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Application of material assessment methodology in latent heat thermal energy storage for waste heat recovery

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HIGHLIGHTS

- A comprehensive assessment methodology of PCMs for TES systems is proposed.
- Multi-Criteria Decision Making employed to build the methodology.
- Validation of methodology with building simulation from literature.
- Applied methodology to assess PCMs for WHR in cogeneration plant.
- Effective performance assessment reduces simulation in design of LHTES.

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ABSTRACT

This study proposes a comprehensive and systematic methodology of Phase Change Materials assessment for Latent Heat Thermal Energy Storage design, which comprises prescreening, ranking and performance objective examination based on Multi-Criteria Decision Making tools. Firstly, a large candidate pool is pre-screened with crucial boundary constraints. The materials are then ranked by employing the Analytical Hierarchy Process and Techniques for Order Preference by Similarity to Ideal Solutions. Three distinctive objective functions are suggested to explicitly evaluate the performance of Phase Change Materials. Pareto solutions and *Utopia points* are additional tools in the performance objective examination. A good agreement observed between assessment results and a building thermal comfort simulation results from literature validated the proposed methodology. For the first time, performance assessment of Phase Change Materials with the methodology is carried out in an initial design phase of a Latent Heat Thermal Energy Storage system for Waste Heat Recovery application in a cogeneration plant. The performance of prescreened PCMs is evaluated and the results provides a clear ranking list and quantitative performance indicators which will provide a high level of confidence in selecting the best performing materials during the design phase.

1. Introduction

1.1. TES system in industrial waste heat recovery process

The long-standing problem of climate change urges the industries to undergo necessary energy efficiency programs so as to mitigate the problem [1]. Literature shows that 20–50% of industrial energy input is estimated to be lost in the form of exhaust gases, cooling water and heat, which is summarized as waste thermal energy in general [2]. This leads to an increasing demand of industrial Waste Heat Recovery (WHR) in recent years. Waste heat can be recovered in two different kinds of situations. When there is an instantaneous need of thermal energy, such as heating or cooling, waste heat can be collected and reused directly. However, when demand and supply of energy do not occur simultaneously in the same site, Thermal Energy Storage (TES) systems can be implemented in WHR systems to accommodate the time-lag between load and supply, to improve industries' thermal efficiency, and to contribute to the reduction of carbon emission in the long run.

Latent Heat Thermal Energy Storage (LHTES) system employs Phase Change Materials (PCMs) to store and release heat by reversible liquid/solid phase transformation [3]. LHTES is believed to be one of the most promising energy storage methods, owing to its high energy storage density and its ability to provide constant temperature output [4,5]. Since 1970s, LHTES has been applied

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Nomenclature

Acronyms/abbreviations

AHP	Analytical Hierarchy Process
FOM	Figure of Merit
HVAC	Heating, Ventilation and Air-Conditioning
LHTES	Latent Heat Thermal Energy Storage
MADM	Multi-Attribute Decision Making
MCDM	Multi-criteria Decision Making
MODM	Multi-Objective Decision Making
ORC	Organic Rankine Cycle
PCM	Phase Change Material
STES	Sensible Thermal Energy Storage
TES	Thermal Energy Storage
TOPSIS	Techniques for Order Preference by Similarity to Ideal Solutions
VIKOR	multi-criteria optimization and compromise solution (Vise Kriterijumska Optimizacija I Kompromisno Resenje)
WHR	Waste Heat Recovery

Greek symbols

ρ	material density (kg/m^3)
ΔT	temperature interval of charge/discharge (°C)

Symbols

C_m	cost per unit kg of material (USD/kg)
$C_{p,l}$	specific heat capacity at liquid phase (kJ/(kg K)
$C_{p,s}$	specific heat capacity at solid phase (kJ/(kg K)
D	dimensionless distance of material to Utopia point in objective plot
f_1	thermal energy stored per unit cost (kJ/USD)
f_2	thermal energy stored per unit of volume (kJ/m^3)
f_3	PCM equivalent thermal diffusivity (m^2/s)
L	latent heat of fusion (kJ/kg)
m	mass (kg)
k	thermal conductivity (W/(m K))
T_{mp}	melting point temperature (°C)
V	volume (m^3)
X_{ij}	the value of property "j" possessed by material alternative "i"

