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Evaluation of the scraping forces in active latent heat thermal energy storages

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Abstract

Low-cost Phase Change Materials (PCM) usually have a low thermal conductivity. During the discharge process, solidified PCM on the heat transfer surface acts as a thermal insulator, resulting in a reduction of the heat transfer between the PCM and the heat transfer fluid, thus the discharge power is reduced as the PCM solidifies. In active latent heat thermal energy storages (ALHTES), the solidified PCM layer is mechanically removed from the heat transfer surface by a scraper to maximize the heat transfer. In this study, this parasitic mechanical energy is quantified experimentally for the first time to optimize the design of future ALHTES. The required scraping force is measured for decanoic acid and paraffin, resulting in a value between 150 and 350 $N \cdot m^{-1}$ depending on the angle of the scraper.

Keywords: Active Latent Heat Thermal Energy Storage, Phase Change Material, Heat Exchanger, Solidification

1. Introduction

With latent heat thermal energy storages (LHTES), thermal energy can be stored at an almost constant temperature by utilizing the phase change enthalpy released during the liquid to solid transition of a Phase Change Material (PCM) and vice versa. Due to the almost isothermal character, LHTES are mainly utilized in applications where a high thermal energy demand is required at a small temperature range. This includes residential applications due to the limited well-being temperature of humans within buildings [1], but also industrial processes that have an isothermal process, e.g. the evaporation and condensation of a fluid.

A wide range of materials has been characterized to be used as PCM so far. Thereby, all non-metallic PCM for medium to low temperature, namely organic and inorganic non-metallic PCMs, have a low thermal conductivity of usually less than 1 $W \cdot m^{-1} \cdot K^{-1}$ [2,3]. During the discharge process of LHTES, a layer of solid PCM is growing at the heat exchanger wall. Since the phase change enthalpy is released at the boundary of liquid and solid PCM, the heat has to be transferred through the whole solid layer of PCM, which decreases the heat transfer. To overcome this decrease in the heat transfer, several approaches has been investigated in the past, which can be mainly divided into passive and active systems. Passive systems focus either on the increase of the heat transfer surface or in the modification of the PCM to increase the heat transfer. Active systems achieve a significantly high heat transfer by mechanically removing the solid phase of the PCM from the heat transfer area. These active systems can be further divided into four main principles: modification of the PCM to achieve a pumpable slurry after the solidification, transport of macro-encapsulated PCM, direct contact heat exchanger and scraped heat exchangers. Different types of scraped heat exchangers for latent heat storage have been previously studied [4,5]. To the best of our knowledge, the power required for the mechanical scraping of the PCM has not been detailed analysed yet. In this paper, an experimental test rig has been built to systematically analyse and quantify the scraping forces and the required energy to separate two PCMs (decanoic acid and paraffin) from the heat transfer surface of an active heat exchanger.

2. Materials and method

Two PCM were investigated in this study, namely decanoic acid (98 %, supplied by Sigma Aldrich, melting point T_m = 31.5°C) and paraffin (RT44HC, supplied by Rubitherm GmbH, melting area T_m = 41 - 44°C). Both are well known PCMs for low temperature applications. The detailed properties of decanoic acid are summarized in [4], those of paraffin in [5].
To quantify the scraping forces, a linear moving test rig has been designed and built. A schematic drawing of the test rig is shown in Figure 1. In Figure 2, a picture of the real test rig in the lab is shown. Thereby, the molten PCM is placed on a stainless-steel metal sheet. Given that the ambient temperature is below the melting point of both, decanoic acid and the paraffin, the PCMs solidify afterwards on the surface of the metal sheet. The metal sheet is placed on a linear moving unit, driven by a controllable electrical engine by a gear drive. A scraper is placed on the top of the metal sheet, loosely connected by a rotary bearing. The angle of the scraper towards the metal sheet (α) can be adjusted (see Figure 1). A force sensor is placed behind the swing holding the scraper. The metal sheet with the solid PCM is moved towards the scraper. During the scraping process, the swing is pressed onto the force sensor by the scraping forces. The speed of the moving sheet (v) is measured with a wheel speed sensor. The thickness of the PCM layer can be measured with a laser distance sensor. The temperature of the PCM layer shortly before the scraping process is measured with an infrared thermometer.

In this work, the scrapers width is 55 mm and the angle has been set to 15°, 45° and 60° towards the metal sheet. The speed of the moving sheet was set in the range of 0.6 - 0.8 m/s. The temperature of decanoic acid during the scraping test was between 30-31.5 ºC and that of the paraffin between 39-40.5 ºC.

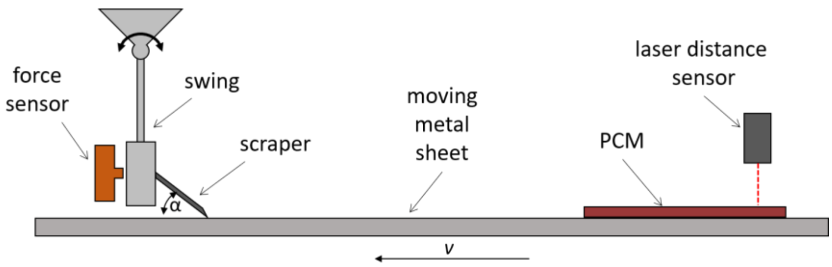

Figure 1: Schematic drawing of the linear moving scraper test rig.


Figure 2: Picture of the linear moving test rig.

