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Correlation between temperatures of air, heat carrier liquid and seabed sediment in renewable low energy network

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Abstract. The low energy network based on renewable seabed sediment heat has been monitored for several years in Vaasa, Finland. In this study the temperatures of air, heat carrier fluid and seabed sediment are compared to each other and correlations between them are investigated. In this study data from one year 2014, was used. Correlations between these subjects clearly exist. The sizing of installed network seems to be correct; no overuse was detected.

Key words: Renewable energy, heat energy, sediment energy, carbon-free, distributed temperature sensing (DTS) method.

INTRODUCTION

The local renewable energy sources are available everywhere. The harvesting of those sources is going on worldwide in order to mitigate the global warming. The seabed sediment heat is one geothermal heat energy source which has been utilized in Vaasa, Finland since 2008. Actually this heat source is mostly generated by the sun which is common with heat sources near the soil surface. In Finland the impact of seasonal variation in air temperatures is observed to affect even in the depth of 10–15 meters from the soil surface. In Vaasa the seabed sediment heat is delivered to total of 42 households via heat collection pipes and heat pumps. This low energy network has also been used for cooling those houses in the summertime. There have been implemented temperature measurements of air, heat carrier liquid and sediment during 8 years. Mäkiranta et al. (2015) have noticed in their measurements that in the seabed sediment the temperature difference between October and the coldest month stays stable at 8 degrees.

Hiltunen et al. (2015) have investigated the dependency between air temperature and fluid temperature on the area. They observed that the heat carrier liquid achieved its maximum temperature typically after one month of the peak value of the air temperature. In this study the sediment temperature will be compared to the values of fluid and air temperature and the correlation of these three variables is analysed. The aim is to discover if the collection pipeline is sized correctly: if a high correlation between these subjects exists, then a proper interaction is likely.

MATERIALS AND METHODS

The observations of air temperature were acquired from Finnish Meteorological Institute. The heat carrier fluid temperatures were measured by one resident of the sediment heat network. The sediment heat temperatures were measured by the renewable energy research group of University of Vaasa. Temperatures of seabed sediment have been acquired by optical measurement device. The distributed temperature sensing (DTS) method observes the data with the spatial resolution of even 1 m. The optical cable (sensor) is installed along one 300 m long heat collection tube. Temperature data is collected on the shore from the distribution well. The data indicates the sediment temperatures in the 3–4 m depth, starting at the shore and extending to the distance of 300 m in the sea.

DTS method

The temperatures of the seabed sediment are measured by distributed temperature sensing (DTS) method where optical fibre functions as linear sensor. Temperatures can be measured as a continuous profile along the whole fibre not only at some points. In other words temperature measurement is distributed. Fibres can be even several kilometres long and they are typically made from doped quartz glass.

DTS-measurement device emits short optical pulses (laser light), which illuminate the glass core of an optical fibre. Different types of scattering are subjected to optical pulse while it moves along the core of fibre. One type of scattering is Raman scattering which consists of Anti-Stokes and Stokes band. Anti-Stokes band is temperature dependent, while Stokes band is not. The ratio of the Anti-Stokes and Stokes light intensities indicates the local temperature of optical fibre. The speed of optical pulse is used to evaluate the spatial position of the temperature (Ukil et al., 2012).

Measurements on the site

Seabed sediment temperature measurements were made by Oryx DTS device. The patch cord was used to calibrate the device and to secure cleanliness of the channels in the device. The rugged laptop (Fig. 1) acquired the data instantly at the measurement site. One measurement took 10 minutes which means 20 measurements totally by one measurement channel. Temperature changes are relatively slow at the seabed sediment. That is why one measurement session per month was justified and 10 minutes for data acquiring per session was observed to be long enough.

Figure 1. DTS-device was in commission at the low energy network site in Suvilahti.

The original measurement data of seabed sediment temperatures for one year period is shown in Fig. 2.

