Energy and Buildings 159 (2018) 357–369

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Hybrid thermal storage using coil-encapsulated phase change materials

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ARTICLE INFO

Article history:
Received 24 August 2017
Received in revised form 23 October 2017
Accepted 30 October 2017
Available online 8 November 2017

Keywords:
Phase change material
PCM
Thermal storage
Heat storage
Air-source heat pump
Domestic heating
Grid-stress

ABSTRACT

Compact thermal storage using a hybrid phase change material (PCM) store for domestic heating applications is investigated. The primary focus is on thermal demand during the electrical grid-stress period (16:00 h–20:00 h on winter weekdays) when the primary heat source, a heat pump, is turned off. Though this phenomenon may be evident in other countries, the main focus of this work is on electrical grid-stress in UK conditions. In this work, PCM encapsulated in pipe coils surrounded by water in a hot water storage tank is considered. Two alternative samples of salt hydrate are evaluated experimentally and the results are used to inform system modelling. A new model is proposed for relating the enthalpy and temperature of the PCM during melting and solidification. A compact hybrid store design is proposed and a detailed thermal model of the hybrid store with an air-source heat pump is constructed and applied to an example house. Seasonal energy results compared with a conventional water tank are broadly similar but the hybrid store offers better comfort tracking during grid stress periods – average house temperatures falling below 19 °C for 22.7% of the time with a conventional store but only 5.8% of the time using the hybrid store.

1. Introduction

Heat pumps are expected to undergo a period rapid growth for domestic heating in order to reduce carbon emission as well as to help to diversify the heating energy mix. In the UK for example, a current dependence on gas heating boilers for approximately 80% of housing is expected to give way to a significant take-up of both air- and ground-source heat pumps and their hybrids in the coming years [1]. Continuing progress on the introduction of cleaner and more sustainable forms of electricity generation will accelerate this trend.

A particular challenge with increased heat pump use is the question of electricity grid capacity and the need for its reinforcement. Peak demand for electricity tends to occur on winter weekdays starting at about 16:00 h. Using data from [2], Fig. 1 shows the daily weekday demand profile for four randomly-selected weekdays in November 2015 through February 2016 in the UK. A consistent period of electricity demand growth starting at 16:00 h and running through until about 20:00 h is evident. In this paper, this will be referred to as the 'grid-stress' period.

The growth part of the grid-stress period unfortunately coincides with the typical day time switch-on point for most domestic heating systems in housing as workers begin to return home for the evening. Therefore, growth in electric heat pumps for domestic space heating will severely exacerbate the grid-stress problem. Measures are therefore needed to head this problem off consisting either of electrical grid reinforcement (expensive) or through load shifting such as the introduction of local energy storage enabling the heat pump to start at a time outside the grid-stress period such that the energy storage system can contribute to satisfactory space heating continuity through this period whilst the heat pump remains idle or at very light load. In practice, it is likely that a combination of these measures will be needed as energy infrastructures move forward in this way. For electric heat pumps, the energy storage option can be considered on the thermal (heating system) side of the system or, conceivably, on the electrical connection side of the system in the form of batteries. Recent developments in phase change materials (PCMs) [e.g. 3–9] make the former method particularly promising. In this paper, the development of a compact thermal storage system based on PCM for the specific purpose of grid-stress mitigation when heat pumps are used is considered.

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https://doi.org/10.1016/j.enbuild.2017.10.095
0378-7788/

