THE EXPLORATION OF THE USE OF A HEAT EXCHANGING ASPHALT LAYER AS A PROSUMER IN A LOW TEMPERATURE HEATING GRID

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ABSTRACT

Climate change, limited resources, limited space and increasing energy demand are only a few of the challenges in order to reach a sustainable built environment. These challenges do not end at the boundaries of the building or infrastructure as illustrated by e.g. electric mobility, district heating and recycling of building materials. Next to buildings, also road infrastructure is directly and indirectly responsible for a large demand on natural resources. Asphalt, exposed to solar radiation, can reach temperatures up to 55°C which, for commercial systems, offers potential to harvest a yearly maximum of 0,8 GJ/m² of thermal energy. Heat Exchanging Asphalt Layers (HEAL) is a construction in which tubes are embedded into asphalt with a cold fluid running through in summer conditions and a warm fluid running through in winter conditions. Research has proven that a HEAL system cannot be cost-efficient when compared to modern solar collectors, however, other benefits should be taken into account: space is useable for multiple purposes and lowering the temperature interval inside the asphalt pavement leads to a reduction in rutting during summer and a snow-free pavement during winter, which improves the quality – hence safety – and the service life of the pavement. A prototype (30m²), installed at the site of Campus Groenenborger, is used to validate a Finite Element Model in Comsol, which is developed for structural and thermal analysis. This paper will demonstrate the possibilities to integrate the asphalt collector as a prosumer in a low temperature heating grid.

KEY WORDS: Sustainable heating/cooling technologies, asphalt collector, low temperature heating grid.

1. INTRODUCTION

Current trends of research aim at the reduction of conventional fossil fuel consumption so as to mitigate anthropogenic global warming and thus combat climate change. This necessity encourages the research community to develop more efficient and environmental friendly energy resources.

Every day asphalt road surfaces absorb significant amounts of solar radiation, up to 40 MJ/m² over the course of a day during summer, which causes high temperatures in the pavement structure [1]. This thermal energy can be harvested using a heat exchanging system embedded inside the pavement. The heat exchanger fluid cools down the pavement, thus extracts energy, which could potentially be used for different purposes: production of domestic hot water, building heating or even cooling of buildings via adsorption cycles, de-icing etc. Such a system is often referred to as an asphalt solar collector (ASC). In this research, the use of a heat exchanging asphalt layer (HEAL), as a means to extract low temperature heat from the pavement, is studied in detail. In this paper, a FE model has also been discussed that accurately predicts the energy output of the ASC, as well as its outlet temperature.

The valorisation of low temperature heat of HEAL, and the optimal use of this low temperature heat in useful applications, besides keeping the road ice-free during winter is ongoing. An asphalt solar collector has an annual energy production of 0,5 - 0,8G J/m^2 [2], and reuses about 20% of its own produced and stored heat during winter to stabilise road temperatures [3]. The excess heat produced by the collector is available for other purposes, but due to its low temperature profile difficult to integrate directly in for example a DH (district heating network).

1.1. Feasible test cases

1.1.1. Introduction

The integration of a HEAL-system depends on the performance view of the energy system. The most obvious applications for HEAL-systems are bicycle paths, residential areas, highways and parking lots. All four applications need a different point of view in terms of feasibility and priorities. For bicycle paths it speaks for itself that traffic safety is the most important factor and smart use of space is less important. For parking lots on the other hand, traffic safety is less important, when compared to the importance of smart use of space.

1.1.2. Bicycle paths

In recent decades, environmental and mobility problems, generated by the growing use of cars and massive peri-urbanisation have highlighted the need to develop and encourage more sustainable modes of transport. In addition, an increasingly sedentary lifestyle is expected to take a heavy toll on public health. In urban centres in particular, a shift from car to bicycle could reduce road congestion and traffic related air pollution since cycling has low space requirements and is a non-polluting transport mode.

Safety concerns and the lack of an adequate infrastructure are major hindrances to bicycle use. Thus, making bicycle use safer is one of the most essential elements in initiating a substantial shift from car to bicycle. [4]

1.1.3. Parking lots

The significance of this concept lies in the massive installed base of parking lots and roadways. The significantly high surface area can offset the expected lower efficiency (compared to traditional solar cells) by several orders of magnitude, and hence result in significantly lower cost per unit of power produced. The system uses an existing lot, so does not require purchase or lease of new real estate. The system has no visible signature, which means, the parking lot looks the same. This compares well against rooftop silicon panels that are often bulky and unattractive. The fact that roads and parking lots are resurfaced on a ten to twelve year cycle could be a good selling point for the road energy system. Any time the pavement is replaced, an energy system can be installed.

