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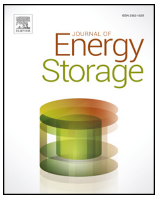

Enhancement in peak shifting and shaving potential of electrically heated floor residential buildings using heat extraction system

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ABSTRACT

Peak shifting plays a vital role in easing the stress on electrical grids as well as in reducing the electricity bill for consumers by taking benefit of the time-of-use tariff. In cold climates, this can be achieved effectively by storing the heat during off-peak periods and releasing it during peak periods. In this regard, electrically heated floor (EHF) with high thermal mass (e.g. bricks, concrete) can be beneficial. However, residential buildings in places like North America face practical constraints for incorporating high thermal mass on each floor. To overcome this limitation, the present work proposes a forced ventilation system or also called as heat extraction system (HES) to transfer the heat from zones that are heated by EHF with high thermal mass to zones with no such provisions. In this study, an experimental house (multistory), in which the EHF is mainly installed on the basement floor is modeled and validated using the field measurement data. The validated model is then utilized to conduct parametric analysis (effect of air flow rate and outlet location) for investigating the performance of HES and to evaluate its peak shaving potential. Simulation results show that HES increases the peak shifting potential of EHF up to 19%. On the other hand, it is also inferred that the proposed methodology increases the energy consumption by 18% but decreases the daily heating cost by 24%. It should be mentioned that the increase in energy consumption is due to the prolonged operation of the basement EHF during the off-peak period and the decrease in energy cost is because of shifting the peak to the off-peak period. The proposed concept would be a benefit to both the supplier and consumer in terms of peak shifting and heating cost saving.

1. Introduction

In Canada, space heating accounted for 55% of the total energy consumption in commercial and institutional sectors in 2013, while the energy spent for space heating was 63% for residential sector [1]. Since heating demand mainly occurs in cold season, the energy consumption gets further intense during winter. Besides, due to occupant living habits and climatic factors, daily peaks of energy consumption generally occur during the morning (e.g. 6 a.m.–10 a.m.) and/or late afternoon (e.g. 4 p.m.–10 p.m.) [2]. This high electricity demand during peak periods further increases the stress on the electricity grid. If the energy consumption during the peak period exceeds the normal demand, utility providers should spend additional costs to either generate the additional load or purchase power at higher prices from neighboring grids [3]. As a result, many countries adopted time-of-use tariffs [4]. This means that changing the energy consumption pattern or taking methods to reduce peak demand will not only release the stress of the electricity grid but also enable the consumers to save their electricity bill. To decrease the peak demand, several suggestions/solutions have been proposed in the literature: (i) encouraging consumers to change their energy consumption habits (e.g. postponing the use of the dishwasher and hot water from peak periods to off-peak periods); however, the anticipated reduction of peak demand in this case might be negligible [5]; (ii) increasing the thermal resistance of building envelopes, thus decreasing the energy consumption of space conditioning systems [6]; (iii) storing the energy during off-peak periods or during periods with availability of solar energy and utilizing it later during peak periods [7]. Considering the uncertainty in the performance of the first suggestion

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Abbreviations: ASHRAE, The American Society of Heating Refrigerating and Air-Conditioning Engineers; ANSI/BPI, American National Standards Institute/Building Performance Institute; CAD, Canadian Dollar; EHF, electrically heated floor; FEMP, federal energy management program; HES, heat extraction system; IPMVP, International Performance Measurement and Verification Protocol; PCM, phase change materials; TES, thermal energy storage; TRNSYS, TRaNsient SYstems Simulation program

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Nomenclature

abs(*NMBE*)	Absolute value of NMBE [%]
c	Global flow coefficient [m^3 s^{-1} Pa^{-n}]
c_j	Flow coefficient for component *j* [m^3 s^{-1} Pa^{-n}]
$c_{j,lit}$	Flow coefficient for component *j* from the literature [31] or [32] [m^3 s^{-1} Pa^{-n}]
c_{test}	Global flow coefficient of the whole unit measured by air-tightness test [m^3 s^{-1} Pa^{-n}]
CFM	Cubic feet per minute [ft^3 min^{-1}]
CV(*RMSE*)	Coefficient of variance of the root mean square error [%]
D_{peak}	Duration of peak period [h]
D_{mid}	Duration of mid-peak period [h]
D_{off}	Duration of off-peak period [h]
E_{peak}	Electricity price during peak period [CAD/kWh]
E_{mid}	Electricity price during mid-peak period [CAD/kWh]
E_{off}	Electricity price during off-peak period [CAD/kWh]
F_{ST}	Floor surface temperature [°C]
i	Zone number [—]
j	Component number [—]
m_t	Measured value at time *t*
$\overline{\mathbf{m}}$	Average of the measured values
NMBE	Normalized mean bias error [%]
n	Global flow exponent [—]
$n_{j,lit}$	Flow exponent for component *j* from the literature [31] or [32] [—]
n_{test}	Global flow exponent of the whole unit measured by air-tightness test [—]
N	The number of measured data points [—]
p	The number of adjustable model parameters [—]
ΔP	Pressure difference [Pa]
$P_{ave,basement}$	Average power consumed by the basement [W]
$P_{nominal}$	Nominal power of EHFs [W]
P_{peak}	Power consumption during peak period [kW]
P_{mid}	Power consumption during mid-peak period [kW]
P_{off}	Power consumption during off-peak period [kW]
Q	Global volumetric flow rate [m^3.s^{-1}]
s_t	Simulated output at time *t*
T_{in}	Interior air temperature [°C]
$T_{ave,mean}$	Average mean second floor air temperature [°C]
$T_{max,mean}$	Maximum mean second floor air temperature [°C]
$T_{\max}$	Maximum room temperature within the second floor [°C]
$T_{min,mean}$	Minimum mean second floor air temperature [°C]
$T_{min,mean}$	Minimum mean second floor air temperature [°C]

