Thermal inspection of water pit heat storages using drones

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Abstract

Water pit heat storages can be used to cover the mismatch between solar thermal generation and heat demand and achieve high solar thermal fractions in district heating systems. The most expensive part of such storages is the floating insulating lid, which is crucial to ensuring high efficiency by minimizing heat losses. So far, two different insulation materials have been used in the lids, namely Nomalén and LECA, both of which are sensitive to moisture. Therefore, it is important that leakages, which existing storages have been prone to develop, are fixed quickly. Manual inspection is costly and inefficient due to the lids' large surface area (>10.000 m2). This study investigates whether thermal drone imaging can identify leakages in pit storage lids by inspecting all existing pit storages in Denmark. The investigations identified leakages in two different pit storages and proved that drone thermal imaging is a very effective tool for leakage detection.

Keywords: drones, thermal imaging, pit thermal energy storage, heat storage, leak detection

1. Introduction

In Denmark, district heating supplies heat to more than 60% of residential consumers (Danish Energy Agency, 2017). The district heating networks utilize heat from various sources, including gas, waste incineration, coal, oil, combined heat power (CHP) plants, and surplus heat from industry. Renewables are also used, including solar thermal, geothermal energy, biomass, and heat pumps powered by renewable electricity (Lund et al., 2014). Although there is an effort to increase the share of renewables, there are many situations where the heat demand and supply do not coincide. This mismatch can happen either due to short-term weather-induced fluctuations or seasonal variations. For example, most solar irradiation in North and Central Europe is received between May and September, whereas two-thirds of the heat demand occurs between October and April.

As a solution to this problem, seasonal heat storages can store heat produced by solar thermal collector fields during summer and deliver it in winter (Mangold and Deschaintre, 2015). The mismatch between consumption and production typically limits district heating systems from achieving solar thermal fractions greater than 20%. However, using seasonal energy storages, solar thermal fractions can be increased up to 50% (Sveinbjörnsson et al., 2017).

One of the cheapest and most promising types of large-scale heat storage technologies is pit thermal energy storages (PTES), which have been demonstrated in combination with large solar collector fields in Denmark (Soerensen and From, 2011). In principle, a PTES is a large water reservoir that is used to store thermal energy. The storage duration depends on the application, ranging from days to months. First, a pit is excavated in the ground and is lined with a watertight polymer (Jensen, 2014). The excavated soil from the pit is used to form embankments around the pit, such that soil does not have to be transported off the site to minimize construction costs. Then, the storage is filled with treated water, which has the advantages of being inexpensive, non-toxic, allows stratification, and has a high thermal capacity (Schmidt et al., 2018). After the pit has been filled with water, it is covered with an insulated floating lid. One of the main advantages of the PTES technology is the low cost compared to other storage technologies and that high charge and discharge rates can be achieved.

The floating lid is the most expensive part of the storage; hence, many investigations have been performed for various designs and materials (Jensen, 2014). Nonetheless, liner ruptures or penetration has occurred in

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numerous situations, causing water to leak into the lid, significantly reducing insulation performance. This leads to increased heat losses and reduces storage efficiency.

From experience, it has been proven that liner ruptures in the lids are difficult to locate due to their large surface area (>10.000 m2). In the past, leakages have been located by manual inspection, which is costly and inefficient. This paper presents experiences from drone thermal imaging of PTES, seeking to provide an effective and cost-efficient alternative to traditional methods.

2. Methods

In this section, the specifications of the PTES in Denmark are first presented, along with the corresponding insulation materials. Next, drone thermal imaging is introduced as a method for inspecting the lids of PTES for leakages due to the large lid areas. A major benefit of drone thermal leakage inspection is speed since the entire PTES lid area can be mapped in approximately 20 minutes. The specific setup used for the drone mapping is discussed in Section 2.3.