1.2. Caveats

Next to different advantages, there are also risks involved in the use of HEAL-systems.

- Integration of HEAL-systems on a large scale, needs to be looked into case by case;
- In case of damage to the system, the repair costs of the road will be higher than for a standard road;
- Correct installation by highly trained personnel.
- Real ecologic benefits should be calculated by LCA and LCC;
- Uncertainty of energy prices in the future makes it hard to calculate the payback period.

These kind of uncertainties make the HEAL-system a risky investment at this moment. However, at the University of Antwerp, these factors are evaluated in order to incorporate and optimize HEAL-systems in the most efficient way for large scale use into road infrastructure in the future.

2. THERMAL ANALYSIS OF HEAL

2.1. Set-up

Since there are many variables that need to be taken into account when designing a HEAL-system, research is being done on three different levels. First of all, a large scale prototype is installed at the site of the University of Antwerp. Secondly, a Finite Element Model (FEM) will be valorised with the support of actual data from the prototype. Finally, in order to fine tune the FEM, small scale lab tests are put up.

2.2. Prototype

The large scale prototype of proposed dimensions (approx. 30m² (8,5mx3,5m)) is designed including all necessary technical installations and sensors. Next to the HEAL system, a reference section is constructed with the same structure. The prototype consists of four circuits of pipes, each with a total length of approx. 50m. These circuits can be connected in "every possible way". Besides this, a bore hole with a depth of approximately 100m has to be constructed to store the extracted energy from HEAL during summer and winter. From the bore hole, water passes through a heat pump into the asphalt. Adjustable taps regulate the flow through the pipes and a weather station saves data of the most important weather parameters. At different depths inside the asphalt, thermocouples are installed in order to generate data for the FEM. Continuous monitoring of temperature, as well as the weather parameters result as input to validate the thermal finite element model. For this prototype, different variables are adjustable in view of research, namely the length of the pipes, the inlet temperature of the water and the flow of the water. The most important variables that are not adjustable for this prototype are depth, diameter and material of the pipes and also the composition of the asphalt (as a heat exchanger).

2.3. Finite Element Model

This research aims to develop a modelling framework for the HEAL system using COMSOL Multiphysics software and validate it with a self-instructed laboratory experiment. Such a model allows for a detailed parametric study of the system and to optimize the design on the performance of the system. A long-term energy output of the system, which is currently lacking, is calculated based on results of a study on weather parameters.

In this study, the entire HEAL-system is modelled in 3D using finite element techniques. In this model, HEAL is simulated using the heat transfer in solids module and CFD2 module in the COMSOL Multiphysics software. The governing equations are time-dependent continuity, Navier Stokes and heat equations. Development of flow is important which makes CFD a necessity[5]. Even though the CFD module is used in 3D geometry, certain assumptions and simplifications regarding the fluid flow (laminar flow) through the heat exchanger are made to reduce the computation time. The input data are thickness of the layers, material properties and effective evolutions of climatic parameters (Antwerp 2013 weather data, Belgium). These parameters are latitude, month and day, maximum and minimum air temperatures, day average atmospheric transmissivity, day average wind velocity, day average relative humidity. These six parameters are used to calculate the following variables during the simulation of the HEAL: incident solar radiation, the dry-bulb air temperature, the hypothetical sky temperature, the heat transfer coefficient regarding convection. These calculated variables are required in the boundary condition equation at the surface of the HEAL. These variables are determined using the functions in the FE model, which are simply linked to the FEM of the HEAL via the interpolation functions in COMSOL. The outputs are the profiles of temperature fields along the depth of the slab and its soil sub-base. Some evolutions are computed at particular depths corresponding to sensors positions, in order to be compared with the measured values.

With such simulations, a FE model with pipe length of 50m length is developed, which makes it easier to calculate an estimate how much energy can be harvested from the pavement. For a total pipe length of 200m (30m² HEAL) a total work/m² of about 79 kWh/m²·year is determined from COMSOL Multiphysics. This is an average amount over the course of a typical average year. The model can, therefore, be used to evaluate possible benefits of the system on pavement life and to help analyse the use of the generated thermal energy.

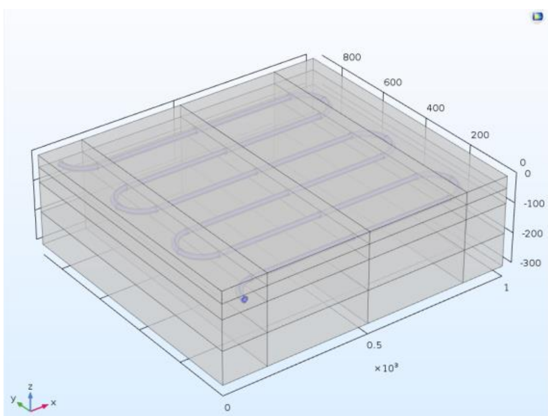

Figure 1: Elaborate FE Model of HEAL.

