DESIGN TOOL FOR THE THERMAL ENERGY POTENTIAL OF ASPHALT PAVEMENTS

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ABSTRACT

This paper describes the development of a design tool for the calculation of the thermal energy potential of a so-called asphalt collector. Two types of numerical models have been developed and validated against experimental results from a full-scale test-site.

The validation showed to be a tedious procedure due to the complexity of the full-scale testing of this type of systems. Nevertheless, the models are found to be applicable for performing design studies with.

Example results presented in the paper indicate that the thermal energy potential of an asphalt collector is lower than that of a normal solar hot water system. The quality of the energy is also less. However, further advantages of the use of an asphalt collector are found in the reduced maintenance of the road and the avoidance of slippery roads in winter time. The latter is also an example of the heat exchanger capabilities of the asphalt collector.

INTRODUCTION

Asphalt pavements have gained attention in recent years as an interesting new renewable energy source. As asphalt pavements can heat up to 70 degrees Celsius during solar irradiation, a comparison with solar hot water systems seems obvious. Given the enormous area of asphalt pavement that is available the thermal energy potential therefore appears infinite. This heat can be applied in several ways. Generally the energy will have to be stored over seasons. For example in an aquifer.

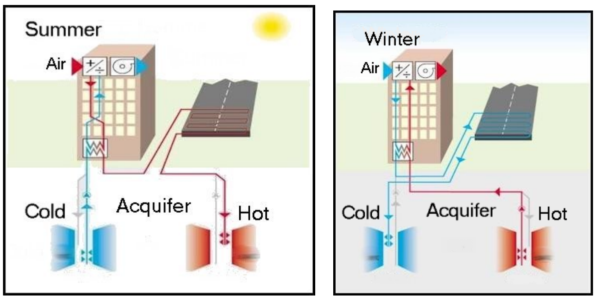
Over the last years, several designs have been developed to extract heat from an asphalt pavement. Most available solutions apply a heat exchanger design by incorporating tubes in the asphalt pavement. This type of asphalt pavement in the Netherlands now is known as ´asphalt collector´.

Besides the energy potential, the advantage of the use of an asphalt collector is also found in the maintenance of a road. In summer time the maximum temperature of the asphalt pavement can be damped so that the chance of formation of ruts is reduced. In winter time, it is possible to avoid slippery roads by damping the minimum pavement temperature.

Though these additional advantages of the use of an asphalt collector are obvious, interest in such a collector is mainly focussed on the energy potential and the application of this energy in the built environment. In terms of cost-effectiveness, this aspect of the application of the asphalt collector is most important.

To clarify the application of the asphalt collector in the built environment Figure 1 presents an example of the use of the asphalt collector as part of a larger energy system. In this figure the demand side is presented by the building, the energy supply is presented by the asphalt pavement. Through the use of an aquifer, the difference in timing between supply and demand is covered to a large extent. Figure 1 shows that the presented set-up is also able to adhere to the other advantages of an asphalt collector.

Figure 1. Example of the application of an asphalt



collector in a larger system in summer condition and winter condition.

The first question however is what the thermal energy potential of an asphalt collector will be and what parameters are critical in this respect. The second question relates to the efficiency of the collector in the total energy system as shown in Figure 1. In the project described in this paper focus was put on the first question in order to verify the potential of the asphalt collector and its critical parameters.

The paper first will deal with the theoretical background of the problem and the development of two simulation models. For validation purposes and practical experience (also with the laying process) a test-site with an asphalt collector was built. Some measurement results from this test-site are shown and discussed. Next, the validation of the models is dealt with. Finally, some design data are shown that are derived from the developed design tool. The results from this tool may be used to integrate with the total (thermal) energy balance of a building or a building complex.

THEORY

Figure 2 presents the principle of the asphalt collector and the accompanying heat transport. Generally an asphalt pavement (from top to bottom) consists of a layer of dense or porous asphalt concrete, a layer with a specific type of asphalt in which the heat exchanger is enclosed, base asphalt layers and the soil. Between the different layers also some thin adhesive layers are present, but these layers may be neglected with respect to the heat transfer. The soil can consist of different layers, depending on the history of the soil. The moisture content can also differ in the different layers of the soil. This will affect the heat transfer characteristics of these layers.