2.1. Lid insulation materials

Until 2020, only two different insulation materials have been used for PTES, namely Nomalén and LECA. Nomalén insulation is sold as mats made of cross-linked polyethylene foam (PEX) with a closed-cell structure, while LECA (Light Expanded Clay Aggregate) are small, expanded clay pebbles. However, there have been issues related to the usage of both technologies. Nomalén has in some cases collapsed to a fourth of its original thickness due to exposure to moisture and high temperatures (~90 ºC) for long periods. LECA, on the other side, has a natural tendency to absorb water, and mechanical ventilation is necessary in order to dry out the material. Both of these issues decrease the insulating properties of the insulation material and increase the heat loss of the PTES. In Tab. 1, information about the existing PTES in Denmark is presented, along with the used insulation types.

Tab. 1: Information about PTES in Denmark

Storage	Size (m^3)	Estimated lid area (m^2)	Insulation type	Reference
Dronninglund	60,000	8,300	Nomalén	(PlanEnergi, 2015, 2013)
Marstal	75,000	10,900	Nomalén	(PlanEnergi, 2013)
Toftlund	70,000	11,500	LECA	(Rambøll, 2016)
Gram	125,000	14,500	LECA	(PlanEnergi, 2016)
Vojens	200,000	22,500	LECA	(Rambøll, 2015)

2.2. Thermal imaging

Thermal cameras, also known as infrared or thermographic cameras, create images based on infrared (IR) radiation emitted by objects. They detect wavelengths in the infrared spectrum, typically from 750 to 1350 nm, whereas regular cameras detect visible light in the range of 400 to 700 nm. Therefore, thermal cameras do not directly detect temperature but instead rely on the principle that every object emits infrared radiation. Thermal cameras can detect radiation in the IR part of the spectrum that the human eye cannot see (OPGAL, 2018).

However, the conversion of infrared radiation to temperature can be complex. For example, in most cases, the emissivity of an object must be estimated since it affects the wavelength of the emitted infrared radiation. Emissivity is a surface radiative property, quantified as the ratio of emitted energy from a surface to that of an ideal blackbody surface. The emissivity range is from 0 to 1, corresponding to a perfect mirror and an ideal blackbody, respectively. A surface's emissivity depends primarily on the material and the surface finish, e.g., polished, painted, etc. Water affects emissivity, as wet or even moist surfaces have a different emissivity than dry. The water emissivity is 0.96, which results in damp areas of an object being erroneously detected as having a higher temperature. Surface water can also affect an object's temperature due to the evaporation of the water, reducing the temperature of the object. For obtaining an accurate surface temperature, images should be taken of dry surfaces, and the correct emissivity should be used, which can be adjusted in the settings of most thermal cameras.

2.3. Drone thermal imaging

The drone used for the inspection of PTES is a DJI Matrice 200 equipped with a DJI Zenmuse XT2 640x512 resolution thermal camera. The Zenmuse XT2 is a dual camera that captures a regular image concurrently with the thermal image. The thermal camera has a 13 mm lens that detects radiation in the spectral band 7.5-13.5 µm. Capturing both RGB and thermal images is helpful as it makes it easy to compare the features of the thermal image with that of a regular photo. For example, in the case of pit storage inspection, a thermal image abnormality might be caused by debris, which can be detected in the RGB image, and should not be further investigated.

The thermal investigation of the PTES was carried out during nighttime to avoid reflections from the sun. For this reason, RGB images of the storage were taken before the thermal inspection while it was still daylight. Pictures of the drone used can be seen in Fig. 1. The drone images were taken using the app DJI Pilot. Between 250-700 images were taken and stitched together for each inspection to form a large overall image called an orthomosaic. It was found that the images had to be taken at the height of 60 m for best orthomosaic results and a high level of detail. In order to ensure sharp images, the flight speed has to be set at a low value, depending on the battery capacity of the drone. For the orthomosaics presented in this study, a speed of approximately 2.3 m/s was used.

The stitching of the images was done using either DroneDeploy (commercially available) or OpenDroneMap (open-source). Unfortunately, neither software can generate a colormap for the orthomosaics for indicating the temperature at each spot. However, this is not of major concern, as the images are primarily used to detect differences in the relative temperature between different lid areas.