2.4. Lab testing

The moment the FEM is valorised with the prototype, small scale lab tests are used in order to fine tune the HEAL-system. Variables that are not adjustable for the prototype can be adjusted in small scale slabs. It is important to keep in mind that the application of HEAL-systems is very case depended. In combination with the FEM, small scale lab tests can be used both for thermal and structural analysis of feasible test cases (also see 5. Feasible Test Cases).

3. INTEGRATION IN A DISTRICT HEATING SYSTEM

3.1. Asphalt solar collector heat profile

To get an idea about the heat potential of HEAL, a heat profile as shown in figure 2 is generated based on a FEM analysis with same 'as built' properties as at our campus test facility, a tube length of 50m and the local (Antwerp, Belgium) weather of 2013. The plot shows the difference between in and outgoing water temperature in function of a hourly frequency over the summer period. A temperature difference of 4°C is set as the minimum. Main temperature difference between in and outgoing water temperature in function of the frequency is found to be 8°C. Approximately 430 hours have a higher potential than 8°C during that year. Although the low difference in temperature, it is important to point out that only 50m was simulated. Higher water temperature differences are easily feasible by extending the tube length.

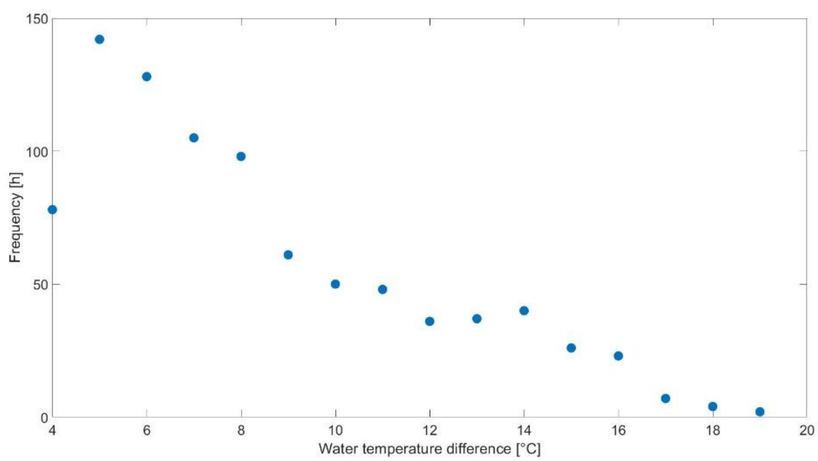

Figure 2: Heat Profile of ASC for 50m Pipe Length.

3.2. Integration into a district heating network

To fulfil the European climate objectives (20% renewable energy, 20% more energy efficiency, 20% greenhouse gas reduction by 2020 etc.) [6], multiple European countries started to introduce smart, decentralised energy grids as a partial solution. 'Heat roadmap Europe' [7] shows that with district heating, the EU energy system will be able to achieve the same reduction on primary energy supply and carbon dioxide emissions as the existing alternatives studied, but at a lower fulfilment cost. Additionally, a cost reduction of 15% on heating and cooling is estimated. The past few years, multiple studies [8], [9], [10] showed that the most energy efficient way of transporting heat using district heating is by a ULTDH (ultra-low temperature district heating network), due to grid losses, with a typical supply temperature between 35°C and 50°C. By lowering the water temperature, various difficulties have arisen such as the control of legionella and inadequate capacity of heat exchange devices in buildings. However, besides the reduction on grid losses, lowering the temperature creates the ability to integrate renewable energy sources such as solar and geothermal heat. The integration of solar thermal systems in DH systems is a growing common practice in some countries. The general idea behind including solar collector fields in DH networks is to lower or completely supply the low heat demand of a DH network during the summer months. Previous studies have shown that a high solar fraction in solar district heating is feasible only by introducing a large scale seasonal storage into the system [11]. Brange et al. [12] proposed a case study in Sweden to evaluate the potential of small scale prosumers contributing in a district heating network based on the excess heat. The paper focused on heat from large scale cooling machines/compressor chillers, used for district cooling purpose, available at a temperature of 30°C. Five different cases were analysed whereby combinations were made with varying factors such as additional electrical units added to supply DHW and the possibility to deliver heat to neighbourhood networks. In the subcases were no electrical DHW supply was assumed, the heat was raised to a supply temperature of 65°C by a not specified type of heat pump before injected into the heat network. Although the paper, not surprisingly, concluded that the cases with a district temperature of 30°C are not realistic due to non-adapted buildings and network architecture, less difference is found between the prosumer cases with electric DHW heating and the cases with heat pump temperature rise. The overall potential of excess heat in the case was estimated to be 50% to 120% of the total annual heat demand. Project ‘Open district heating’ [12], [13] is an example of an ongoing project, based on the prosumer concept, where excess heat from super markets and buildings with high cooling demand is sold to DH companies at market price. Within the project, prosumers excess heat is often raised with a heat pump before heat is injected in the network. Besides the effect that a ‘proof of concept’ was realized, the project shows that it can be an economically viable option for both prosumers and the DH company to use excess energy at low temperature. Winterscheid et al. [11] performed a simple but detailed methodology to integrate solar heating systems into a district heating network with existing heat suppliers. Overall, the paper concluded that the integration of solar collectors in DH networks is, besides more environmental friendly, most beneficial when the produced heat can be used to react on electricity price fluctuations when the main heat supplier is an CHP unit.