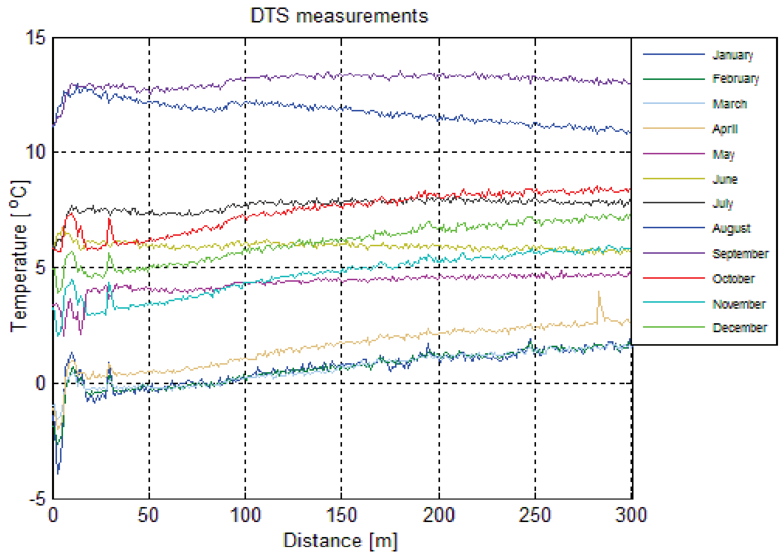


Figure 2. The original data for DTS measurements in year 2014.

Analysing method for data

First, the original data was analysed on the basis of its temperature profile. This provides a very rough estimate about the sediment temperature behaviour.

The next phase is to compare the sediment temperature to the air and heat carrier fluid temperatures. As the air and liquid temperatures are scalar, we have selected temperature data at two different points. A problem is that the temperature data is very noisy due to nature of the measurement itself, environment and other factors. This was solved using moving average-method to smooth the data. The selected window size is nine; i.e. a point value is replaced with an average of values from the point and from four other points before and after the point.

Theory and modelling

Correlations were evaluated between the following data: I air temperature and liquid temperature, II air temperature and sediment temperature and III sediment temperature and liquid temperature. The correlation was calculated using Pearson product-moment correlation coefficient and Spearman's rank correlation coefficient. A short description is provided in this article, as a more comprehensive overview is available in many statistical textbooks (e.g. Sprinthall 2012).

Pearson product-moment correlation coefficient (Pearson r) measures linear correlation or dependence between one subject's temperature data (symbol x) and another subject's temperature data (symbol y). The r –values can be between +1 and -1 where 1 is total positive correlation, -1 total negative correlation and 0 is no correlation.

The Pearson r is defined as

$$r_{x,y} = \frac{cov(x,y)}{\sigma_x \sigma_y} = \frac{E[(x-\mu_x)(y-\mu_y)]}{\sigma_x \sigma_y} \tag{1}$$

where cov indicates covariance, σ is the standard deviation, μ is mean, E is expectation, subindex x indicates the first subject's data, and subindex y indicates the second subject's data. The entire range of each subject's data is assumed to be normally distributed. The temperature values (Celcius degrees here) naturally belong to interval data.

The significance of Pearson r is tested against the null hypothesis: the correlation is due to chance. The significance is assessed using Pearson r table with the degree of freedom (the number of pairs of scores minus 2) (Sprinthall 2012).

Another metric used is Spearman's rank correlation coefficient (Spearman's r_s) which is a nonparametric measure. All temperature data values for each subject are converted into ordinal ranks. For each month, the absolute difference d between temperature ranks is calculated and squared. The Spearman's r_s is calculated using the following formula:

$$r_s = 1 - \frac{6\sum d^2}{N(N^2-1)} \tag{2}$$

where N is the number of pairs. It is used here to evaluate the statistical dependence between temperatures. This metric compares their relationship to a monotonic function. The values are again between +1 and -1.

RESULTS AND DISCUSSION

Correlations between the fluid temperature and sediment temperature as well as the air temperature and sediment temperature are evaluated. The sediment temperature is measured at different distances along the pipe but two different points (distances 150 m and 250 from the shore) are used for correlation calculations. A high correlation is assumed to mean that sizing of the pipeline is done correctly. The appropriate and adequate sizing is vital for improvement of renewable low energy network.

The DTS temperature profile was noticed to change depending on the month. Fig. 3 shows profiles from January to April as well as from October to December. The measured temperatures are lower near the shore than further away in the bay. These months are also the typical months when a heating is needed for the houses in Finland. Also the month November has lower temperature values than month December. This might be due to appearance of ice cover or stratification effect in bay water in December.