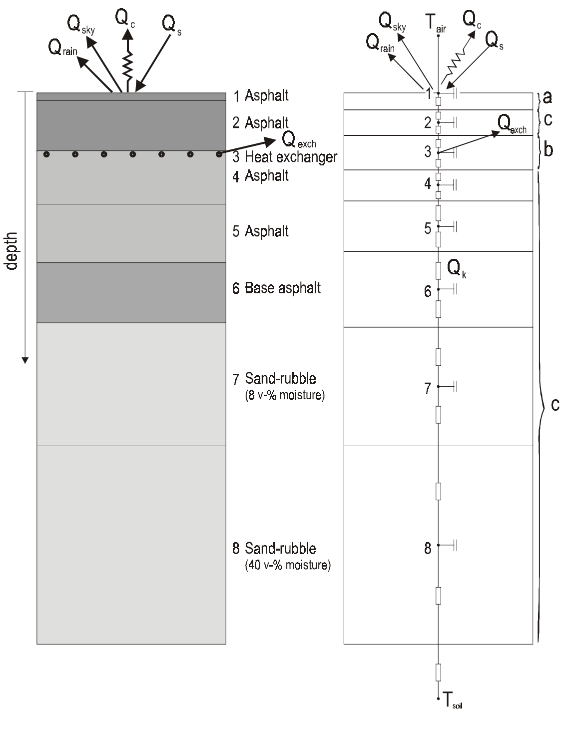


Figure 2. Schematic representation of the design of an asphalt collector and the derived network model.

In order to model the unsteady heat transport in the asphalt collector a network model can be used. These type of models normally are applied to model relative simple heat transfer problems. Figure 2 presents an example of a one-dimensional network model. By coupling several one-dimensional networks a more dimensional network can be derived.

The schematic asphalt collector is divided in three different type of layers:

a) The layer that borders the air.
b) The layer from which heat is extracted through heat transfer via the tubes.
c) The remaining layers that make the asphalt pavement.

For all layers the heat balance is solved. This results in the following equations for an unsteady situation:

Layer a: $$\rho c V \frac{dT}{dt} = Q_s + Q_{sky} + Q_c + Q_k \quad (1)$$

Layer b: $$\rho c V \frac{dT}{dt} = Q_k + Q_{exch} \quad (2)$$

Layer c: $$\rho c V \frac{dT}{dt} = Q_k \quad (3)$$

Each heat source is treated separately. Most of these sources are relative straightforward. Nevertheless, all sources contain parameters that relate directly to the asphalt pavement and/or the applied heat exchanger.

For the solar energy source (Q_s) the absorption coefficient is most important. For (clean) asphalt this coefficient is relatively high (α_s = 0.88 … 0.93 (de Bondt and Steenvoorden 1995)). A different colour/ age of the asphalt pavement influences this value.

For radiation loss to the sky (Q_{sky}) the view factor, the mean temperature of the surrounding obstructions and the sky temperature are most important. The latter is calculated according to Kondratiev (Bergmeijer and Oversloot 1989) and includes, amongst others, the degree of cloudiness.

For the convective heat loss (Q_c) to the environment the convective heat transfer coefficient (h_c) is most important. This coefficient contains a free and forced part. For the forced part, the local wind velocity is of importance. The velocity generally is derived from wind velocity data at a nearby weather station by correcting this data with a wind reduction factor (wrf).

For the conduction heat transfer (Q_k) the heat conduction (k) of the asphalt layers is of importance.

For the heat transfer to the heat exchanger (Q_{exch}) its total heat transfer coefficient (U_{exch}) is of importance.

This coefficient comprises the internal heat transfer to the fluid that flows through the tubes, the heat transfer through the tube material and the external heat transfer to the surrounding asphalt material. For the internal heat transfer the Reynolds and Prandtl number of the fluid flow are of importance (Holman 1997). For the external heat transfer the contact surface ratio (A_c) and the average size of the air bubbles around the tube (L_g) are important parameters.