3. Results and Discussion

The results of the scraping test are shown in Figure 3. For decanoic acid, the values for the three tests varying the angel to 15°, 45° and 60° are presented. In the case of paraffin, only for the angles of 45º and 60º data are presented. In the tests carried out with an angle of 15º, no measurable values were obtained because the solid layer was scraped off with a force below the lower detection limit of the sensor.

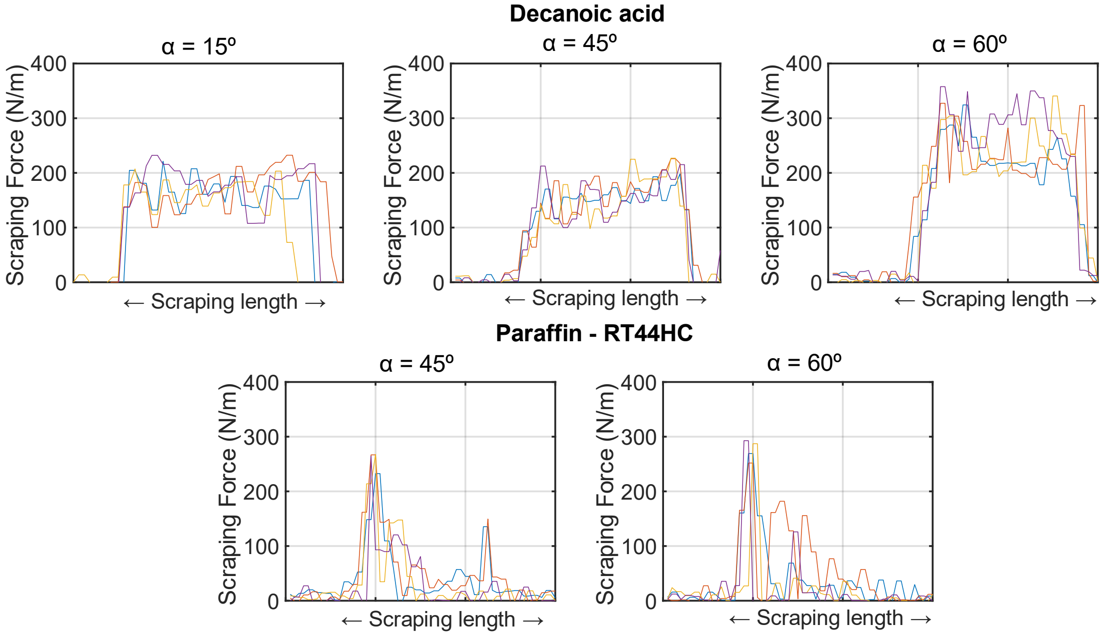

Figure 3: Scraping force of two PCM with different inclinations.

In the tests carried out with the decanoic acid, almost constant values were obtained throughout the entire length of the scrape. In addition, similar values were observed for the 15º and 45º angles, with an average scraping force of about 150 $N{\cdot}m^{-1}$ and an increase of 66% for the 60º angle, obtaining an average force of about 250 $N{\cdot}m^{-1}$. In the tests carried out with paraffin, zones of high force of up to 300 $N{\cdot}m^{-1}$ at the beginning of scraping followed by zones of low force of well below 100 $N{\cdot}m^{-1}$ were observed for the two angles studied. The different behavior can be seen in Figure 4. While decanoic acid peels off as the scraper advances, paraffin peels off in larger portions. The reason for the different behaviour of the two materials when subjected to scraping forces needs to be investigated in detail based on material aspects, which is beyond the scope of this paper.

Finally, the required power *P* for the scraping process in real scraped active latent heat thermal energy storages can be calculated for linear moving scrapers using the force *F* and the velocity *v* by

$$P = F \cdot v \tag{1}$$

and for rotating scrapers via the torque *M*, meaning the distance *r* between the point of application of the force and the point of rotation multiplied by the force *F* and the angular velocity ω *by*

$$M = F \cdot r \tag{2}$$

and

$$P = M \cdot \omega. \tag{3}$$

Figure 4: Picture of scraped PCM. Left: Decanoic acid. Right: Paraffin.

In [5] a latent heat thermal energy storage system based on a rotating drum heat exchanger is investigated, using decanoic acid as PCM. The solidified PCM is scraped off a drum with a diameter of 0.184 m and a length of 0.4 m with each rotation. In the experiments, the rotational speed was up to 25 min^{-1}. Applying an average scraping forces of 200 $N{\cdot}m^{-1}$ to the dimensions of the rotating drum heat exchanger results in a required mechanical energy of 20 W, what is in the same order of magnitude as the values between 44 W and 79 W mentioned in [5]. Thereby, the quoted values have been obtained by comparing independent measurements of the heat transfer and no direct investigation of the required scraping force has been carried out.

4. Conclusion

In this work, the scraping forces required to remove solid PCM from a metal sheet, which is necessary for the optimal design of future ALHTES, were investigated for the first time. Results were presented for two PCMs at different scraping angles. On the one hand, almost constant scraping forces have been obtained for decanoic acid associated with a gradual detachment of the PCM. On the other hand, the forces obtained for paraffin consist of punctual peaks associated with punctual detachment of large portions of PCM. Maximum values of 350 $N{\cdot}m^{-1}$ have been obtained for decanoic acid and 300 $N{\cdot}m^{-1}$ for paraffin, both with the highest inclinations studied.

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