Fig. 1: DJI Matrice 200 equipped with a Zenmuse XT2 camera flying over the solar collector field in Vojens (left) and close-up photo (right) (Drones Made Easy, n.d.).

3. Results

This section presents the results of the investigations of the PTES using Nomalén, followed by the storages that use LECA as insulation. The presented thermal images are accompanied by a color bar indicating the temperature range on the storage's surface. The large differences between the temperatures of the plots are mainly due to the different ambient and sky temperature at the time of filming; thus, temperatures between plots should not be compared.

3.1. PTES using Nomalén

Nomalén is used as insulation material for the lid in the PTESs in Dronninglund and Marstal. Fig. 2 shows a thermal image and daylight photo of the Dronninglund PTES lid. One of the most noticeable observations in the thermal image is the many warm (yellow color) oval shapes on the lid. When comparing the locations and shapes of these to the RGB image on the left, it can be seen that they are water puddles. They are detected as warmer than the adjacent areas because the emissivity of water is higher than that of the lid surface. The water puddles can therefore not be compared with the surrounding areas; however, the puddles' temperatures can be compared with each other. By comparing the detected temperature of the different water puddles, it was identified that the puddle in the top left corner was warmer than the rest. The puddle temperature in the top left corner was 30.6 °C, while the average temperature of the rest of the puddles was 20 °C. The plant manager was informed about this finding, and the warmer pond was manually inspected. The inspection showed that the liner under the lid was torn in this area, and warm water from the storage was entering the lid. Afterward, the leak was fixed, resulting in a positive impact on the storage performance and lifetime of the insulation. By inspecting the thermal image in Fig. 2, a rectangular grid of thermal bridges can be noticed, corresponding to the gaps between the insulation mats underneath the top liner. The average temperature of the thermal bridges was 18 °C.

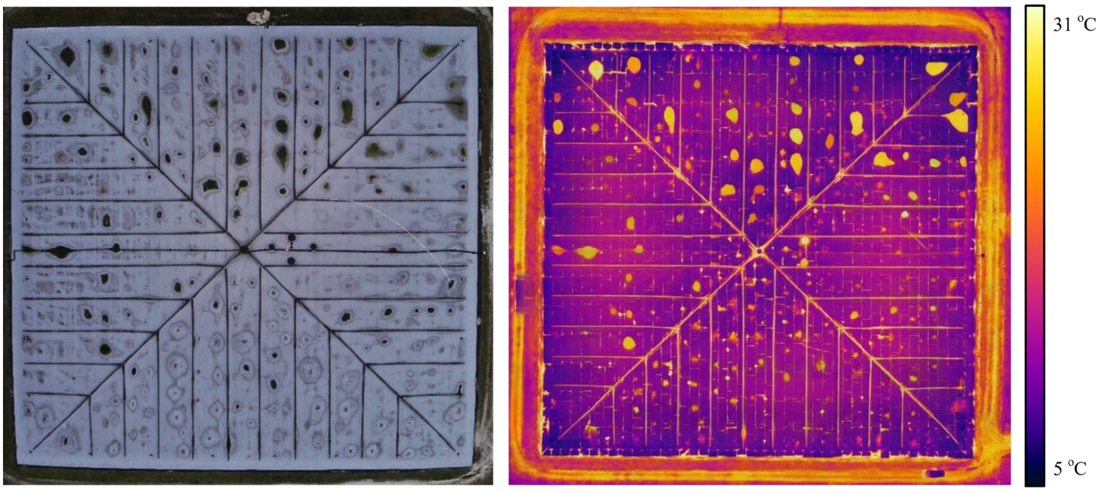

Fig. 2: RGB (left) and thermal (right) image of the PTES in Dronninglund.