In the equations (1 to 3) two other heat sources have not been taken into account, i.e. the heat loss due to the influence of rain and due to movement of the groundwater. The first one affects the top layer of the asphalt pavement, the second the temperature built up in the soil. Too little information was available to include these sources in the current work and it was expected to be of second order importance. Both sources nevertheless can be implemented in a network model.

MODELLING

To calculate the energy potential of an asphalt collector, applying the above described network model, a one-dimensional model of the asphalt collector was developed in the Matlab-environment (Mathworks 1998). In order to investigate the effect of the distance and the position of the tubes also a more-dimensional model was developed within a Fortran environment (Lahey 1995). For the latter, use was made of an earlier developed and validated model (Wijsman and den Ouden 1980).

The heat transfer characteristics visualised in Figure 2 and described in Equations 1 to 3 have been included in both models. The main difference between the two models was the procedure through which the heat exchanger was included.

For the one-dimensional model the heat exchanger eventually was modelled on a theoretical base as there was only a very limited amount of measurement data available to verify the relation between the heat transfer coefficient of the heat exchanger and its output temperature. A separate one-dimensional network model was built to calculate the average heat exchanger flow temperature and energy gain as a function of the heat transfer coefficient of the heat exchanger, the asphalt temperature and the supply flow temperature. The thus derived look-up tables were used in the one-dimensional model of the asphalt collector. Through interpolation intermediate values in the look-up table could be derived. This model therefore was indicated as a 1½-D model.

The main drawback of the 1½-D model is that the mutual influence of the position of the tubes in the asphalt on the energy output cannot be included. In the more-dimensional model therefore the asphalt collector was modelled including the tube and the tube lay-out. In this case no additional routine for the calculation of the heat exchanger data was required. Figure 3 sketches the principle of the more-dimensional model. In this case the heat transport in the soil is calculated in the vertical and horizontal direction. Nevertheless, the heat transfer in the z-direction was neglected. This model therefore was indicated the 2½-D model. The original program of Wijsman and den Ouden (1980) for the heat exchange in a soil heat exchanger was adapted to deal with the flow problem at hand. The solver procedure of the program was kept original. The rest was adapted to the problem at hand, including, e.g., the heat exchanger lay-out and position, the interaction with the outdoor environment and the file handling.

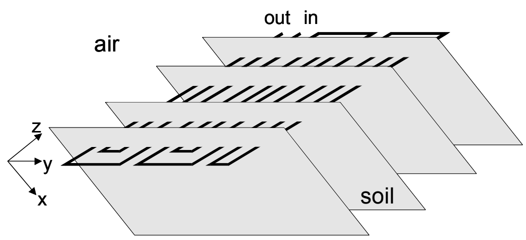


Figure 3. Sketch of the principle of the more-dimensional model.

MEASUREMENTS

In order to validate the developed models, measurements have been performed at a test site where different compositions of asphalt collectors where constructed. This site, a sand loading site, was chosen such that also the constructive aspects of the asphalt collector could be tested. Heavy trucks, loaded with sand, where directed over the asphalt collector test sites.

The different test sections were equipped with flow and temperature sensors. Weather conditions were recorded at an alongside installed weather station. After preliminary test measurements extra equipment, a radio net meter, was installed to register the absorption and emission of the asphalt surface. The use of this radio net meter avoided the derivation of the absorption coefficient. Through some extra measurements, this coefficient eventually could be derived from these measurement results.

Besides the measurement equipment, also a control system was installed to control the flow and supply temperature. A cooling unit was used to maintain the supply temperature at a sufficiently low value.

An example of a measurement result is given in Figure 4. In this case the supply and output temperature of the heat exchanger at the test site is shown for a period of 3.5 weeks.

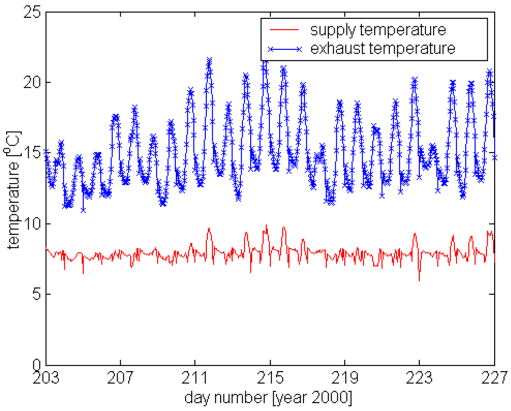


Figure 4. Supply and exhaust temperature of the heat exchanger over a period of 3.5 weeks.