and initial investment/renovating cost of the second solution, shifting peak power consumption using thermal energy storage (TES) systems is worth investigating from a sustainability standpoint.

In TES systems, energy could be stored in three forms: sensible heat, latent heat and thermochemical energy storage [8,9]. Although latent and thermochemical storage systems have higher storage density, sensible storage, which stores energy by changing the temperature of a storage medium (e.g. water, bricks, clay, concrete, etc.), is widely adopted due to the convenience in implementation and controlling as well as lower cost. Envelopes constructed with materials of high thermal mass could be considered as one way to incorporate sensible TES into buildings. In general, building structure components such as walls, ceilings or floors which are constructed by bricks or concretes can be utilized as a storage unit [10]. However, ceilings and floors are highly recommended for thermal mass activation than walls, because wall surfaces are usually used for household domestic purposes. Favre et al. [11] studied the influence of thermal mass on peak shifting in a well-insulated building during a cold week (with exterior temperature various around −7 °C–4 °C). Their results showed that the high thermal mass envelopes (wall and floor constructed by concrete) allowed shifting the heating consumption of a building for almost 15 h, while low thermal mass envelopes (timber frame) only delayed the peak load for a short time (around 2 h).

In terms of heating, a floor assembly can be incorporated with a hydronic floor heating system or electrically heated floor (EHF) system [12]. Hydronic heated floor provides heat by pumping hot water through pipes which are usually laid under the flooring, while the EHF system works with electric cables or mats incorporated into the floor. The main determining factor of their peak shifting potential is thermal mass when just sensible storage is considered.

Dréau et al. [13] developed two building models in EnergyPlus to compare the peak shifting flexibility between a baseboard heating system and a hydronic floor heating system. They found that the hydronic floor heating system showed better peak shifting potential while maintaining the indoor air temperature within a comfortable range. A similar comparison between a fan-coil heating system and a hydronic heated floor system has been done by Li et al. [14]. It was reported that when the exterior temperature was around 10 °C, turning OFF the heating system resulted in indoor temperature dropping rate of 0.214 °C/h and 1.57 °C/h for floor heating system and fan-coil heating system, respectively. Jin et al. [15] analyzed the peak shifting capability of a hydronic heated floor with 10 mm wood and 30 mm concrete on top of the water pipes. Under specific boundary conditions, during the peak period (8 a.m.–5 p.m.), the heating system was turned OFF and the average generation rate was found to be about 54.6 W/m^2.

As mentioned earlier, EHF heats the building directly by electric cables or panels placed under the floor surface. Thus, unlike the hydronic heated floor, additional heating device, e.g. hot water tank, and hydraulic balance are not required for EHF. This means the installation of EHF is easier than the hydronic heated floor. Besides, the operation pattern (ON/OFF) of EHFs could be flexibly adjusted according to occupants' desirable interior set-point temperature as a function of time. However, the response time of hydronic heated floors would be longer due to the complexity of changing fluid temperature and flow rate [16]. Therefore, it is easier to achieve the set-point temperature difference between off-peak and peak periods in an EHF system than in a hydronic heated floor system.

Thieblemont et al. [17] proposed a method to integrate EHFs into TRNSYS and carried out a parametric study to analyze the effect of floor assembly on the EHF performance. Their simulation results showed that the thickness of concrete layer below or above the EHF and thickness of the insulation layer have significant influence over the peak shifting ability of the EHF system. To guarantee an acceptable indoor environment thermal comfort, Thieblemont et al. [12] studied the peak shifting potential of an EHF in a multi-room house by using a partial night-control strategy. It was reported that the EHF could shift 84% of building loads to the off-peak period. However, the building model developed in their study was validated using the data collected from the house with baseboards and not with EHF. The same drawback exists in their recent study [18], where a self-learning predictive control strategy for EHF was proposed to reduce the energy demand during peak period.

Barrio et al. [19] indicated that the concrete mass in EHFs was widely utilized to store the useful sensible heat energy during the off-peak period; however, incorporation of phase change materials (PCMs) into EHFs achieved high energy storage density by latent heat storage. Mays et al. [20] investigated the performance of an EHF incorporated with PCM in an insulated house. The results indicated that the hybrid EHF possessed the ability to maintain the room temperature above a minimum desired temperature for about 6 h after turning OFF, when the average ambient temperature was 14 °C. However, in their study, the indoor air temperature was allowed to reach 28 °C, which sacrificed the thermal comfort. Lin et al. [21] developed a model to simulate the