PHASE CHANGE THERMAL ENERGY STORAGE – THE EXPERIENCE OF THE MATERIALS PREPARATION FOR THE SPECIFIC APPLICATIONS

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ABSTRACT

Thermal energy storage and temperature stabilization is very important in many engineering applications. There are three kinds of thermal energy storage: sensible heat, latent heat and reversible chemical reaction heat. Phase change materials (PCM) absorb, store and release large amounts of energy in the form of latent heat, at constant temperature, called the transition temperature. Many innovative applications could be found for phase change materials in an increasingly growing field, which is protection of the environment through energy saving, use of renewable energy sources, especially solar, raising the efficiency of equipment and technologies in the industry, construction and transport. Main potential possibilities of using PCM materials are as follows: accumulation heat from the solar collectors and other renewable sources, the accumulation of heat in structural elements of buildings, the food industry. Therefore the applications of the PCM are of promising perspectives, especially in some climate regions. In the present paper, the experience of phase change material use for the specific applications and the results of its thermophysical properties examination are presented.

INTRODUCTION

The applications of PCMs can be divided into two main groups: thermal protection or inertia and storage. These two substantial fields of application are strongly dependent on the thermal conductivity of the substance and the phase transition temperature.

The areas in which PCM are currently applied are listed below: solar thermal energy storage systems, thermal protection of electronic devices, passive cooling of building by heat storage in building fabrics, cooling during off-peak loads to reduce installed power, heating sanitary hot water, using off-peak loads, thermal protection, preservation and transport of food items, encapsulation in textile fabric to maintain human comfort temperature, medical applications in transport of blood at controlled temperature, operating tables etc.

CHARACTERISIC OF PHASE CHANGE MATERIALS (PCM'S)

Use PCMs have the ability to accumulate, store and release heat at a specific temperature. When the ambient temperature rise PCM accumulates and stores heat, and when the ambient temperature drops previously accumulated heat is released [Huang M. J., 2006].

Classification of phase change material

Phase change materials can be divided into three main groups: organic compounds (e.g.: waxes, paraffins, fatty acids, alcohols), inorganic compounds (hydrated salts) and eutectic mixtures. These compounds have different phase change temperature ranges which determines their usability in specified applications [Huang M. J., 2006].

Croperties of pcm's

PCMs belonging to the macromolecular hydrocarbons (paraffins and waxes) may find their application as stabilization temperature of a PV modules, food and buildings construction. This compounds have many good advantages using as phase change materials, such as: high thermal capacity, non-toxic/safety, chemically neutral, reliability, non-corrosive, low price (cost). However, organic phase change materials have also some drawbacks e.g.: low thermal conductivity ~ 0,2W/(m·K), wide range of melting temperatures, pure paraffin waxes are very expensive (technical grade paraffins can be used), low volumetric latent heat storage capacity, flammable [Huang M. J., 2006].

THEORETICAL CONSIDERATIONS

Energy-saving buildings

The heat transmission through a building wall or similar construction can be expressed as the heat flux $\dot{Q}$:

$$d\dot{Q} = U \cdot A \cdot dT \quad (1)$$

where dT is the temperature difference between two sides of wall.

The lower the U – factor, the greater the material's resistance to heat flow and the better is the insulating value. U – value is the inverse of the resistance to heat flow in each layer R:

$$U = \frac{1}{\sum R_i}. \tag{2}$$

Resistance to heat flow of the single R_i layer can be expressed as:

$$R_i = \frac{d_i}{\lambda_i}. \tag{3}$$

If inside the layer in addition to the heat transfer the additional phenomena occurs (e.g. in the case of the air layer – convection), the total thermal resistance of the layer, depending on the thickness of the layer, must be determined by experiment. This value should be included in the equation (2). Thermal resistance for unventilated air layers [(m^{2}K)/W] is listed in EN ISO 6946:2007 [EN ISO 6946:2007 *Building components and building elements. Thermal resistance and thermal transmittance. Calculation method*].

STABILIZED TEMPERATURE PHOTOVOLTAIC MODULE

Solar cells and solar panels work best at certain temperatures, according to their material properties. Many techniques have been tested in order to improve the overall efficiency of photovoltaic panels. The most common were: anti-reflection coatings, radiation concentrators and ventilation. Some researchers have used cooling water as heat transfer material, however, such a solution on the long term proves to be quite expensive and liable to breaks due to leaks in such installations [Radziemska E., 2003]. Promising materials to improve photovoltaic cells efficiency can be phase change materials, which are capable to stabilize photovoltaic cells temperature of PVT system in the range of 25-30°C.