The measurement period was during summer time where on most days the solar irradiation was more than 500 W/m^2. The average air temperature was around 14^{o}C and the average wind velocity 1.7 m/s. The average daily heat gain for this period was determined at 4.7 MJ/[day.m^2]. The efficiency of the asphalt collector, based on the total solar irradiation over that period, was roughly 30%.

Besides the measurement of the heat gain several other measurements were performed. For example, the measured temperature distribution in the asphalt layers showed that at the asphalt surface the presence of an asphalt collector decreases the surface temperature by 3.1^{o}C on average (σ = 0.7 ^{o}C). At 60 mm the difference is 4.5 ^{o}C (σ = 0.7 ^{o}C). This difference is smaller than expected, mainly because of the fact that the surface temperature of the reference asphalt pavement remained relatively low under the summer conditions in which the tests were done. This effect is mainly explained by the specific test site constraints that allowed pollution of sand on the asphalt, despite regular cleaning, and the open location of the test site alongside a large water area.

The pollution of the road with sand also shows in the derived absorption coefficient of the asphalt at the test site. This coefficient was calculated from the measurement data at 0.8 whereas in general a value of 0.9 is found for this type of asphalt pavement. Another explanation is found in the type of mineral aggregate that was used that eventually led to a light grey asphalt surface.

With respect to the asphalt temperature at the depth of the heat exchanger and the output temperature of the heat exchanger a nearly constant temperature difference was found. The applied flow rate was sufficiently low to follow the temperature fluctuations (frequency and amplitude) in the asphalt pavement.

Finally, temperature measurements were made at 0.5, 1.0 and 2.0 m depth. These measurements indicated that the long term average soil temperature of 10^{o}C is found at a larger depth than normally expected. This is due to the effect of the nearby large water area.

In order to derive the convective heat transfer at the asphalt surface also a general correction coefficient was derived to translate the wind velocity at 10 m height to a wind velocity close to the asphalt surface. This wind reduction factor (wrf) was calculated at 0.25. It was not possible to derive a wrf as a function of the wind velocity and wind direction.

In general it was concluded that measuring the heat gain of an asphalt collector under practical conditions and in a (worse-case) real world situation was very difficult. It was tried to measure as many parameters as possible for validation purposes and for the in-situ applicability of the asphalt collector. During the measuring project it was however not possible to correct some imperfections found. The main shortcomings relate to the boundary conditions at the asphalt surface, i.e. the solar irradiation and the effect of moisture in and on the asphalt surface, and the heat exchanger flow rate.

With respect to the solar irradiation it was concluded that local variation was possible due to the sand pollution effect. It was only possible to measure the actual solar irradiation at one point of the asphalt collector. With respect to the moisture, based on the available weather data, it was concluded that the amount of rain during the measurement periods was limited and would not have led to moisture accumulation on the asphalt pavement. Heavy rainfalls could be traced in the available data as solar irradiation then was significantly lower. The applied flow meters for the measurement of the heat exchanger flow rate were less well equipped for the rough conditions at the test site. This resulted in the break down of several meters and allowed for a limited reliability of the meters.

VALIDATION

An analytical as well as an empirical validation has been performed. For the analytical validation the problem of unsteady heating of a semi-infinite medium was investigated (Holman 1997). Figure 5 presents the results for both models. From the results one can conclude that both models perform adequately. The short term response is very good, whereas for the long term response the effect of the finite depth of the modelled medium shows.

For the empirical validation the asphalt pavement configuration and measured boundary conditions for the above described test site were used. The measured and simulated temperatures and heat gain then were compared.

