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Reducing energy consumption in cold stores using a freely available mathematical model

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ABSTRACT

The ICE-E model is a user-friendly tool that allows cold store operators to predict the energy consumption of their stores as heat loads vary due to changes in ambient conditions and store usage patterns. Weather data and construction and usage details are used to predict heat load and refrigeration COP on an hourly basis over a whole year. The model was validated against the industry standard CoolPack model and the features of the models were compared. The ICE-E model is better suited to non-technical cold store users who may not know details such as *U*-values, air change rates, respiration rates, condensing and evaporating temperatures, and it has additional features such as the ability to change efficiencies of lights and fans. It can help users to identify which cold store features and operating parameters have the greatest impact on energy consumption, and assess the scope for measures aimed at reducing it.

1. Introduction

Food cold store facilities generally store food at chilled temperatures (typically between −1 and 5 °C) or frozen temperatures (typically below −18 °C) to maintain quality and safety of the food. For some specialised products ultra-low temperatures (some fish, and specialised foods) or modified atmosphere storage (fruits and vegetables) are used. All chilled and frozen food and temperature controlled pharmaceutical products are stored in a cold store at least once during their journey from production to the consumer. In 2012 in Europe there were approximately 1.6 million cold stores, of which 67% were small stores with a volume of less than 400 m^3 (Mudgal, Tinetti, Bain, Cervantes, & de Prado Trigo, 2011).

Cold storage rooms consume considerable amounts of energy. In 2002 the IIR estimated that the Specific Energy Consumption (SEC) of cold stores was between 30 and 50 $kW\,h\,m^{-3}\,year^{-1}$ (Duiven & Binard, 2002). The minimum value from this study was similar to values from a study carried out in the Netherlands by Bosma (1995) which found the average energy consumption of cold stores to be 35 $kW\,h\,m^{-3}\,year^{-1}$. In the UK, Energy Technology Support Unit (ETSU, 1994) also found that stores consumed at minimum 34 $kW\,h\,m^{-3}\,year^{-1}$ but that consumption could also be up to 124 $kW\,h\,m^{-3}\,year^{-1}$. Other studies in the USA by Elleson and Freund (2004) and Singh (2006) found SECs of between 19 and 88, and 15 and 132 $kW\,h\,m^{-3}\,year^{-1}$, respectively. In one of the most comprehensive recent surveys, carried out in New Zealand by Werner, Vaino, Merts, and Cleland (2006), the performance of 34 cold stores was compared. The SECs recorded varied from 26 to 379 $kW\,h\,m^{-3}\,year^{-1}$ and savings of between 15 and 26% were found to be achievable by applying best practice technologies. Evans et al. (2013) showed that considerable savings (between 8 and 72%) could be made by optimising usage of stores, repairing current equipment and by retrofitting energy efficient equipment with relatively short payback periods (the majority being less than 3 years).

Much of the information provided to cold store end users is generic (reduce condensing temperature, increase evaporating temperature etc.) and little is specifically tailored to end users' particular needs. This was found to be a particular problem in audits carried out by Evans et al. (2013) where options to reduce energy in cold stores varied widely between stores. Most energy saving options were only selected and installed after a case had been made for a relatively short payback period. This often required a level of knowledge not possessed by most cold store operators. It was therefore difficult for cold store operators to obtain a clear and unbiased view on whether energy saving options would be worthwhile in terms of carbon and financial savings.