To compare the performance of different solar power modules uniform operating data have been defined as Standard Test Conditions (STC): temperature of the cell: 25°C; Solar Irradiance: 1000 Watts per square meter, air mass AM=1.5. Standard test conditions (STC) occur very rarely. Temperature of the module (cells) can rise much more above STC, causing a power and efficiency drop of crystalline silicon PV module with a coefficient of -0.4 to -0.65 %/K above STC temperature. At normal and lower temperatures, 298 K, silicon is a good material, but at high temperatures, 200°C for instance, silicon efficiency dropped to 5%.

The temperature dependence of the solar-cell open-circuit voltage (V_{oc}) is given by [Carlson D., 1989]:

$$V_{oc}(T) = V_{oc}(T_0) - \left[\frac{E_{g0}}{e} - V_{oc}(T_0)\right]\left[\frac{T}{T_0} - 1\right] - \frac{3kT}{e}\ln\frac{T}{T_0}. \tag{4}$$

During the work of a solar cell, if the temperature rises e.g. by 40 K, in case of $T_0 = 300$ K and $T = 340$ K: $\ln\frac{T}{T_0} \cong 0.125$ and $\frac{3kT}{e}\ln\frac{T}{T_0} \cong 10$ mV can be neglected. Thus, we get from Eq. (4) an approximately linear function:

$$V_{oc}(T) = V_{oc}(300\text{K}) - const\,(T - 300\text{K}). \tag{5}$$

The change of V_{oc} with temperature as calculated from Eq. (4) is:

$$\frac{dV_{oc}}{dT} = -\frac{\frac{E_{g0}}{e} - V_{oc}(T_0)}{T_0} - \frac{3k}{e}. \tag{6}$$

In case of $T_0 = 300$ K, $E_{g0} = 1.21$ eV and $V_{oc}(T_0) = 0.55$ V, typical for a silicon solar cell, we get from (6) the decrease V_{oc} with the increasing temperature of $\frac{dV_{oc}}{dT} = -2.45$ (mV)/K or about –0.4 %/K, measured relative to V_{oc} at 25°C [4]. This value is also in agreement with Green [Green M.A., 1992].

The electrical efficiency η_{el} is given as a function of temperature:

$$\eta_{el} = \eta_0\left[1 - \beta\left(T_{cell} - 298\text{K}\right)\right]. \tag{7}$$

where temperature coefficient of efficiency for silicon cells: $\beta = -4.5 \cdot 10^{-3}$ K [Zondag H.A., 2002], $\beta = -6.6 \cdot 10^{-3}$ K [Radziemska E., 2003] or $\beta = -6.4 \cdot 10^{-3}$ K [Tripanagnostopoulos Y., 2002].

To reduce the temperature of the PV module the layer of proper PCM material about thickness *0.01 [m]* was applied on the rear surface of the module. The heat transferred through the PCM layer should drain the redundant heat from the module.

Using the results of own measurements or published by other researchers, knowing energy value *E [Wh/m^{2}day]*, which should be drain from the module surface, on the base of value of photovoltaic efficiency, we can calculate the sufficient thickness of the PCM material:

$$dQ = \rho_{PCM} \cdot Sdx\left[cp(t_m - t_1) + h + c_p(t_2 - t_m)\right], \tag{8}$$

then:

$$x = \frac{E_{day}(1-\eta)\cdot S}{\rho_{PCM} \cdot S\left[cp(t_m - t_1) + h + c_p(t_2 - t_m)\right]}. \tag{9}$$

Double-wall iceless bottle for cold drinks

Maintaining a suitable temperature of beverages by using phase change materials (PCM) is very important in sunny days, when we want to have cold drink or in winter, when we prefer hotter (warm) beverages.

The bottle with a capacity of 0.5 dm^3 is filled with the cold drink and the aim of the proposed solution is to keep it cool as long as possible. For this purpose the idea of the two-layer wall of the bottle is proposed. The outer layer of the bottle is prepared with the Styrofoam of the thickness d_{St}: 0.002 *[m]* while the inner layer with the PCM material of mass m_{PCM}: 0.468 *[kg]* thickness d_{PCM}: 0.0188 *[m]*.