Fig. 4 displays the temperature profiles for the warm months from May to September. The temperature profiles exceed their highest temperature at September. The form of temperature profile is different than in Fig. 3 which contains the cold months.

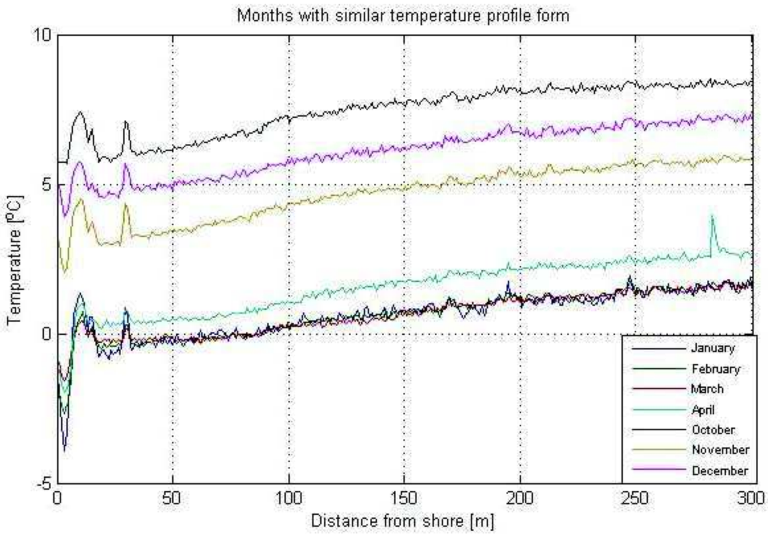


Figure 3. The temperature profiles for seven cold months in year 2014.

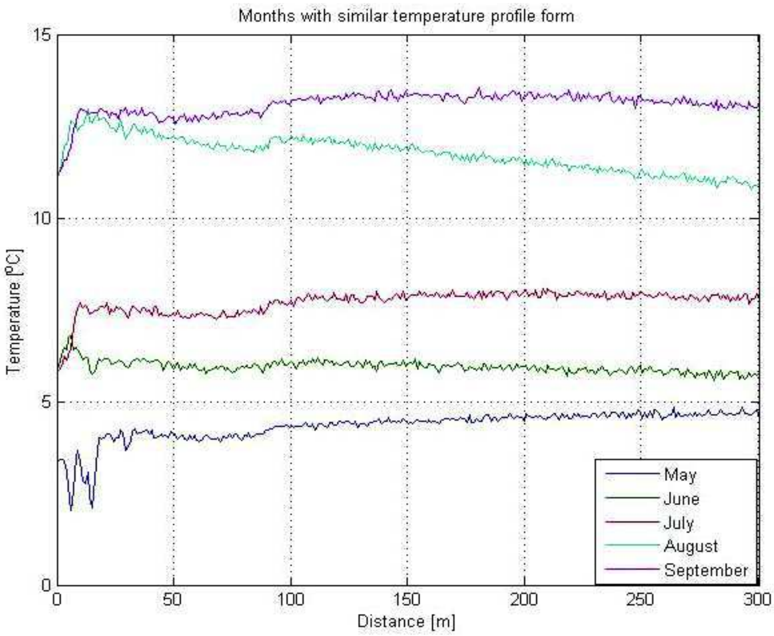


Figure 4. Temperature profiles for 5 warm months in year 2014.

The temperature profiles for year 2014 indicate that the sediment reach the maximum temperature at the late summer as well as there is a minimum temperature limit under which the current usage cannot drive.

The original data was subjected smoothing with a moving average method with window size of nine. The results for smoothing as well as selected points for correlation calculations are shown in Fig. 5. The selected analysing points were taken of the distances of 150 m and 250 m from the shore.