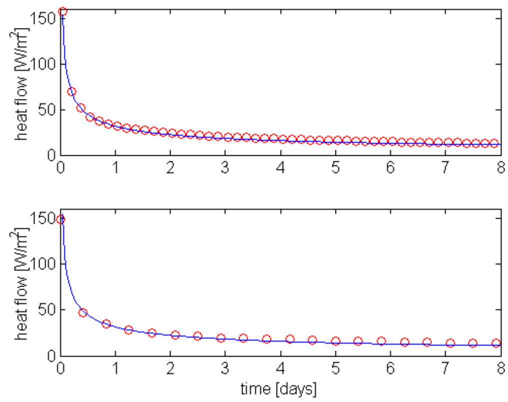


Figure 5. Result analytical validation (top: 2½-D-model, bottom: 1½-D model; line: analytical result).

A comparison of the measured and simulated temperatures in the asphalt pavement at the surface and at a depth of 60 mm shows a good qualitative agreement for both models. The daily variations in temperature are followed well. Nevertheless, some differences are found which are ascribed to the local conditions at the point of measurement and the fact that the values are averaged over the investigated surface area whereas local differences are very well possible.

For the 1½-D model the peaks in the reference pavement temperature are overestimated compared to the 2½-D model and experimental results. This difference is explained from the difference in the type of solver that has been applied and is not due to the difference in discretisation (Wijsman 2000). This effect can also be found in the analytical result. The heat flow for the 1½-D model immediately after the temperature step is lower than for the 2½-D model.

The energy gain of the heat exchanger is shown in Figure 6. First the output temperature of the heat exchanger is shown, next the daily energy gain is given.

As for the soil temperatures the results in Figure 6 indicate that the 2½-D model is able to calculate the output temperature variation as a function of the boundary conditions. This is also the case for the 1½-D model.

Quantitatively the deviation is obvious. The simulated output temperatures are lower than the measured ones. As a result the energy gain is lower than measured. The deviation for the 2½-D model is 15% and for the 1½-D model 25%.

Three main explanations are found for this deviation. Firstly, the difference partly is due to the two real variables in the validation process of the asphalt collector: the contact surface ratio (A_c) of the heat exchanger and the average size of the air bubbles

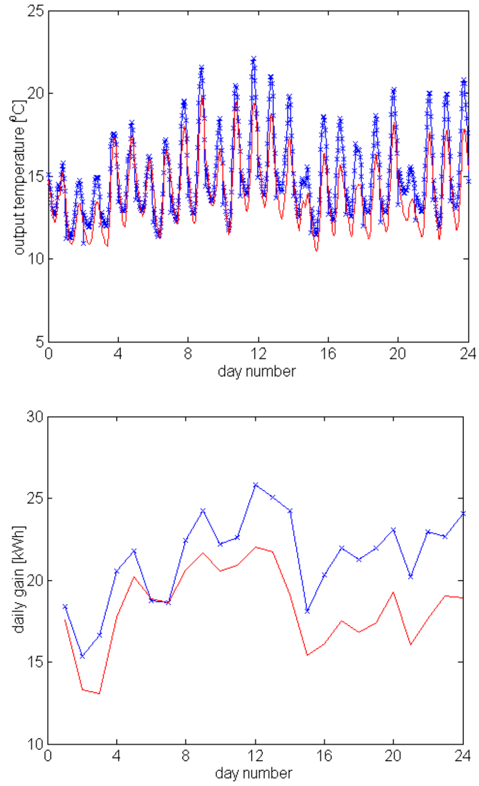


Figure 6. Measured + simulated output temperature and daily energy gain of the asphalt collector (2½-D model; [-] measurement, [x] simulation).

near the tube (L_g). The applied values have been estimated based on experience and destructive testing. Nevertheless, even when applying optimum heat transfer conditions for the heat exchanger, this cannot solely explain the total difference between measurement and simulation.

The second explanation is found in the local deviations of the measured net irradiation on the asphalt collector. By a different treatment of the available data, applying the actual solar irradiation, the local effect was reduced. This resulted in a 4% higher simulated gain.