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Nomenclature

A	surface area (m^2)
e	efficacy of lighting lamps (lm W^{-1})
COP	coefficient of performance of the compressor
E	effectiveness of door protection or blockage
EL	elevation (radians)
d	day of year (integer)
F	density factor
g	acceleration due to gravity (9.81 m s^{-2})
h	heat transfer coefficient (W m^{-2} K^{-1})
H	height of cold store door (m)
HRA	hour angle (radians)
I	ratio of solar radiation incident on each of the cold store walls at an angle to the sun to that normal to the sun (ratio)
k	thermal conductivity (W m^{-1} K^{-1})
l	latent heat of fusion for water (J kg^{-1})
L	length of door seals (m)
LF	luminous flux (lm m^{-2})
LST	local solar time
m	mass flow rate (kg s^{-1})
n	stage coefficient
N	number
M	mass loaded per day (kg day^{-1})
P	electrical power (W)
q	heat flow per unit area (W m^{-2})
Q	heat flow (W)
r	proportion of solar radiation incident on surface (ratio)
t	duration (s)
S	shaft power (W)
T	temperature (°C)
U	overall heat transfer coefficient (W m^{-2} K)
v	volume flow rate through seals per metre of seal length (m^2 s^{-1})
V	wind speed (m s^{-1})
x	fractional vaporisation of refrigerant in evaporator on expansion from liquid to saturation at discharge
X	concentration of water in air
α	empirical constant for different refrigerants
β	declination angle (degrees)
Δ	thickness (m)
ρ	density (kg m^{-3})
μ	efficiency
φ	latitude

Subscripts

24	in 24 h
ad	air through door
c	condensing
comp	compressor
cond	condenser
d	door
do	door opening
ds	door seals
de	defrost
e	evaporating
f	floor
fl	fork lifts
fu	fusion
i	inside
l	lights
me	evaporator fan motor
mc	condenser fan motor
o	outside
ot	other
pe	personnel
pr	product
r	respiration
s	solar
T	total
v	vapour
w	wall
wp	water from product/packaging

There are a number of openly available simulation models designed specifically to model the performance of refrigeration systems. Most of these are aimed at retail refrigeration and include SuperSIM (Ge & Tassou, 2000), ORNL Supermarket spreadsheets (Baxter, 2003), Getu & Bansal model LT-case (Getu & Bansal, 2006) the EKS program (Saint Trofee), RETScreen (Natural Resources Canada), EnergyPlus (US-DOE, 2010) and Cybermart (Arias, Lundqvist, Sawalha, & Axel, 2010). There are also specific programs for refrigeration systems and cycles, e.g. CoolPack and Pack Calculation, (IPU, Denmark).

Becker, Brian, Fricke, and Sartin (2012) analysed the capabilities of CoolPack and Pack Calculation II to determine the energy efficiency of walk-in cooler and freezer refrigeration systems as a function of the ambient dry-bulb and wet-bulb temperatures surrounding the walk-in and its condensing unit. They found that CoolPack was not capable of simulating the performance of a refrigeration system whose load varies according to ambient conditions that vary with the weather. Pack Calculation II cannot model a temperature-dependent refrigeration load so the effects of weather data on refrigeration load (conduction and infiltration) are ignored.

This paper presents a new user-friendly tool (ICE-E model) that allows cold store operators and technicians to predict cold store energy consumption when refrigeration load varies according to ambient weather conditions. The model was verified and compared with the industry standard CoolPack model. Weather data was used to predict both heat load and refrigeration COP through the whole year at 3 different locations in the world. The accuracy of using mean ambient weather conditions compared to varying annual weather was investigated using the ICE-E model.

2. Model description

A spreadsheet-based mathematical model with Visual Basic macros (referred to as the ICE-E model) was developed in Microsoft Excel™. To operate the model the user was required to input data about the cold store as shown in Fig. 1. A detailed list of the parameters is shown in Table 1.

Energy consumption was calculated every hour for a whole year. External heat loads from ambient were calculated every hour based on historical local weather data imported from the U.S. Department of Energy, EnergyPlus Energy Simulation Software, weather database. (http://apps1.eere.energy.gov/buildings/energyplus/cfm/weather_data.cfm).

The ambient parameters which changed every hour were the ambient temperature, relative humidity (RH), ground temperature, wind speed, solar radiation and the position of the sun in the sky. All other heat loads were averaged throughout the year. Refrigeration condenser ambient conditions were also calculated from the hourly weather data. This allowed a yearly profile of energy consumption to be evaluated.

The daily heat loads for each month of one year were shown as a bar graph. The hourly heat loads during the day for the months