In Fig. 3, the thermal and RGB images of the Marstal PTES are presented. As of April 2020, a new lid was installed consisting of twelve square sub-sections. Each sub-section is covered with gravel to ensure a slope towards the center, where a rainwater drainage system is located. Consequently, it is the only inspected PTES with no water ponds on its surface, and thus an easier assessment of the thermal image can be made. The bright yellow dots indicate the pump wells at the center of each sub-section. Additionally, several air vents and the three maintenance holes can be identified in the thermal image. The average temperature of the pump wells, vents, and maintenance holes was 20 °C. No issues were identified during the inspection that took place in October 2020. It can be observed that there was a small problem with the thermal image stitching at the top of the thermal image, though this did not significantly alter the thermal inspection.

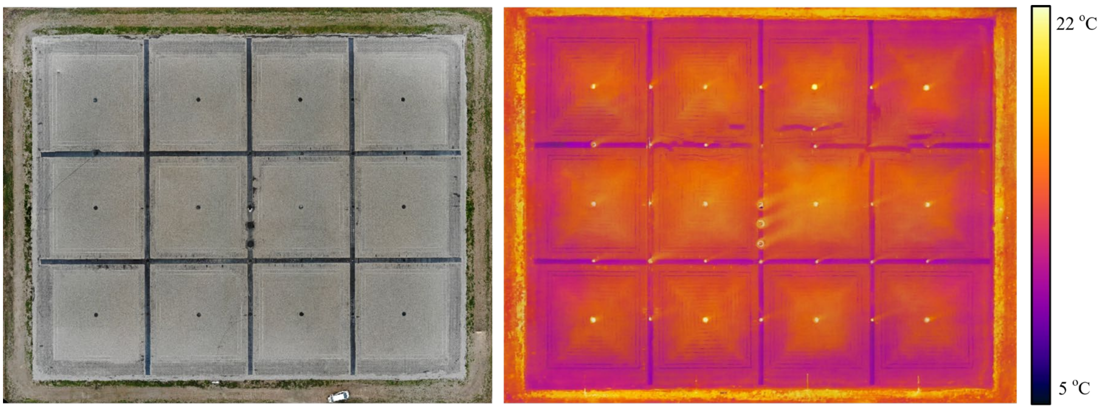

Fig. 3: RGB (left) and thermal (right) image of the PTES in Marstal (October 2020).

A second inspection of the Marstal PTES was done in October 2021, a year after the first one, to verify the performance of the new lid technology. The results can be seen in Fig. 4. Overall, no significant differences were spotted between the two inspections, indicating that the performance of the lid has not degraded significantly during this period. However, a warmer area was detected at the connections of the left-most modules (marked with a white oval in Fig. 4). This is due to the separation of insulation covering the joint between the modules, which is thought to be caused by lid expansion. In general, the temperature of the hot spots where the insulation was separating was between 10 – 12 °C, whereas the temperature of the rest connections was around 8 °C. The separation of the insulation creates a thermal bridge and increases the heat loss of the lid.

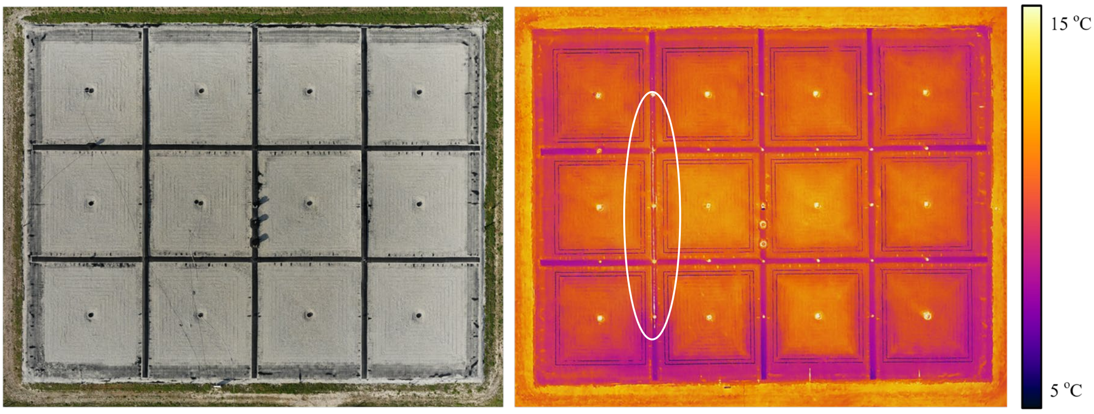

Fig. 4: RGB (left) and thermal (right) image of the PTES in Marstal (October 2021).