Finally, the deviation is blamed on the applied flow rate measurement technique. A resistance measurement technique was applied that was less able to cope with the harsh conditions at the test site. This resulted in a breakdown of several of the flow meters. Furthermore, in retrospect, the number of flow meters that was applied was to small to obtain all relevant data. Some additional instantaneous contact free flow measurements indicated that the flow rate for the above discussed measurement period was 12% lower than the continuously measured flow rate. Given the stable flow that was controlled during the measurement period, this is regarded a systematic deviation. As in the simulations the output temperature of the heat exchanger is highly influenced by the flow rate. This has a major impact on the energy gain. Applying a 10% lower flow rate results in a 5% lower heat gain, as the output temperature increases.

Based on the validation and the given explanation for the deviations that are found it is concluded that both models are able to predict the thermal energy gain potential of an asphalt collector qualitatively. Trends are predicted correctly. Quantitatively the results are less solid, but this is largely caused by measurement uncertainties.

Therefore an inaccuracy of 10% should be applied for the 2½-D model. Given the uncertainty in the currently available data it is not possible to improve that figure. Additional measurement data then are required, best obtained under laboratory conditions. It is however assumed that a good prediction of the absorption and emission coefficient of the asphalt pavement and a reliable estimation of the heat transfer conditions of the heat exchanger will improve the reliability of model. The time dependent variations in the boundary conditions are well predicted and allow for a good estimation of trends in a parameter study.

For the 1½-D model similar conclusions can be given as for the 2½-D model. However, due to the indirect method through which the heat exchanger data is calculated, i.e. look-up tables, the energy gain is approximately 15% lower than for the 2½-D model. The effect of the difference in solver method is included in this figure.

The effect of the configuration of the heat exchanger in the asphalt pavement, that can be determined with the 2½-D model, shows that a 50% reduction of the distance between the tubes results in a 28% increase in the thermal energy gain per m^2. Doubling the original distance reduces the gain with 38%.

The use of the 2½-D model is preferred over the simpler 1½-D model. However, the 1½-D model allows for a significant reduction in calculation time for the calculation of the yearly thermal energy potential of an asphalt collector and therefore is interesting for performing parameter studies. Furthermore, it allows for a more easier coupling with a building simulation program or for investigating different control strategies.

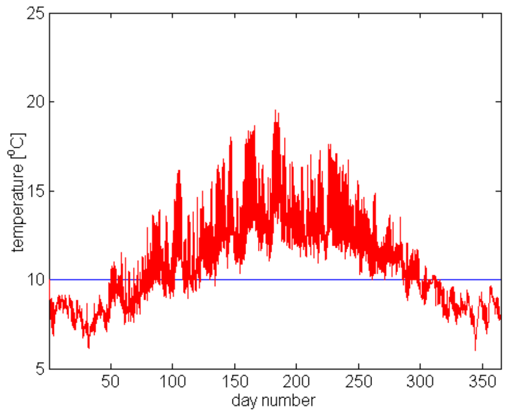
The mutual tube influence as a result of the tube configuration in the asphalt pavement works out positively on the heat gain. This effect increases with higher solar irradiation and decreases with improved heat transfer characteristics of the tubes.

MODEL RESULTS

Given the above described and validated models several annual thermal energy gain calculations have been performed for the typical asphalt pavement set-up that was also applied at the test-site. A short description of the main parameters is given in Table 1. Figure 7 presents calculated output temperatures of the heat exchanger and the monthly thermal energy gain respectively. These results were derived with the 2½-D model. Table 2 presents the thermal energy potential as calculated with both models.

Table 1. Summary of main characteristics of the asphalt collector.

size asphalt pavement	16.4	m^2
tube length	105	m
depth tubes (centre tube)	135	mm
distance between tubes	0.15	m
supply temperature	10	°C
flow rate (fluid: water)	0.05	l/s
absorption / emission asphalt	0.8 / 0.85	-
Weather: Test Reference Year De Bilt		



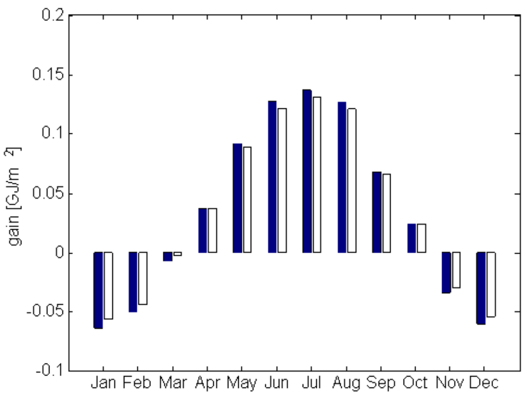


Figure 7. The calculated output temperature of the asphalt collector (top; 2½-D model) and the monthly thermal energy gain (bottom; closed: 2½-D model, open: 1½-D model).

