HIGH PERFORMANCE PASSIVE SOLAR HEATING SYSTEM WITH HEAT PIPE ENERGY TRANSFER AND LATENT HEAT STORAGE

H.A.L. van Dijk
E. van Galen
J. Hensen
Institute of Applied Physics TNO-TH
P.O. Box 155
2600 AD DELFT, The Netherlands

Technical University of Eindhoven
P.O. Box 513
5600 MB EINDHOVEN, The Netherlands

ABSTRACT

Preliminary results are reported from a current project on the development of a high performance passive solar heating system. Two special components are introduced:

a. A heat pipe as a thermal diode tube for the efficient transfer of collected solar heat from the absorber plate to behind an insulation layer.
b. A latent heat storage section with high storage capacity at moderate operating temperatures.

Additional advantageous characteristics: the maintenance costs are negligible and the performance is highly insensitive to inadequate control of the system by the inhabitants.

A first global design of the system showed significantly higher predicted gains than a conventional storage wall at however still high manufacturing costs; although the cost-benefit ratio was already competitive with a similar active solar system.

The project will be concluded at the end of 1983, with an optimized design of the system. First optimization exercises and series of measurements on the single components lead to the expectation that the final optimized design will be characterized by significantly reduced manufacturing costs.

1. INTRODUCTION

Within the passive solar approach, the direct gain and convective loop systems are the most simple and therefore cheapest solutions. These kind of systems, however, are characterised by high indoor temperature swings and high solar heat supply on the hours of least demand.

A thermal storage wall has a advantageous accumulation of solar heat which results in low temperature swings and a time delay between the absorption of solar energy and the heat supply to the building.

The main disadvantage of a conventional thermal storage wall, however, is the higher temperature of the solar collecting surface which in combination with the high thermal capacity of the wall can lead to considerable heat loss to the outside. Multi-glazing can limit this heat loss to a certain extend, but is costly. Movable insulation is also expensive, has a slow response and needs careful attention for a reliable and effective operation. Furthermore, the extra mass introduced into the building may pay off to extra costs particularly in multi-story buildings and valuable space within the building is occupied by the system.

2. AIM OF THE PROJECT

This project aims to develop a passive solar heating system which has the advantages as mentioned above. This can be achieved by the introduction of two special components:

a. A thermal diode tube, which act with small temperature difference already as a high performance thermal conductor. It transfers heat from the collector to behind an insulation layer, but does not transfer heat in the reverse direction. With a low capacity collector the system responds rapidly to changes in outdoor conditions, while needing no movable parts or manually or automatically operated control equipment.
b. The latent heat storage. With thermal storage in elements containing phase change material a reduction in storage volume compared with concrete down to 20% can be achieved at a moderate storage temperature level. The thickness and weight of the complete system can then be restricted.

3. SYSTEM DESCRIPTION

The design of the passive solar element is based on the following mechanisms (see fig. 1):
Fig. 1. Schematic drawing of the high-performance passive solar heating system.

- One glass pane cover (1)
- Small air gap
- Absorber plate (2) to collect the solar radiation
- S-shaped heat pipes as thermal diode tubes to transfer the absorbed heat through an insulation layer (3)
- A back plate (4) to distribute the heat from the diode tubes to the latent heat storage elements (5)
- A air cavity is formed with a common insulation sheet (6) to separate the system from the room
- When the air cavity is open to the room, air flows under the buoyancy force through the cavity (7), thus transferring the heat from the storage material (6) to the room. The cavity can be closed when there is no heat demand.

The thermal characteristics of a heat pipe in inclined position can be shortly described as follows: the heat pipe is basically a closed hollow tube partially filled with a working fluidum, in equilibrium with its vapor.

When the lower end is heated the fluid absorbs this heat by evaporating. At the - colder - upper end the vapor will condense and release the latent heat, the liquid will return to the lower end by gravity force. With reverse temperature difference the upper end will dry out and no heat transfer takes place in this element (thermal diode effect). The working fluid and the heat pipe tubing are chosen on the basis of the operating temperature and their mutual compatibility.

4. A FIRST GLOBAL DESIGN OF THE SYSTEM

4.1 Characteristics

A first step in the project was to draft a first global design of a high performance passive system. Table 1 shows the main characteristics.

4.2 Net heat gains

The annual heat gains of the first global design have been calculated in preliminary calculations with a steady state model. The heat demand is taken hourly from a well-insulated living room with consequently quite low annual heat consumption. The calculations have been performed with an average Dutch heating season (table 2).