3.2. PTES using LECA

LECA is used as insulation material in the lid for the PTESs in Gram, Toftlund, and Vojens. Fig. 5 illustrates the orthomosaic for the PTES in Gram. This image looks vastly different from the PTESs in Dronninglund and Marstal. The reason for this is the different insulation materials used within the PTES lids. The brain-like pattern visible in Fig. 5 is thought to be due to heat convection within the lid. This phenomenon should be minimized as much as possible, as it enhances the thermal losses from the storage. The image clearly illustrates the presence of thermal bridges, which are most likely due to convection. The average temperature of the thermal bridges was 22 °C. It is suggested that smaller clay pebbles should be used in the future, or a convection membrane should be installed. Lastly, in Fig. 5, it was possible to identify a significantly warmer puddle (33 °C) on the lid near the top diffuser, indicating a potential leak.

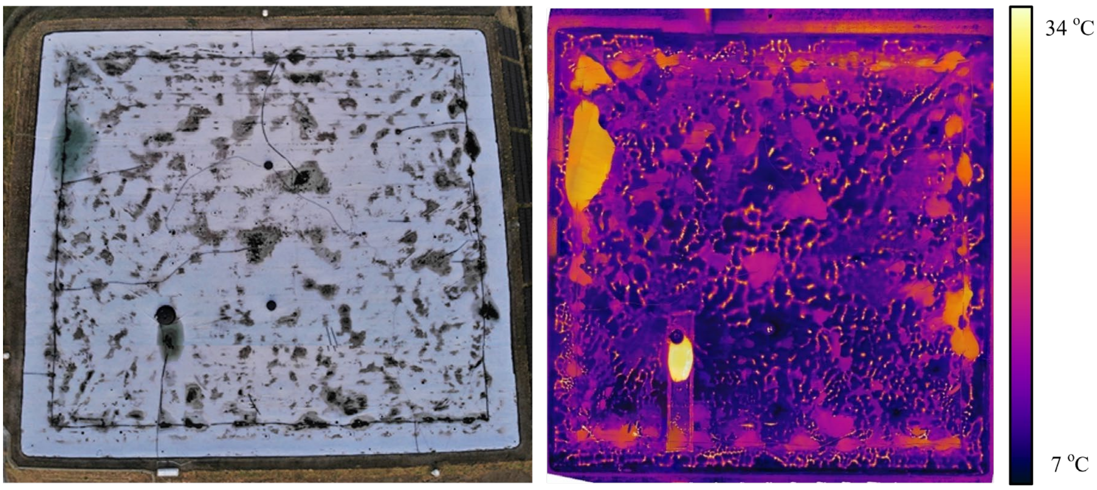

Fig. 5: RGB (left) and thermal (right) image of the PTES in Gram.

In Fig. 6 and Fig. 7, the RGB and thermal images of the PTESs in Toftlund and Vojens are shown, respectively. Similar to Gram, these PTESs use LECA as lid insulation, and thus brain-like patterns due to convection can be observed in the thermal image. However, contrary to Gram, in both PTES, there seem to be areas of the lid where this phenomenon is more intense, indicating that either a thinner layer of LECA exists in these areas or that LECA is wet, resulting in higher heat losses.