Assuming that the final temperature should not be higher than t_2, heat flux from the ambient of temperature t_{amb} and the surface area of the wall *A*: 0.0557 m^2 can be described by the following equation:

$$\frac{\rho_{PCM} d_{PCM} \cdot A}{\tau}\left[c_{sol}\left(t_m - t_1\right) + h + c_{liq}\left(t_2 - t_m\right)\right] = \frac{\lambda_{St}}{d_{St}} A\left(t_{amb} - t_1\right) \cdot \quad (10)$$

The equation (10) shows the relationship between the thickness of layers of the used materials and the time to maintain the beverage at a predetermined temperature.

The additional mass of the system should also be taken into account.

EXPERIMENT

Experiment: energy-saving buildings

The heat loss from buildings is made of two components: construction loss occurs by conduction of heat through the various elements of the building construction (walls, windows, roofs, doors); ventilation loss occurs when cold outside air replaces the heated indoor air, by a mixture of designed ventilation and undesigned air infiltration. The present work is dedicated to minimizing the construction losses, especially from the walls and roofs.

Two identical buildings were constructed using standard residential home construction practices. Walls were constructed with OSB plates with fibreglass insulation, siding was finished with gypsum board and plastered. Roof sheathing was covered with roofing felt. These two structures were built on a concrete slab and mounted outside the building (on the special platform constructed on the laboratory roof). Microprocessor DALLAS DS18B20 temperature sensors were fastened in the walls. All sensors, 5 per inside the building and 2 external, placed in surrounding air, have been connected to two 8-channel thermometric digital loggers AVT5330, providing data reading with resolution of 0.1 K and an accuracy of 0.25 K in temperature range of 0-80°C. Thermometric modules were then attached to computer, which allow collecting data and controlling independent heating system for single building. The scheme of the installation was presented in Figure 1. It was decided to maintain constant temperature in each building, and measures its power consumption. In one building walls were prepared to fill with PCM material, while the other building served as a reference. Simulation of such installations in natural working conditions during full year time should confirm the usefulness of the PCM usage for this purpose and indicate possible future modifications in such installations.

Experiment: Double-Wall Iceless Bottle for cold drinks

The space between bottle walls was filled with the phase change material with suitable thermophysical properties and insulated with Styrofoam (Figure 2).

Temperature were recorded with the use of six thermocouples type Dallas AVT 570. In a glass bottle filled with ethyl alcohol two thermocouples were placed, in the space between the glass bottle and the plastic containers have been placed two thermocouples. The remaining two thermocouples were used to measure the ambient temperature.

Measurements were made for the reference sample (system without insulation) and the probe with phase change material layer.

The authors performed two measurements: reference test (without PCM): cooling in the freezer 0.5 liter glass bottle of beverage placed in a plastic container which covered with a layer of polystyrene and experimental test (with PCM): cooling in the freezer 0.5 liter glass bottle of beverage placed in a plastic container filled with PCM material (0.6 l), which covered with a layer of polystyrene. The Double-Wall Bottle with thermal-insulated walls keep the pre-chilled bottle with drink cool for up to 7 hours (Figure 3).