Subscripts

e	outlet
i	inlet
p	ranking number of non-dominated materials
u	Utopia point

frequently in the metal process industry (high grade waste heat) [6] and food industry (low grade waste heat) [7]. As depicted in Fig. 1, a typical LHTES coupled industrial refrigeration system [8] can charge with excess waste heat from industrial processes, store energy overnight, and discharge it during peak electrical tariff period or for backup application. In the case of middle and low grade industrial waste heat (boiler exhaust, refrigeration condensates, waste steam, air compressors, bearings and lubricants in industrial processes), very limited applications of LHTES have been observed. Future research is required to address this issue.

1.2. Assessment of phase change materials for thermal energy storage

Based on their family groups, PCMs are classified into organic, inorganic, and eutectics [5]. Organic PCMs include paraffin based and non-paraffin PCMs such as fatty acids, sugar alcohol, while inorganic PCMs include salts, salt hydrates and metals. Eutectics are divided into organic-organic, inorganic-inorganic, organic-inorganic combinations, and salt-water solutions. In terms of phase change temperatures, salt-water solutions are found to have sub-zero phase change temperatures, while paraffins, fatty acids and salt hydrates have low phase change temperatures (0–100 °C) and sugar alcohols, salts and metals have higher phase change temperatures (>100 °C) [2,9]. In terms of thermal physical properties, most organics except for sugar alcohols have comparatively lower latent heat of fusion (<200 kJ/kg) than those of inorganics. In most of the cases, their densities are less than 1000 kg/m^3, thermal conductivities lower than 0.4 W/m K, but they show good thermal and chemical stability, non-toxicity with little supercooling. Inorganic PCMs exhibit higher latent heat of fusion, densities and thermal conductivities, but they present potential unstable cyclic behavior such as segregation for salt hydrates [10], and sometimes high toxicity or chemical instability [2]. Salt hydrates also tend to cause corrosion to metal envelops [11].

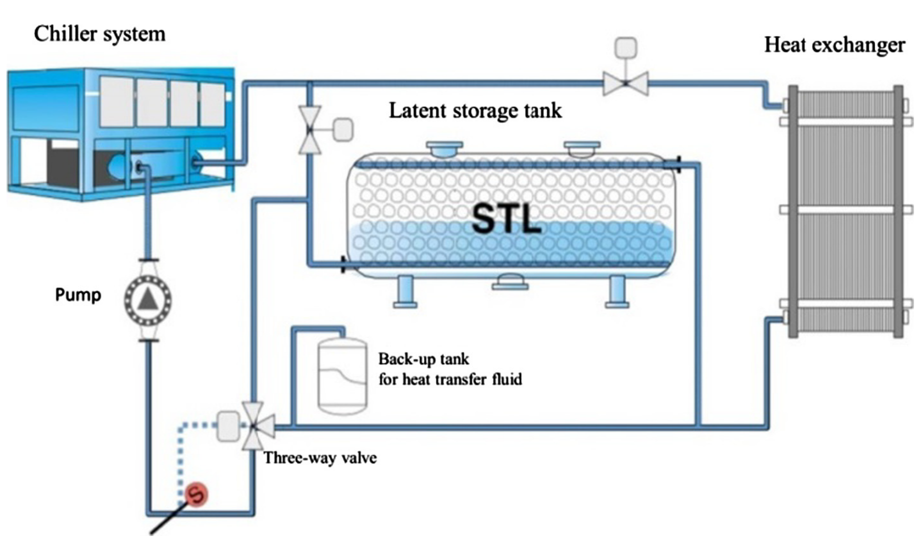

Fig. 1. Schematic view of a typical TES coupled industrial refrigeration system by Cristopia Energy System [8].