For comparison a similar (but unsteady state) calculation has been performed with an active system under the same climatic conditions. The heat transfer ornaments of this active system have been designed with extreme great dimensions to maintain a low temperature level. Although this is energetically the most favourable (but the most expensive) design, the high performance passive system seems to yield competitive results.

<table>
<thead>
<tr>
<th>Thermal resistances:</th>
<th>description</th>
<th>resistance (m² K/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>component</td>
<td></td>
<td></td>
</tr>
<tr>
<td>cover</td>
<td>single glass</td>
<td>RU = 0.25</td>
</tr>
<tr>
<td>absorber plate</td>
<td>spectral selective layer</td>
<td></td>
</tr>
<tr>
<td>heat pipes</td>
<td>5 heat pipes per m² provided with extra heat exchange surface</td>
<td>Rp = 0.05</td>
</tr>
<tr>
<td>air cavity</td>
<td></td>
<td>Ra = 0.09</td>
</tr>
</tbody>
</table>

Effective absorption transmission factor AT = 0.80

Overall heat removal factor: Pr = 0.65 (Pr = RU/(RU + Rp + Ra))

TABLE 1. Main characteristics of the first global design, according to preliminary calculations.
TABLE 2. Preliminary calculation of the net heat gain of the high performance passive system and a preliminary comparison with an active and a conventional passive system. Average Dutch heating season.

<table>
<thead>
<tr>
<th>system</th>
<th>characteristics</th>
<th>net heat gain kWh/m²/year (south orientation, vertical)</th>
<th>remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>HP passive system (table 1)</td>
<td>4 m² collector area F_r  = 0.65</td>
<td>85</td>
<td>room with small heat demand</td>
</tr>
<tr>
<td>Similar active system</td>
<td>4 m² collector area F_r  = 0.95</td>
<td>105</td>
<td>room with small heat demand; low temperature ornaments</td>
</tr>
<tr>
<td>Conventional storage wall</td>
<td>2 x 2 m² area, single glass, spectral selective (ɛ = 0.50)</td>
<td>50</td>
<td>ideal control by inhabitants; room with unlimited heat demand</td>
</tr>
</tbody>
</table>

Moreover it should be emphasized, that the presented net heat gains for the passive system should be considered against a (well insulated) normal opaque wall with an annual heat loss of about 50 kWh/m².

Also a preliminary calculation has been performed with a conventional storage wall. The net heat gains of this system have been calculated assuming ideal conditions: the air cavity between glass cover and wall is always ventilated when the cavity air temperature exceeds the room temperature and the cavity is always closed when the temperature in the cavity drops below the room temperature. Moreover in this calculation a room has been chosen with unlimited heat demand. Nevertheless the results in table 2 show that even then a conventional passive system still yields significantly lower gains. These gains can of course be increased by providing the conventional storage wall with night time insulation, which means extra manufacturing and maintenance costs and extra attention needed from the inhabitants. One should realize also, that the performance of a conventional storage wall is highly sensitive to use of the dampers in the air cavity. For the high performance passive design this is not the case, because the dampers in the air cavity of this system only distribute the heat - which already passed the thick insulation layer - between storage and direct gain. More precise, unsteady state calculations are planned for the last step in this project when the high performance passive design will be optimized.

4.3 Manufacturing costs

The first global design has been subjected to a detailed analysis of manufacturing costs. In this analysis it has been assumed that this first design would be the basis for the production of a number of systems without any serious attempt to optimize the detailing of the design. From this analysis it was shown that the chosen design principles and details made the system very labor-intensive and therefore a commercial production quite expensive (Dfl. 700 - 900 per m²). With these results the high performance passive system would already be competitive with comparable active systems. Nevertheless it is aimed to bring down the manufacturing costs to a significant lower level. This can be achieved in three ways:

1. by reconsidering the need for some expensive components which are not essential to the performance. It has e.g. already been concluded that the dampers to the outside, provided in the original design for summer ventilation, should be omitted. When performing unsteady state calculations on a more definitive design e.g. the necessity of the thick insulation sheet between cavity and the room air can be investigated.