About 80% of the produced heat by an ASC is available for other purpose than stabilizing the road temperature during winter[3]. Although asphalt can reach temperatures up to 55°C, the FEM model previously discussed, shows that the outlet water temperature will not be higher than 28°C when using 200m pipe length. The direct integrating of an ASC into an ultra-low district heating network is for that reason not possible. Often, a heat pump or sun heating collector as an intermediate unit is proposed to raise the water temperature and create the possibility to provide a basic for domestic hot water during summer in districts were for example no residual heat is available and large thermal solar systems are impossible due to the available roof space etc. To date, multiple small scale projects such as ‘Road energy systems’ [14], ‘Zonnige kempen’ [3] or ‘Serso’ [15] are successfully installed. Road energy systems used a combination of a borehole storage system and a heat pump to provide local space cooling and heating during summer and winter, while Serso stored heat into a rock during summer to keep the roads ice-free. At the best of our knowledge, no research is being done on the use of an ASC into a district heating network. Future research can focus on integration of ASC into DH networks, fast mathematical models to simulate dynamic hydronic behaviour and the potential of electrical peak shaving in DH networks when combining storage systems and a CHP, based on an economic predictive control.

4. DIFFERENT VIEWS ON THE PERFORMANCE OF THE ENERGY SYSTEM

4.1. Increasing sustainability of asphalt pavement

There are different ways to increase the sustainability of asphalt pavement, e.g. increasing durability of the asphalt mixture itself or to decrease external negative environmental effects during the use phase of the pavement. In order to prolong the use phase of the asphalt (service life), it is important to minimize the damage patterns inside the asphalt. Integrating a HEAL-system into the road counters three different damage patterns: rutting, cracking and ravelling. During summer, the asphalt will be kept cooler, which decreases the effect of rutting. During winter, the temperature of the asphalt is increased above freezing point in order to avoid brittleness of the bitumen. Also, winter maintenance done by the use of salt or brine has two major drawbacks. Firstly, it reduces the life span of the road, since it causes the snow on the top layer to melt, which will cause premature crack formation when refreezing. Secondly, it has a severe environmental impact on groundwater quality and in turn vegetation. This way of installing HEAL, ravelling and cracking are minimized.

4.2. Increasing traffic safety

Improving traffic safety with a HEAL-system can be demonstrated as:

- Snow- and ice free roads during winter;
- Minimization of damage patterns such as rutting throughout the year, avoiding aquaplaning.

Improvement of these road conditions leads to safer roads, which automatically lowers the amount of accidents on that road. It is expected that the integration of HEAL-systems into bicycle paths will lead to a more frequent use of these bicycle paths and thus a lowering in the use of cars.

4.3. Smart use of space

At this moment, standard road infrastructure is only used for mobility purposes. The total length of road infrastructure will only increase in the future and this used space could so far not be used for other purposes. However, by integrating a HEAL-system into the road, the road infrastructure is also used for energy gaining purposes. This means that part of the space that otherwise would be used for energy gaining purposes, can now be used for other purposes, such as residential areas, public areas, etc.

5. CONCLUSION

An effective heat exchanger design will be the key in extracting maximum heat from the pavement. In this paper, a modelling framework is discussed using finite element method to predict the thermal behaviour of HEAL. The developed FE model will be validated by comparing the workings of an experimental prototype and FE temperature results. Finally the most promising design of HEAL is evaluated by analysing the system on how the efficiency of the system can be improved by changing the design of HEAL. Although few uncertainties discussed make the HEAL-system a risky investment at this moment.

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