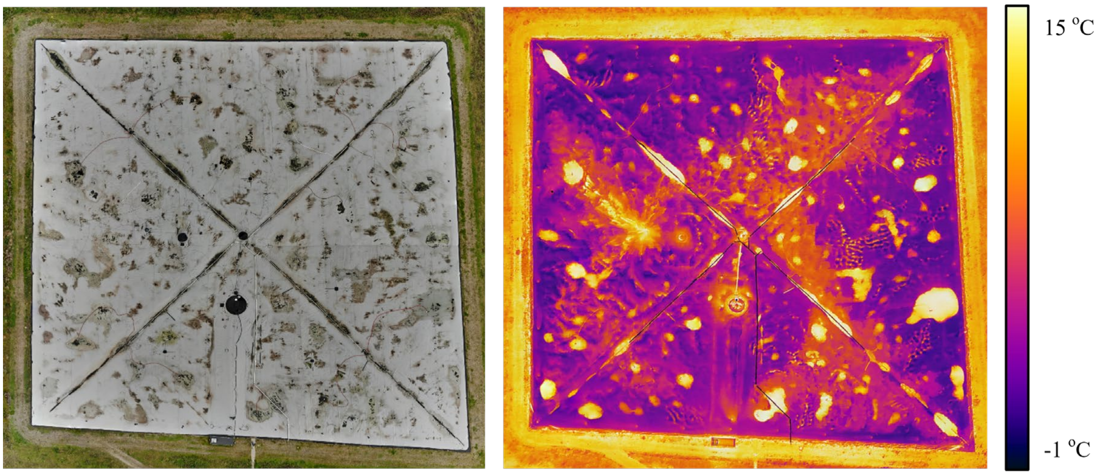

Fig. 6: RGB (left) and thermal (right) image of the PTES in Toftlund.

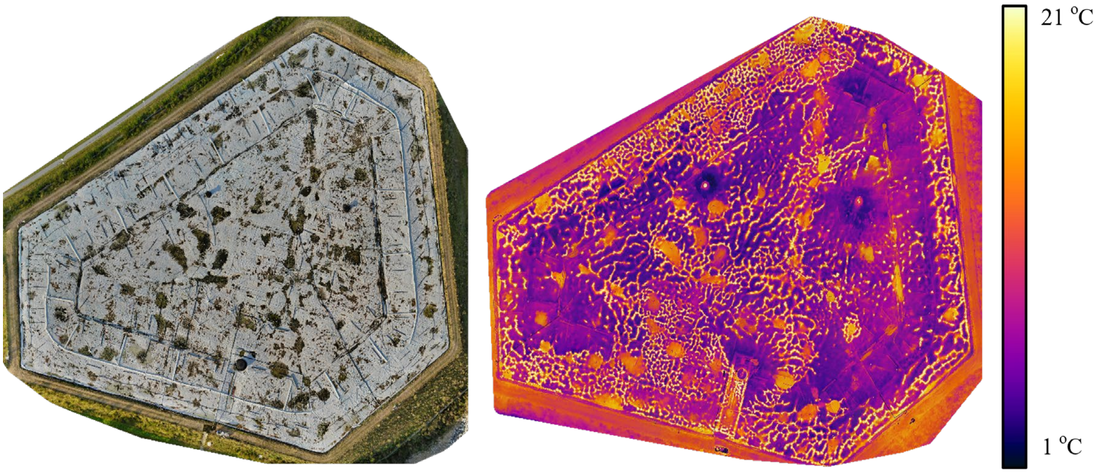

Fig. 7: RGB (left) and thermal (right) image of the PTES in Vojens.

4. Conclusions

This article presents results from thermal inspection of pit thermal energy storages using drone thermal imaging. Two different technologies for lid insulation were investigated, namely Nomalén used in Dronninglund and Marstal, and LECA used in Gram, Toftlund, and Vojens. The results showed that although water ponds on the lid make thermal inspection more difficult, their relative temperature to each other can be used as an indication for leakages. In addition, the thermal images for Nomalén indicate more uniform heat losses than LECA, where brain-like patterns are created due to convection. Lastly, in some pit storages with LECA, areas with very intense brain-like patterns were identified, indicating possibly a thinner layer of LECA or moisture in the insulation. Overall, the performed investigations proved that drone thermal imaging is an effective tool for leakage detection in pit storages.

5. Acknowledgments

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