2. By redefining the design principle. In the first design the system was provided with separate modular elements consisting of a sandwich with absorber plate, heat pipe with insulation and back plate. Although it was expected that this kind of approach would lead to low manufacturing costs (including assembling), the opposite proved to be the case. A high portion of the costs appears to be in assembling the sandwich modules. It is now expected that other principles can also lead to a design which is flexible enough to be applied under a wide range of conditions, e.g. a design with one or two defined heights and unlimited horizontal dimensions with a repeating pattern for e.g. each 0.30 m.

3. By an optimized design of all necessary details. This process will be started when a new global design has been drafted. The result of this process will be a prototype high performance passive system with significantly reduced manufacturing costs. The lower limit consists of the bare costs for the materials of which the functional
components of the system are composed. These costs are estimated to be Dfl. 150 - 300 per m². A second detailed analysis of the manufacturing costs will be performed during the last step in this project. Finally one should note that from the eventual manufacturing costs one should subtract the costs for the conventional wall which has been replaced by the passive system (Dfl. 75 - 100 per m²).

5. OPTIMIZATION OF THE COMPONENTS

5.1 The heat pipes

Measurements have been performed on the thermal resistance of a few types of heat pipes (figure 2). In these measurements the heat flow, working fluid, interior surface treatment and inclination were varied. Table 3 shows the main results of this first series of measurements. It appeared that a plain copper tube filled with water has so far the best results. These results also are better than what had been assumed in the first global design of the high performance system (see table 1).

![Fig. 2. Schematic view on the measurement of the thermal resistance of the heat pipes.](image)

<table>
<thead>
<tr>
<th>Material</th>
<th>copper</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>total: 0.40 m</td>
</tr>
<tr>
<td></td>
<td>vapor zone: 0.20 m</td>
</tr>
<tr>
<td></td>
<td>cond. zone: 0.10 m</td>
</tr>
<tr>
<td>Diameter</td>
<td>13 - 15 mm</td>
</tr>
<tr>
<td>Assumption</td>
<td>5 heat pipes per m²</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Inclination</th>
<th>Working Fluid</th>
<th>Interior Surface Treatment</th>
<th>Thermal Resistance (m² K/W) measured with heat flow:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>low</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(100 W/m²)</td>
</tr>
<tr>
<td>vertical</td>
<td>alcohol</td>
<td>copper wick added</td>
<td>0.060</td>
</tr>
<tr>
<td></td>
<td>water</td>
<td>copper wick added</td>
<td>0.080</td>
</tr>
<tr>
<td>vertical</td>
<td>alcohol</td>
<td>plain copper</td>
<td>0.046</td>
</tr>
<tr>
<td></td>
<td>water</td>
<td>plain copper</td>
<td>0.062</td>
</tr>
<tr>
<td>10 deg. from horizontal</td>
<td>water</td>
<td>plain copper</td>
<td>0.026</td>
</tr>
<tr>
<td>10 deg. from horizontal</td>
<td>alcohol</td>
<td>screw thread tapped in surface</td>
<td>0.026</td>
</tr>
</tbody>
</table>

|             | water         | screw thread tapped in surface | 0.088                                       | 0.026                                     |
Alcohol and water are chosen as working fluids because of their competitiveness with copper. Alcohol is expected to give a better wetting of the surface in the vaporization zone, which indeed leads to better results for the cases in which the interior surface has been treated to increase the fluid surface by capillary forces. However, alcohol has a drawback of having a lower thermal conductivity. Water indeed suffers from bad wetting, but particularly at nearby horizontal position the performance of water indicates a very effective (low resistance) vaporization. This is probably due to boiling effects which let the water spread all over the surface of the heated vaporization zone instead of having the lower end of the heat pipe filled with a water column with a small surface for vaporization. A nearby horizontal position can fit in the system's design very well because the hot respectively the cold end of the heat pipe can be stretched out along the absorber plate and back plate respectively, thus covering large areas of the plate surfaces.

In additional experiments the results obtained so far will be analysed more elaborately in order to obtain a better understanding of the mechanisms, which is a conditio sine qua non for a further optimization of the heat pipe design.