Nomenclature

List of symbols

A	Area (m^2)
ACR	Air change rate (h^{-1})
AU	Area-integrated thermal transmittance ($kW\,K^{-1}$)
C	Thermal capacity ($kJ\,K^{-1}$, $J\,m^{-2}\,K^{-1}$)
c	Specific heat capacity ($kJ\,kg^{-1}\,K^{-1}$)
$\bar{c}$	Mean specific heat capacity ($kJ\,kg^{-1}\,K^{-1}$)
E	Energy (kWh)
F	Fitting parameter for PCM h-T model (–)
f	Resistance rationing factor (–)
FR	Radiant emission fraction (–)
g	Capacitance rationing factor (–)
$Goal$	Optimization objective function goal (K)
h	Enthalpy ($kJ\,kg^{-1}$)
I	Solar irradiance ($Wh\,m^{-2}$)
K	Tank ambient heat loss coefficient ($WL^{-1}\,K^{-1}$)
M	Static mass (kg)
m	Mass flow rate ($kg\,s^{-1}$)
N	Day number (–)
n	Discretised model zone number (–)
$\mathbf{P}$	Optimisation algorithm parameter vector
$\mathbf{P}^{min}$	Minimum parameter vector values
$\mathbf{P}^{max}$	Maximum parameter vector values
Q	Heat transfer (W, kW)
$RMSE$	Root-mean-square error (K)
R	Fabric thermal resistance ($m^2K\,W^{-1}$)
$SCoP$	Seasonal coefficient of performance (–)
SPF	Seasonal performance factor (–)
T	Temperature (°C)
t	Time (s)
U	Fabric thermal transmittance value ($W\,m^{-2}\,K^{-1}$)
V	Volume (m^3)
W	Power (W)
x	Axial distance (m)
α	Surface-solar azimuth (degree)
β	Surface angle of tilt (degree)
Δt	Time step size (s)
ρ	Density ($kg\,m^{-1}$)
ϕ	Site latitude (degree)
τ	Window glass transmissivity (–)
θ	Time constant (s)

List of subscripts

a	Air
ai	Air, internal
al	Ambient environment
ao	Air, external
aux	Auxillary
boost	Boost heater
buffer	Buffer storage
cas	Casual (heat gain)
ch	Charge phase
co	Condenser
cwf	Cold water feed
des	At design conditions
dhw	Domestic hot water
dis	Discharge phase
ev	Evaporator
F	At (nominal) fusion point
g	Ground
h	Heating
hor	Horizontal
hp	Heat pump
i	Inlet, infiltration
max	Maximum
o	Outlet
past	Pasteurising heater
pcm	PCM zone
pinch	Pinch point (heat exch.)
pri	Primary (heating)
v	Ventilation
w	Water zone
wi	Water inlet zone
wii	Inlet to water inlet zone
wo	Water outlet zone
wp	Water/PCM boundary
0	Initial state

Abbreviations

PCM	Phase change material
S32	PCM sample 1 (32 °C)
S46	PCM sample 2 (46 °C)

The aim of the research reported in this paper is to develop and evaluate a proposed design for a compact thermal storage system using phase change material suitable for coupling to a conventional domestic heat pump for hot water space heating and domestic hot water heating. A particular focus of the research is the offset of heating demands that occur through the grid-stress period. A particular feature of the work is that the encapsulation of PCM in coils is considered – something that has not previously been reported in the literature.

The objectives are as follows:

- To develop a test facility for the purpose of measuring the response of coil-encapsulated phase change material (PCM) in a water storage tank.
- To develop a mathematical model of a hybrid PCM/water thermal store parameterised from results obtained from the test facility.
- To propose a design framework for a hybrid PCM/water thermal store for use in a typical modern (well-insulated) house.
- To extend the mathematical model into a full domestic heating simulation and evaluate the performance of the integrated system with particular reference to the grid-stress period.
- To evaluate seasonal energy, heat pump performance and thermal comfort of the integrated system benchmarked against an alternative use of a conventional water tank thermal store.

2. Previous work

Material developments, encapsulation and applications to thermal storage systems of PCMs have received substantial attention in the past 25 years and, particularly, in the past 10 as evidenced by the large number of review-type papers on the subject [3–9]. One of the earliest and one of the most comprehensive of the research reviews includes extensive listings of typical material properties including single salt hydrates, salt blends (eutectics) and organic compounds [3]. Agyenim et al. [4] also present details of a range of PCM properties showing that, for many materials, thermal conductivities are generally low but generally higher in the solid phase than in the liquid phase. This has implications for heat transfer rates during both charging (melting) and discharging (solidification). They also review heat transfer enhancement and containment methods. Further examples can be found in the review of de Cunha and Eames