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Peak load shifting with energy storage and price-based control system

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ABSTRACT

This paper presents an analysis of a price-based control system in conjunction with energy storage using phase change materials for two applications: space heating in buildings and domestic freezers. The freezer used for this experimental study was provided with energy storage trays containing a eutectic solution of ammonium chloride (melting point of −15 °C). In the building application, DuPont wallboards were used to provide thermal storage. Experimental results showed that using thermal storage material in conjunction with the proposed price-based control method can improve performance of these systems and lead to a successful peak load shifting. Depending on electricity price trends, cost savings using the proposed strategy can vary. Savings of up to 16.5% and 62.64% per day were achieved for the freezer and building applications respectively, based on New Zealand electricity rates.

1. Introduction

High electricity usage at certain times of the day, known as peak load, introduces stress to the grid as supplied electricity is inadequate during the high peak demand period. In order to satisfy such demand, expensive peak power generation must be brought on line during the peak period [1]. Also, variability of power generation based on renewable energy such as solar and wind, has a huge impact on the electricity supply [2]. Peak load shifting is a possible solution, with electricity being stored during low load periods for use in peak load periods [3]. Because of the fact that heating, cooling and air conditioning in many developed countries are responsible for almost 30 percent of the total electricity consumption [4], storing heat (or cold) could contribute significantly to peak load shifting.

Variable electricity rate or so-called ToU (time of use) electricity, is one of the tools used to encourage people to use electricity during off-peak periods. Many researchers have suggested using thermal energy storage (TES) to store heat or cold during off-peak periods to be used during the peak period [5]. Usually in TES, energy is stored in form of sensible heat, latent heat [6] and sorption [7]. Sensible heat storage materials have low thermal storage density which leads to large storage volume. PCM (Phase change materials) however, offer a good thermal storage capacity because of their high storage density and they are used in applications where it is necessary to store heat or cold [8,9]. A large number of these studies can be found on application of PCM in hot water cylinders [10,11], fridge and freezers [12], solar power plants [13], and buildings [14].

A number of studies have been carried out on the application of PCM in refrigerators, freezers [15] and cold storages [16]. The main objective of these studies was to improve the performance of refrigerators and freezers by introducing thermal inertia to reduce temperature fluctuation [17]. Azzouz et al. used PCM to improve COP of a household refrigerator by 12% [18]. Gin and Farid also used PCM to prevent significant temperature rise in a freezer through power failure and frequent door openings. These studies showed that application of PCM in a freezer can considerably improve the performance of the freezer [19].

There are many reported studies on the use of PCM in buildings in both active [20] and passive systems [21]. An active system refers to storage systems in which an additional fluid loop is used to charge and discharge the stored energy to supply heating or cooling. On the other hand, a passive system does not involve any additional heat exchanger. Chilled water tanks and ice storage tanks are one of the most common active TES equipment [22]. Underfloor heating using PCM and PCM wallboards are examples of passive systems [23]. The application of PCM in building materials such as wallboards provides a large surface area for heat transfer,

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Abbreviations

AC	air conditioner
CoP	coefficient of performance
DLC	direct load control
DR	demand response
DSC	differential scanning calorimetry
FT	freezer temperature
LHTES	latent heat thermal energy storage
OP	online price
PC	price constraint
PCM	phase change materials
RAC	remote applicant control
RT	room temperature
TC	temperature constraint
TES	thermal energy storage
ToU	time of use

it is very easy to install and does not require any additional space in the building. These characteristics make PCM interesting alternatives to storing energy for passive applications [24].

There have been a number of studies carried out on the application of PCM for peak load application using active systems such as ice storage units [25,26] which resulted in successful peak load shifting. They have also applied a number of optimal control studies on active systems based on the published official variable electricity rates in order to minimize the electricity cost. The use of published official variable electricity rates can, however, cause a number of problems. The main problem is that the expected electricity load might not match the actual demand of the day [27]. Peak load shifting through consumers also can cause serious problems; for instance, DR (demand response) approach frequently failed in many countries as it requires people to adjust their consumption according to a dynamic electricity tariff. Given this approach, a sudden need to make frequent active consumption decisions may lead consumers to grow tired of keeping track of rates and usage. For instance DR was tested in Salt Lake City, Utah, and Puget Sound, Washington and up to 98% of consumers gave up TOU tariffs and returned to fixed electricity rates [28]. In contrast, some researchers have suggested DSM (demand-side management), using DLC (direct load control) as a better solution for peak load shifting problem. However, many DLC projects using RACs (Remote Appliance Controllers) have failed because of their large impact on the users' comfort level [29].