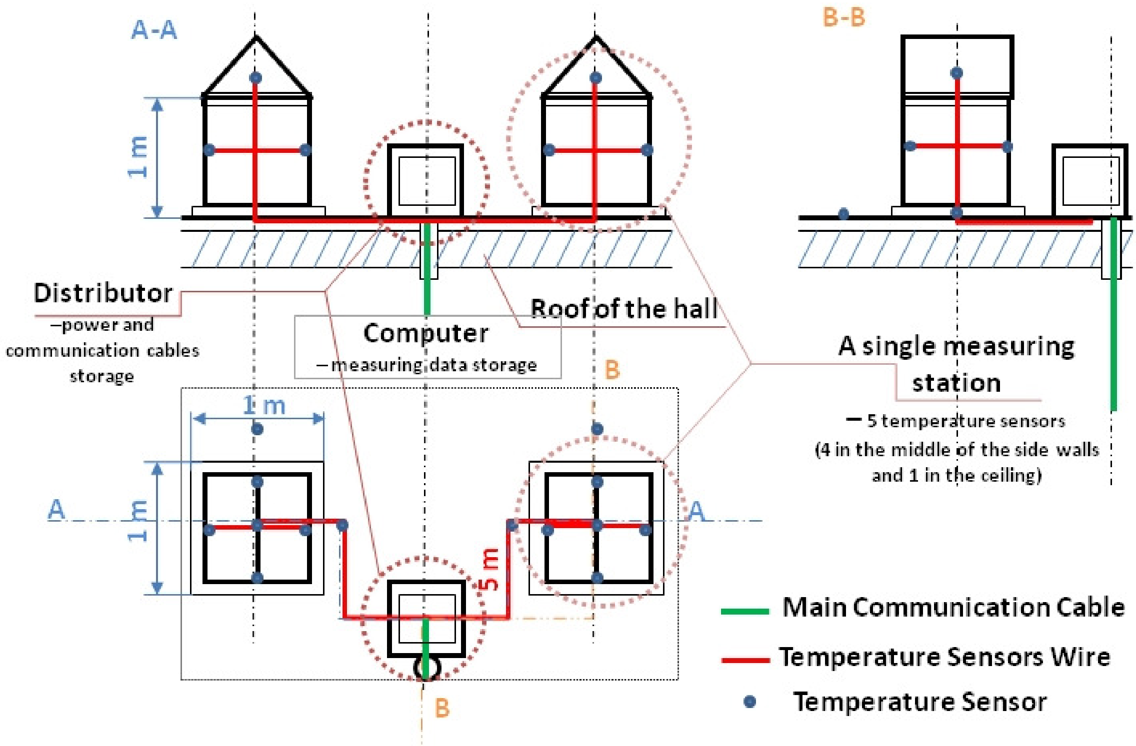

Fig. 1. Scheme studied buildings

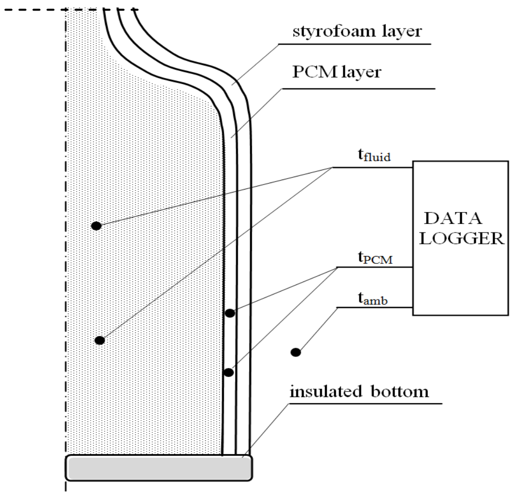

Fig. 2. The construction of tested double-wall bottle

Experiment: Stabilized Temperature Photovoltaic Module

Experimental studies were conducted with the use of PV/PCM system, consisting of crystalline silicon module with the layer of phase change material. The aim of the PCM use is to stabilize the module temperature on the optimal level of 22-23°C. The authors modified photovoltaic modules that was used the test stands. The module was "Solarwatt", type ASE-100-DGL-SM. The module with an area equal 0.75 m^2 consists 72 single cells. This photovoltaic module was modified by applying a single PCM layer of RUBITHERM RT22 material. The experiment was carried out under natural sunlight light with irradiance in the range of 400÷1000 W/m^2 in Gdansk at the beginning of April. The intensity of radiation [W/m^2] was measured by Kipp & Zonen pyranometer SP LITE-2. The authors examined the photovoltaic module without layer of PCMs, and after modification by covering it with a PCM material layer with a thickness of 0.01 m. Schematic view of the experimental stand is shown in the Figure 4.