5.2 Heat transfer in the air cavity

A series of measurements has been performed on the heat transfer in the air cavity, with a experimental set up at the Technical University of Eindhoven. The air cavity is created by an electrically heated hot plate on one side and a thick sheet of insulation material on the other. The heat transfer rate has been measured by metering the electrical supply as a function of the resulting hot plate temperature. The heat balance is checked by measuring the air flow rate at cavity inlet opening and the air flow temperatures at the inlet- and outlet openings. Measurements have been performed at heights 1.80 and 0.90 m, cavity depths 0.02 to 0.10 m and heat flow ranging from 5 to 400 W/m². Also measurements have been performed with the opposite surface covered with aluminium foil to reduce radiant heating of this plate, in order to examine the effect of a deviating temperature difference between the two plates. An illustration of the results is presented in figures 3 and 4. The heat transfer rate at moderate hot plate temperature equals a thermal resistance of \( R = 0.13 \, \text{m}^2 \cdot \text{K}/\text{W} \), which already comes close to the value estimated in the first global design for an air cavity provided with extra heat exchange surface (\( R = 0.09 \), see table 1). Therefore it may be concluded that it will not be difficult to meet the specifications of the first global design of the high performance system.

At this moment, the results are analyzed in order to generate relations for the heat transfer rates which are generally valid for a wide range of cavity dimensions and conditions.

![Diagram](image)

**Fig. 3.** Measurements on the heat transfer rate in the air cavity; heat transfer as a function of plate temperature and cavity width.

![Diagram](image)

**Fig. 4.** Measurements on the heat transfer rate in the air cavity; an example.
5.3 The latent heat storage

With the first results of the measurements described above, preliminary calculations have been performed to the thermal storage. The hour by hour performance of the high performance passive element has been calculated for two typical days in spring, with various types of storage materials and dimensions. From these calculations it has been concluded that the best performance is expected from a high performance passive design with a heat storage as one thin layer (few centimeters) directly attached to the back plate at the cold end of the heat pipes: the efficiency of the system when applied with open cavity for direct gain is hardly affected by the resistance of a few centimeters of storage material. So also for midwinter conditions - when storage would not be needed - the performance remains high. Results have been compared between two types of storage materials which were chosen on basis of 1) commercial availability; 2) well-known characteristics and proven performance and life duration and 3) operating temperatures within the required region. Material A has a melting temperature of 27 °C, material B of 57 °C. Material A has the advantage that the temperature level of the system, thus the threshold value for the solar gain, is lower. The disadvantage however, is that the heat transfer from storage to air cavity is far too slow to extract the absorbed heat by free convection within the required few hours.

A programme of measurements has been initiated to validate these preliminary results. A experimental set up is under construction at the Institute of Applied Physics. Measurements will be performed for unsteady state conditions with 24 hours cycles, both with 24 hours open cavity and with the cavity closed during strong insolation. The air cavity in this set up is a reproduction of the air cavity from the heat transfer measurements in Eindhoven, the results of which can be used in the analysis of the storage performance. As storage materials will be tested:

1. water
2. paraffin (T_melt = 52 - 54 °C)
3. a salt hydrate (T_melt = 57 °C)
4. optional: PCM with intermediate temperature.

7. PRELIMINARY CONCLUSIONS

In this paper first results are reported from a current project on the development of a high performance passive solar heating system. The project is at the moment of writing still in a stage of optimization of the components. The project will be concluded with an optimized design of a prototype high performance system and a performance analysis with an unsteady state model of a dwelling with high performance passive elements in the south facade.

Nevertheless, from the results obtained so far already important conclusions can be drawn:

- A first global design of a high performance passive system has indicated that such a system will have significant higher gains than a conventional storage wall, even if the latter is assumed to operate under ideal conditions concerning heat demand and inhabitants’ attention.

- The manufacturing costs of this first approach seemed however high, although the cost-benefit ratio was already competitive with a similar active solar system.

- First optimization exercises and series of measurements on the components indicate that with an optimized design the high performance can be maintained at significantly reduced manufacturing costs.

- It is expected that at the end of the project, a optimized prototype high performance passive solar system will be designed which reaches a payback period of 10 to 20 years for the Dutch situation, which is comparable with conventional energy conservation measures (e.g. double glazing).

8. ACKNOWLEDGMENTS

The project is financed by the Commission of the European Communities and by the Dutch National Solar Programme.

In this project the following organisations are co-operating in the research: the Institute of Applied Physics ZNO-TH, the Technical University of Delft and Delft, and the B.V. Koninklijke Maatschappij "De Schelde".

9. LITERATURE


(2) High performance passive solar heating system with heat pipe energy transfer and latent heat storage, proceedings of the EC Contractors' Meeting 1-3 June 1983, to be published in Solar Energy Applications to Dwellings (series A), Volume 3, Dordrecht.