corrugated plate (total wall thickness is 0.16 m). The set points experimentation time were different for each one (see table 1). Each chamber has a common pre-chamber space where a devoted sensor is placed. Therefore, three different ambient conditions occur: outdoor, pre-chamber and inside chamber with well known set point (see Table 1).

Table 1. Experimental conditions.

Cold store number	Set point (°C)	Experimentation time (days)	Dates
11	8	13	7th - 19th July
29	7	8	20th - 27th July
40	14	4	28th - 31st July

ZigBee motes

Two ZigBee/IEEE 802.15.4 motes (transmitters) and one base station (receiver) were used, manufactured by Crossbow®. One mote was installed outside the chamber, close to the door and the other one inside, at the other side of the wall. Sample rate was set to 180s.
They have a microcontroller board (IRIS) together with an independent transducer board (MTS400) attached by means of a 52 pin connector. Its processor & radio platform is a XM2110CA, based on the Atmel ATmega1281. The RF power was configured to 3dBm (three times over previous MICAZ Motes). Power was supplied by two AA lithium batteries.
The MTS400 board hosts a variety of sensors: temperature and relative humidity (Sensirion SHT), barometric pressure and temperature (Intersema MS5534B), light intensity (TAOS TSL2550D) and a two-axis accelerometer (ADXL202JE). A laptop computer is used as the receiver, and communicates with the nodes through a Micaz mounted on the MIB520 ZigBee/USB gateway board; this device also provides a USB programming interface. In this study only the data from Sensirion and Intersema is used.

The Sensirion SHT is individually calibrated in a precision humidity chamber. The calibration coefficients are programmed into the memory. These coefficients are used internally during measurements to calibrate the signals from the sensors.
The MS5534B is a SMD-hybrid device including a piezoresistive pressure sensor and an ADC-Interface IC. It provides a 16 Bit data word from a pressure and temperature (-40 to +125°C) dependent voltage. Additionally the module contains 6 readable coefficients for a highly accurate software calibration of the sensor.
Up to six ZigBee/IEEE 802.15.4 motes (transmitters) and one base station (receiver) were used, manufactured by Nlaza®. One mote was installed outside the chamber, close to the door and the others inside in different positions, at the other side of the wall. Sample rate was set to 180s.
Its processor & radio platform is based on the Freescale MC13213. It's one of the second-generation ZigBee platform which incorporates a low power 2.4GHz radio frequency transceiver and an 8-bit microcontroller into a single 9·9·1mm 71-pin LGA package. Power was supplied by three AA lithium batteries that provide it a life time of several weeks.

A laptop computer is used as the receiver, and communicates with the nodes through RS-232 gateway /ZigBee ND-07 board. We can programme the nodes with Sensatel® software. The ND-11 board hosts an unique Sensirion SHT sensor.

Psychrometric data

The ASAE D271.2, defined in April 1979 and reviewed in 2006, is used for computing the psychrometric properties of air (ASABE, 2006). Equations 1, 2, 3, 4 and Table 2 enable the calculation of all psychrometric data of air whenever two independent psychrometric properties of an air-water vapour mixture are known in addition to the atmospheric pressure.

$$Ps = e^{31.96 - \frac{6{,}270.36}{T} - 0.46 \cdot \ln T - ti\theta} \quad (1)$$

-255.38K ≤ T ≤ 273.16K

$$Ps = e^{-\frac{A + B\cdot T + C\cdot T^2 + D\cdot T^3 + E\cdot T^4}{F\cdot T - G\cdot T^2}} \quad (2)$$

273.16 K ≤ T ≤ 533.16 K

T=Temperature (K), Ps= Saturation vapor pressure (Pa) (ASABE, 2006).

$$P_v = P_S \cdot \frac{RH}{100} \quad (3)$$

Pv= Vapor pressure (Pa) (ASABE, 2006).

$$Hum = \frac{0.6219 \cdot Pv}{Patm - Pv} \quad (4)$$

Hum=Absolute humidity (g/kg dry air), Patm= Atmospheric pressure (Pa) (ASABE, 2006).