Table 2. Summary of the yearly thermal energy potential of the asphalt collector.

	2½-D	1½-D
net Q_{exch} total size (16.4 m^2) [GJ]	6.48	5.69
net Q_{exch} [GJ/m^2]	0.40	0.35
summer Q_{exch} [GJ/m^2]	0.61	0.54
winter Q_{exch} [GJ/m^2]	0.21	0.19

Table 2 indicates that for the investigated configuration the net yearly thermal energy gain is approximately 25% of the average gain of a normal solar hot water system (1.6 GJ/m^2). When the thermal energy loss in the winter is applied positively, e.g. for cold storage, then the thermal energy potential is calculated at 0.82 GJ/m^2. An obvious difference between these two systems is that the asphalt collector normally is operating continuously, whereas the solar hot water system is operating at a sufficient supply of solar irradiation.

The quality of the thermal energy is relatively low, as the exhaust temperature does not exceed 20°C. Higher temperatures are possible, but at the expense of the total energy gain.

The 1½-D model underestimates the annual gain by 12%. Based on the validation a correction of this result would be tenable. With respect to the calculated temperatures this correction is not possible. A significant change in the configuration will also affect such a correction.

As a further example, in Table 3 results are shown for the similar asphalt collector set-up as described in Table 1, but now the absorption and emission coefficient are increased to values that can be found in literature (i.e. 0.9 both).

Table 3. Summary of the yearly thermal energy potential of the asphalt collector for an adapted absorption and emission coefficient (both 0.9).

	2½-D	1½-D
net Q_{exch} total size (16.4 m^2) [GJ]	7.53	6.57
net Q_{exch} [GJ/m^2]	0.46	0.40
summer Q_{exch} [GJ/m^2]	0.67	0.59
winter Q_{exch} [GJ/m^2]	0.21	0.19

A clean and dark asphalt pavement, i.e. a high absorption works out positively on the annual thermal energy gain. A 12.5% higher absorption results in a 16% higher gain, despite a 6% higher emission.

DESIGN DATA

Next the 1½-D model has been applied to perform a large number of simulations to come up with design graphs that can be applied for a first order dimensioning of an asphalt collector in design studies. Table 4 presents the conditions for which these data have been derived. These conditions are mainly based on the experiences from the test-site and from the above described investigation. As collector fluid currently still normal tap water is used.

Figure 8 presents the annual thermal energy gain (heat and cold) for different supply temperatures and depths of the tube. Figure 9 presents the average output temperatures that can be obtained as a function of the supply temperature and depth of the tubes. Finally, Figure 10 indicates the number of hours in a year that a specific gain can be obtained as a function of the supply temperature.

Table 4. Boundary conditions for design curves.

size asphalt pavement	22.5	m^2
tube length	150	m
depth tubes (top tube)	31 and 51	mm
distance between tubes	0.15	m
flow rate (fluid: water)	200	l/h
internal diameter	0.013	m
A_c | L_g	0.5 | 0.005	- | m
absorption | emission asphalt	0.9 | 0.9	- | -
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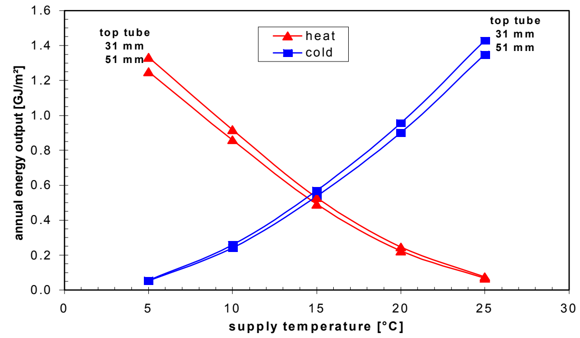

Figure 8. Annual thermal energy gain as a function of the supply temperature and depth of tubes.