To be successful with peak load shifting, a suitable energy storage needs to be incorporated during peak load periods (when the appliance is turned off because of high load) to have a minimum impact on consumers' comfort. In this paper, the application of PCM was investigated to achieve a successful peak load shifting (based on RAC) while minimizing its effect on consumers' comfort level. A price-based control strategy is also proposed which enables the use of online electricity prices and prevents any mismatch between the predicted load and the actual load. The proposed strategy has been tested on a PCM-incorporated domestic freezer as well as on experimental test huts equipped with DuPont PCM wallboards.

2. Methodology

In order to prove the concept, a domestic freezer and experimental huts provided with heat pumps were used as two different case studies. The proposed price-based method was applied and the results with and without using PCM were compared.

2.1. Price-based method

The proposed method shares many common features with the DLC method using RAC, but with some differences. In the proposed method, electricity load is monitored by the electricity provider and, as soon as the electricity consumption peaks, the electricity provider increases the electricity price and then users who are using the price-based control system will automatically stop using electricity. In order to use this method, the electricity provider also needs to set a price constraint for each day.

In order to prove the concept, a program was developed using the LabVIEW software to enable the controller to read the electricity price from any given website when the website address is provided. The developed program reads the electricity price from the Electricity Information website which publishes the wholesale electricity rates in New Zealand [30]. Price constraints need to be suggested by the electricity provider but, since this information is not available yet, a price constraint was selected based on the previous trends.

The importance of a correct price constraint for the day was discussed in the results section. If the electricity company provides a price constraint for each day on the webpage, the same developed program could be used to read the price constraint of the day. Thus, in the later stage of the experiment, in order to mimic a real situation in the future, both price and price constraint were fed directly to the control system remotely from an office located at the University of Auckland's city campus, 12 km away from the experimental huts. The experimental huts are situated at the Tamaki campus, Auckland, New Zealand.

2.2. The experimental setup

2.2.1. Domestic freezer

In the first part of the experimental study, a 153 L vertical freezer (model Elba E150, Fisher & Paykel) with nominal power of 150 W was used. An aqueous ammonium chloride solution (19.5wt% NH_4Cl) with a phase change temperature of −15.4 °C was used as the PCM (phase change material) because of its high latent heat (250 kJ/kg) and its peak melting point [12].

The freezer cabinet temperature was measured using T-type thermocouples. All thermocouples were calibrated against a reference thermometer (Ebro TFX430) from −20 to 20 °C in a stirred flask of methyl alcohol to an accuracy of 0.1 °C. The PCM was contained in anodized aluminium containers because of its high thermal conductivity. The anodised layer provides protection against corrosion. Seven of these panels were placed against the three walls in the freezer, covering 26% of the surface area of the walls, and occupying only 3% by volume of the freezer storage space.

2.2.2. Data acquisition and control in the freezer

As shown in Fig. 1, the controller reads electricity price from the electricity provider and the price constraint of the day from the office situated at the University of Auckland, city campus. As shown in the flowchart in Fig. 2, the controller compares the OP (online price) and the PC (price constraint). If the OP is less than the PC, the controller keeps the freezer running in order to charge the PCM. Otherwise, the control system proceeds to the next step. In the next step, the control unit receives data on the cabinet temperature of the freezer (FT) and if it is lower than the TC (temperature constraint), the compressor is turned off to use the stored energy. During the high peak period, if temperature of the freezer rises above the temperature constraint of −12 °C (FT ≥ TC), the controller ignores the high price and turns on the compressor to prevent any possible food damage, as shown in the flow chart.