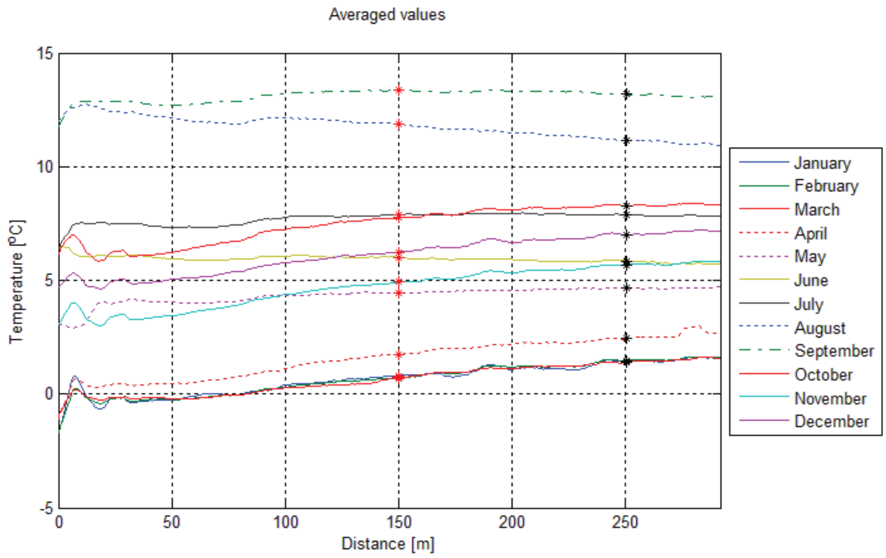


Figure 5. The averaged values are shown for each month. The selected analysing points (150 m and 250 m) are indicated with * marker.

Air, liquid and sediment temperatures were plotted as a function of time in Fig. 6. Naturally, the biggest range appears in the air temperature.

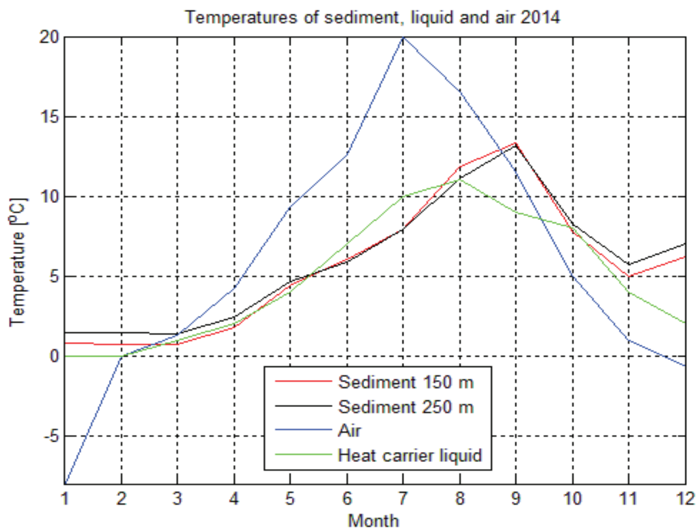


Figure 6. Temperature data from January to December 2014.

During the warmest months (June and July) the heat carrier liquid temperature exceeds the sediment temperatures. This can be understood due to the need for cooling in the houses.

Table 1 shows the correlation coefficient values calculated for different subject pairs. In the first three rows, the correlation between air data and liquid or sediment data is calculated as well as between air data and delayed or advanced liquid or sediment data. As in our earlier paper (Hiltunen et al. 2015), the highest correlation between air and liquid data occurs between liquid data is taken one month later than corresponding air data. There seems to exist also a high correlation between air temperature and temperature of sediment after one or two months.

The last two rows show the correlation between sediment data and liquid data (as well as delayed or advanced data). The correlation is high when the subjects data measured at the same time as well as when the sediment data is compared against previous months liquid data. One could interpret this so that when the liquid heats or cools sediment this affects also sediment temperature at the next months.