Table 2. Coefficients used to compute the psychometric data, according to equation 5 (ASABE, 2006).

R=22,105,649.25	D=0.12558x10-3
A=-27,405.526	E=-0.48502x10-7
B=97.5413	F=4.34903
C=-0.146244	G=0.39381x10-2

Data analysis

A Matlab® code is used to calculate the air enthalpy inside and outside the cold store with temperature and relative humidity obtained from the Crossbow motes and using psychrometric data analysis. On the other hand the real power consumption of the chamber is provided hourly by the warehouse holder.

$$m = \rho \cdot V = (1{,}293 - 0{,}004T) \cdot V \tag{5}$$

$$m = dry\ air\ weight\ (Kg),\ \rho = air\ density\ \left(\frac{Kg}{m^3}\right),\ V = air\ volume\ (m^3)$$

$$H(Kcal) = Enthalpy\left(\frac{J}{Kg}\right) \cdot m\ (kg) \cdot 0{,}24\left(\frac{Kcal}{KJ}\right) \cdot 10^{-3}\left(\frac{KJ}{J}\right) \tag{6}$$

Enthalpy of equation number 6 is graphically calculated from the psychrometric diagram obtained using the ASAE D271.2.

We set a new parameter for the analysis of possible errors in the billing of energy consumed: the subtraction of the energy consumed and the air enthalpy (*Diff*).

$$Diff(Kcal) = Power\ Consumption(Kcal) - H(Kcal) \tag{7}$$

We establish that there are billing errors and malfunctioning valves when a value for this parameter (Diff) is outside the limits of the statistically estimated range where it is the 95 or the 98 per cent of the values.

$$Upper\ Limit(Kcal) = \bar{x} + t \cdot s \tag{8}$$

$$Lower\ Limit(Kcal) = \bar{x} - t \cdot s \tag{9}$$

$$\bar{x} = Diff\ mean,\quad s = Diff\ standard\ deviation,\quad t = t\ Student = \begin{cases} 1.96\ for\ 95\% \\ 2.32\ for\ 98\% \end{cases}$$

3. Results

Psychrometry

The absolute humidity of the air inside the chambers was calculated, based on the ASAE standard D271.2 (1979) (ASABE, 2006), using the data recorded during experiments. Psychrometric charts for chambers number 40 is included in Fig.1, which illustrate the evolution of air absolute humidity (H, kg of water/ kg of dry air) related to the T (ºC). There are several clouds of data that corresponds to the Nlaza® motes placed in the sides that the figure indicates. Door openings created an increment in T (ºC) and H (kg of water/ kg of dry air), which then returns to normal again once the door is closed. The door of cold store number 40 keeps open longer, therefore cloud of data that corresponds to the mote placed outside the chamber is closer to clouds of motes inside the chamber data. When the door of the cold chamber is opened, warm air from the outside mixes with the air inside and this causes the temperatures to equalize. We also can see a relative humidity gradient inside the chamber influenced by the goods stored.