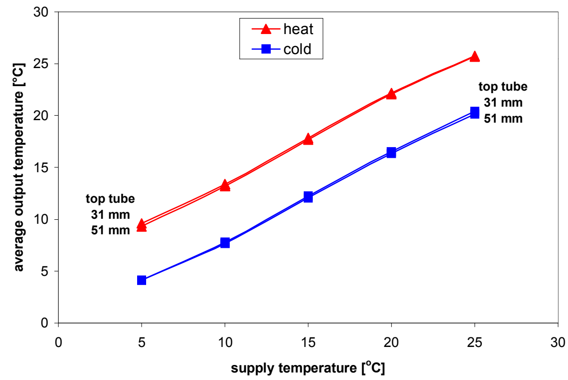

Figure 9. Average output temperature as a function of the supply temperature.

Figure 8 shows that the type of thermal energy is a strong function of the supply temperature. The extreme supply temperature values allow for the highest thermal energy potential. In this figure it is obvious that the depth of the tube has a second order effect on the gain. Nevertheless, the closer the tube is positioned to the surface, the higher the gain is.

The output temperature in Figure 9 has a nearly linear relationship with the supply temperature. From this figure it is obvious that the output temperatures of the asphalt collector are relatively low. Often there will be a need to upgrade the quality of the thermal energy through the use of heat pumps. Nevertheless, the derived temperatures appear well suited for long-term storage in the soil.

Figure 10 indicates that the number of hours with peak gains is relatively low and that the bulk of the thermal energy gain is obtained at a relatively low gain per m^2. The shift in the type of gain as a function of the supply temperature as shown in Figure 8 can also be derived from Figure 10.

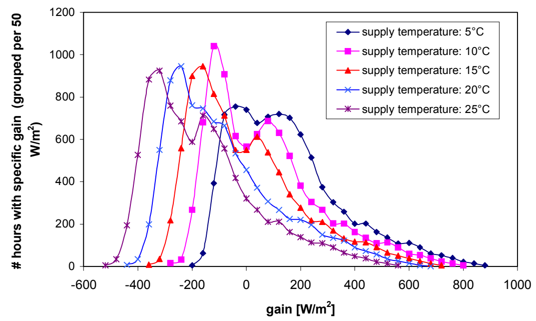

Figure 10. Yearly number of hours of a specific heat gain as function of the supply temperature (15 mm wearing course).

In the figures 8 and 10 no correction has been included for the known underestimation of the 1½-D model that is discussed in the model results.

DISCUSSION

This paper describes the development of a design tool for the calculation of the thermal energy potential of a so-called asphalt collector. Two types of numerical models have been developed for this purpose.

The validation of the models showed to be a tedious procedure as the quality of the measurement data from the experimental set-up at the test site was less good than expected. Nevertheless, for parameter studies both models are useful as qualitatively the results are valid. For early design studies the reduced accuracy of the models is less important and application is possible. For final design studies the available data on the asphalt collector should be incorporated in the total energy system design in order to estimate its potential better.

Measurement results from the experimental set-up of the asphalt collector at the test-site and simulation results show that a heat exchanger that is incorporated in the asphalt pavement is able to collect solar heat. The effectiveness of this collector however is relatively low and the energy is of lower quality when compared to a normal solar hot water system.

However, further advantages of the use of an asphalt collector are found in the reduced maintenance of the road and the avoidance of slippery roads in winter time. The latter case is also an example of the heat exchanger capabilities of the asphalt collector.

The developed numerical models are able to support the design process. The design graphs presented in this paper show some possible results that can be obtained.

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NOMENCLATURE

Q_s [W] solar energy source
α_s [-] absorption coefficient
Q_{sky} [W] radiation heat loss to the sky
Q_c [W] convective heat loss
Q_k [W] conduction heat transfer
Q_{exch} [W] heat transfer to the heat exchanger
U_{exch} [W/m^{2}K] total heat transfer coefficient
A_c [-] contact surface ratio
L_g [m] average size of air bubbles around tube