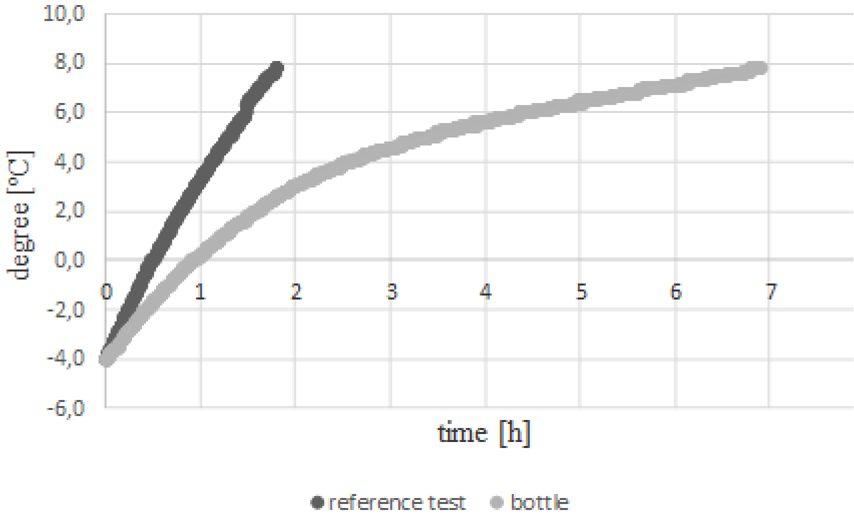

Fig. 3. Graph shows dependence time of the temperature for pre-chilled bottle

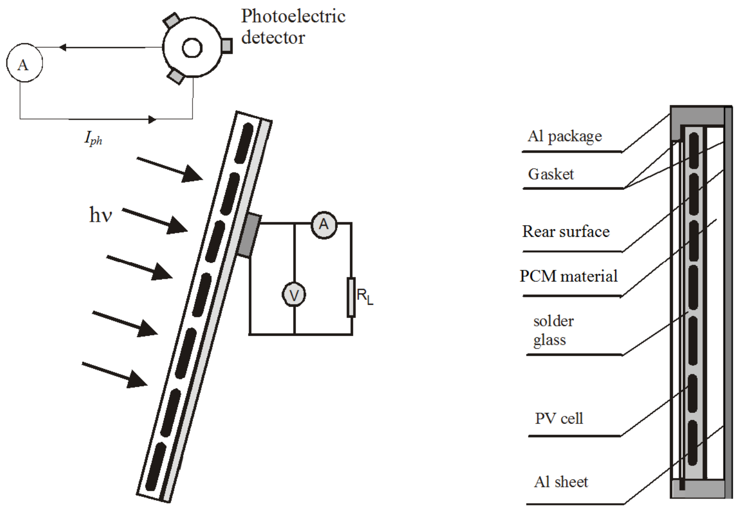

Fig. 4. The construction of tested PV/PCM system

The characteristics of the current-voltage of photovoltaic module modified and unmodified with the PCM layer was measured. Temperature of the modules, measured with the use thermovision camera Fluke type TiR 3.

CONCLUSIONS

The analysis of the graph shows that the bottle without PCM reaches the temperature 8°C during 1 hour and 48 minutes while the bottle with layer of PCM reaches the same temperature during 6 hours and 54 minutes at ambient temperature about 24°C. Use of phase change material allowed for more than three times longer to reach the temperature of 8°C.

Most of the absorbed solar radiation by solar cells not converted to electricity and increases their temperature, reducing their electrical efficiency. The PV temperature can be lowered by heat absorption with a proper phase change material. An interesting alternative to plain PV modules is to use hybrid PV/PCM systems.

It was found out that the temperature of the module (modified and unmodified a layer of PCM material) is nearly the same and it is equal about 55°C – the desired effect of PV module cooling was not achieved. It could be caused by using too thin layer of PCM material or improper selection of PCM material. In the future, authors are going to use thicker layers and other PCM materials, especially mixtures of different paraffin.

The simulation of buildings, with walls filled with PCM, in natural working conditions during full year time will soon confirm the usefulness of this application and indicate possible future modifications for such installations.

NOMENCLATURE

A – the area of the wall, m^2,
c_p – specific heat at constant pressure, kJ/(kg·K),

D – diameter, m,
d – thickness of layer, m,
E – daily irradiation, Wh/m^{2}day,
E_g – band gap, eV,
e – elementary charge, C,
h – enthalpy, kJ/kg,
k – Boltzmann's constant, J/K,
$\dot{Q}$ – heat flux, W, J/s,
R – thermal resistance, Ω,
S – the module area, m^2,
t – temperature, °C,
U – heat transfer coefficient, W/(m^{2}K),
V_{oc} – open-circuit voltage,

Greek symbols

β – silicon efficiency temperature coefficient,
η – efficiency of the module,
λ – thermal conductivity of a material, W/(m·K),
ρ – mass density, kg/m^3,

Subscripts

1 – initial,
2 – final,
amb – ambient,
m – melting,
0 – at temperature of 298 K.

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