Fig.1. Psychrometric chart for cold chamber number 40 data

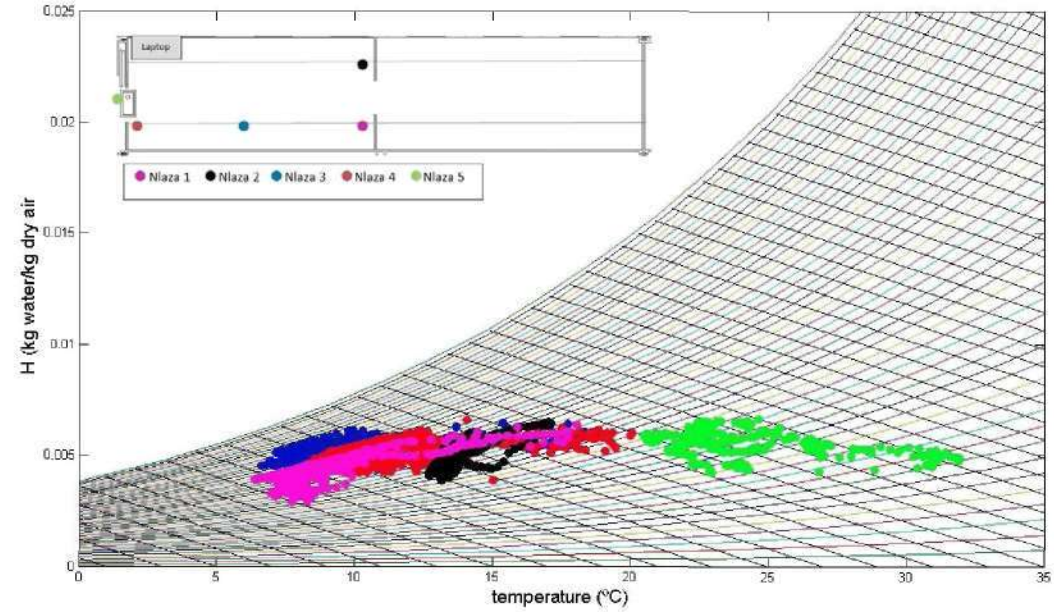
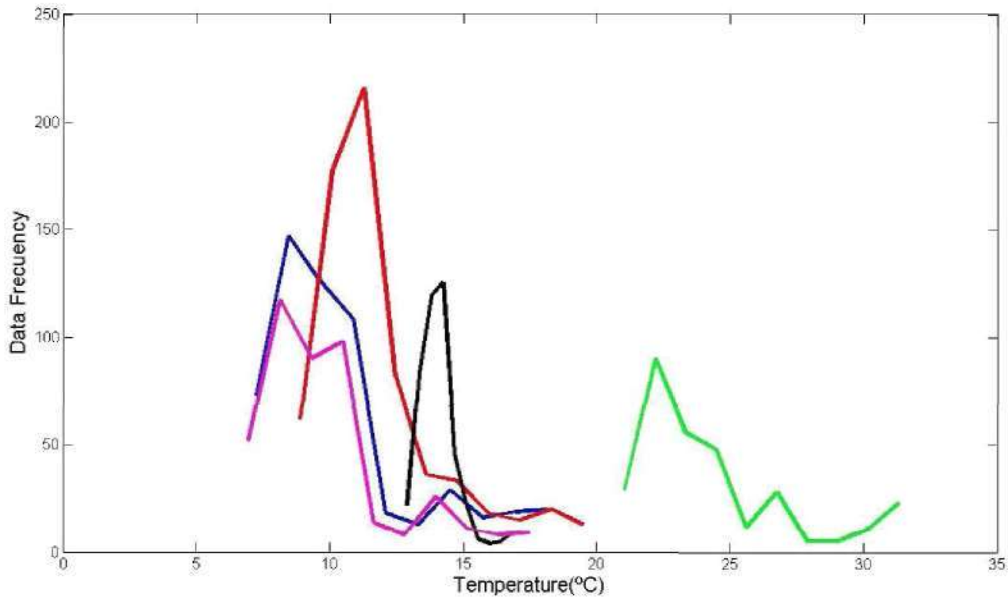


Fig.2. Temperature Histogram of Nlaza® motes in cold chamber number 40.