Table 1. Correlations

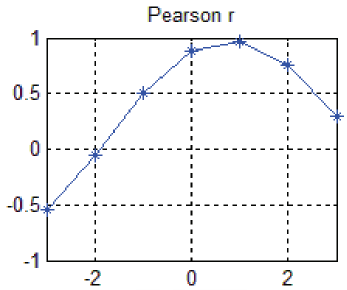
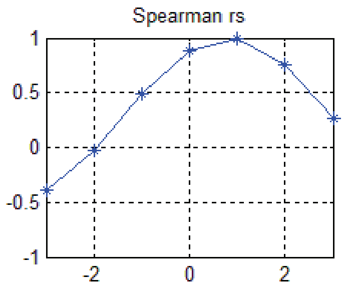
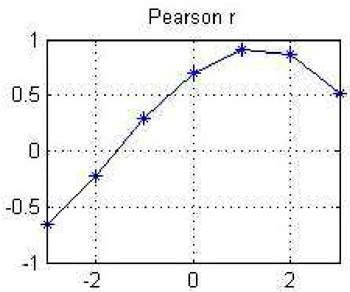
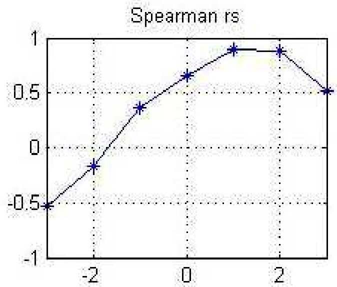
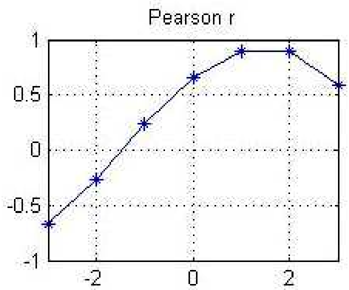
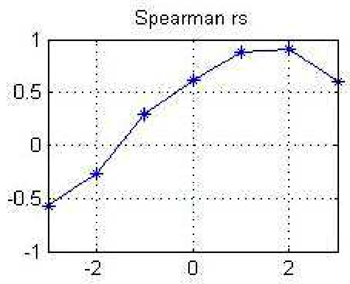
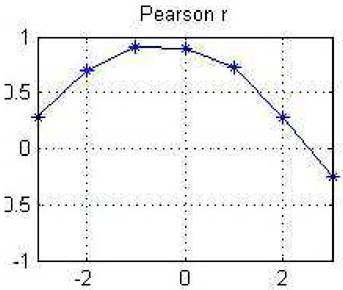
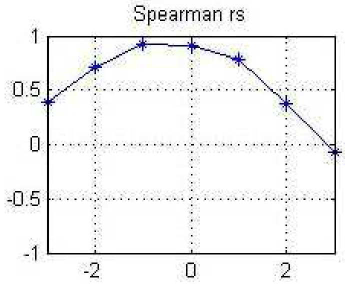
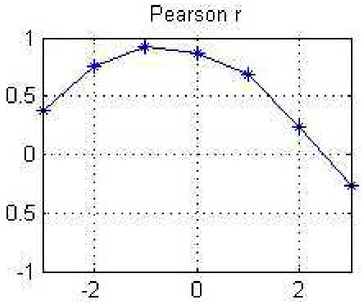
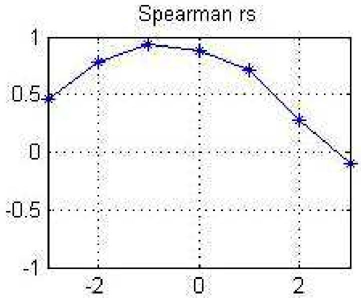
Data	Pearson coefficient	Spearman coefficient
Air temperature and liquid temperature		
Air temperature and sediment temperature 150 m		
Air temperature and sediment temperature 250 m		

Table 1 (continued)

Sediment temperature 150 m and liquid temperature		
Sediment temperature 250 m and liquid temperature		

CONCLUSIONS

There was noticed high correlation between the heat carrier liquid temperature and sediment temperature. Especially, liquid temperature and sediment temperature of next month, as well as, liquid and sediment temperature of the same month are correlating strongly. This may indicate that the low energy system is really working. In winter time the sediment is getting cooler due to the usage for heating. In summer time sediment is warming due the cooling of the houses. Of course there are also other factors that are affecting to the sediment temperatures.

The sediment temperature curve (Fig. 2) seems to rise slightly to the end even in winter time. This might indicate the fact that the sizing of this site`s pipeline is played safe. In other words this network is sized bigger than would have been necessary. This is natural in pilot systems.

The high and significant correlation between air temperature and temperature of sediment after one or two months was also observed. The sediment temperature is indicating the previous weather conditions.

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