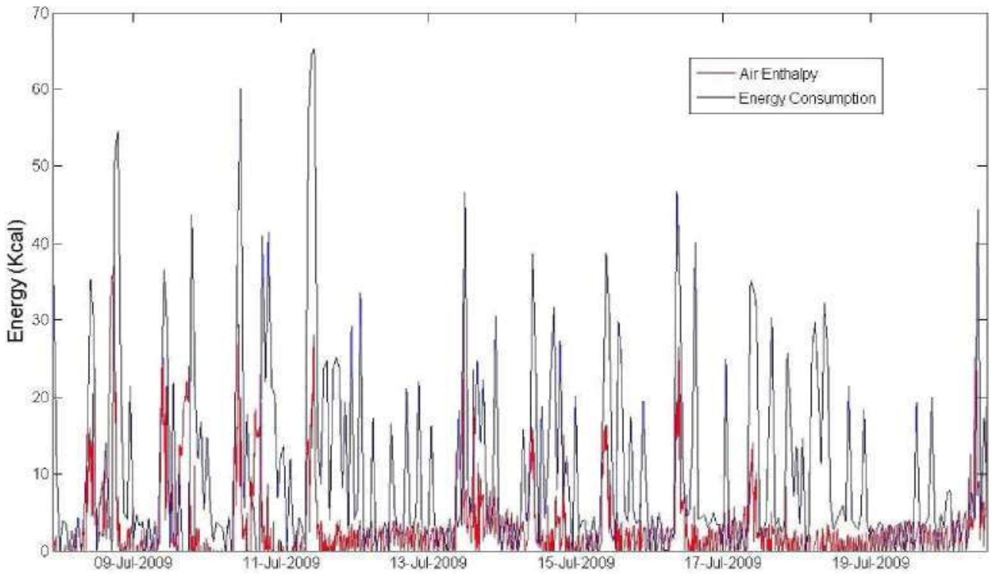


As we see in Fig.2, the closer to the door the sensors are, higher temperature is reached by them. On the other hand, Nlaza 2 mote (black line in Fig.2) is always warmer than others because much of the time there is an operator working in that area.

Air enthalpy and Power Consumption

Air enthalpy inside the cold store has been calculated basing on on the ASAE standard D271.2 (1979) (ASABE, 2006).
There is a correlation between energy consumption billed by the warehouse holder and the calculated air enthalpy (see Fig.3). Air enthalpy changes continuously due to temperature variations inside the cold chamber. Enthalpy peaks usually correspond to times of opening door; because of that there are large peaks of energy consumption. The Energy Consumption data are recorded every hour and the enthalpy of the air every three minutes, so a Power Consumption peak can correspond to multiple jumps of the air enthalpy. Refrigeration system also starts running to compensate for the thermal inertia of the cold chamber. We can see it better in Fig.4.

Fig.3. Air Enthalpy and Power Consumption in cold chamber number 11.



Sometimes, mechanical failures on the inlet valve of cold glycol cause errors in the energy billing. This can be diagnosed by comparison between the energy consumption and the variation of the air enthalpy. It is clearly shown in the case of the cold chamber number 29 (see Fig. 4).

Fig.4. Air Enthalpy and Power Consumption in cold chamber number 29.

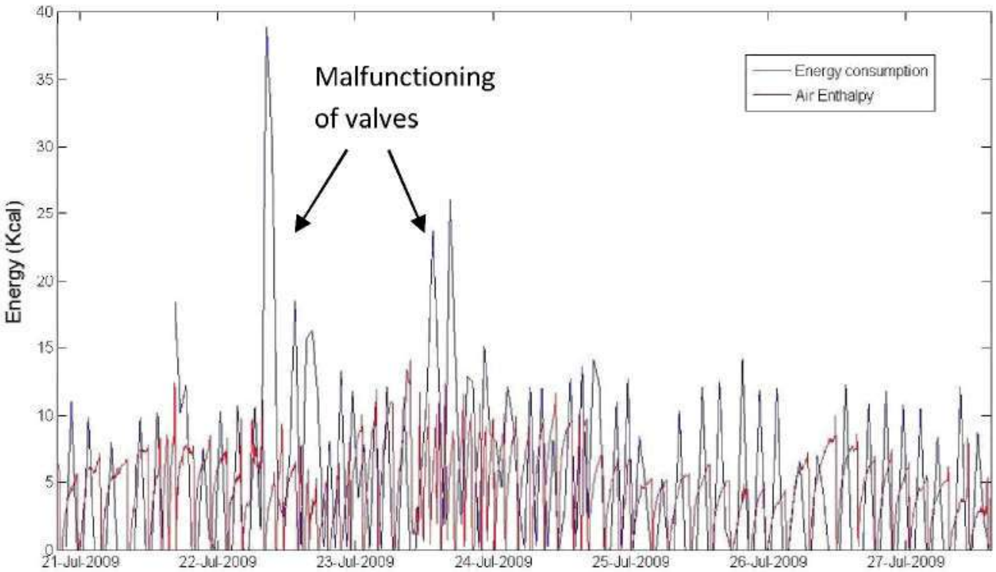
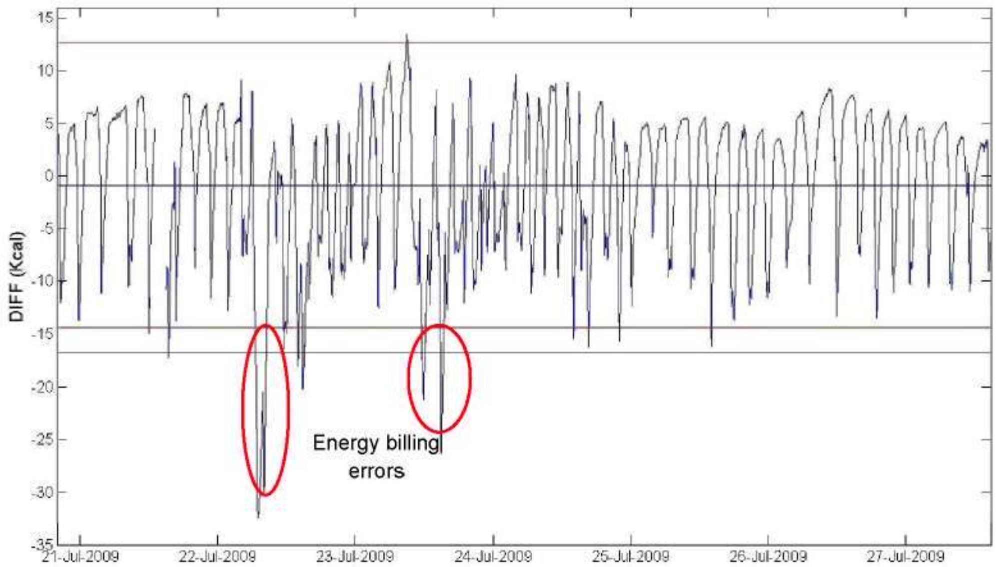


Fig 5. Difference between Power Consumption and Air Enthalpy in cold chamber number 29. Malfunctioning Diagnosis.



If there is correlation between Power Consumption and Air Enthalpy, the subtraction between these two data will fluctuate around a mean value. We see this behavior in Figure 5. Values outside the limits indicated may be considered as a malfunctioning of the valves and billing errors of the consumed energy alarm.

For the cold chamber number 29, the mean of the subtraction between Power Consumption and Air Enthalpy is -0.9Kcal, and de standard deviation is ±6.9Kcal. With that two data we calculate the range where the 95 or 98 per cent of data are found. Out of these limits we can determinate that errors are occurring in the energy billing (see Table 3).

Table 3. Limits for detecting malfunctioning in cooling system and for defining energy billing errors.

	95% (t=1.96)	98% (t=2.32)
Upper limit	12.6Kcal	15.0Kcal
Lower limit	-14.4Kcal	-16.8Kcal

4. Conclusion

The use of Temperature and Relative Humidity together with psychrometric models allow to define smart capabilities for sensors.
Difference in absolute humidity along chambers, air flow across the doors and energy balance are also smart functions that can easily be incorporated on smart sensors.
Smart capabilities allow addressing faults and malfunctioning in the cooling systems. Therefore smart capabilities become system diagnosis at very low cost and high frequency rate.
In this framework, wireless sensor motes proved to be flexible and useful for an easily data monitoring.

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