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Solar heat harvesting and transparent insulation in textile architecture inspired by polar bear fur

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ABSTRACT

Solar thermal technology is a promising key strategy for future renewable energy production. Various concepts exist that use solar collectors and heat mirrors, built from rigid materials, to gather thermal energy from solar radiation. A new approach is the utilization of textile materials to build solar thermal collector systems with flexible material properties, lightweight design and improved material-efficiency. A solar collector, based on a multi-layer arrangement of technical textiles and foil membranes, has been realized by the ITV Denkendorf (Institute of Textile Technology and Process Engineering Denkendorf). The proposed collector system allows transparent insulation in textile-based buildings while gathering thermal energy simultaneously. The system is inspired by the transparent insulation and heat harvesting strategies of polar bear fur and can inform textile-based envelopes of future transparent buildings. In this study, different material arrangements and the influence of different parameters on the temperature distribution along the collector were tested. Air temperatures up to 150 °C (302 °F) could be generated inside the collector system. Furthermore, a closer look at the polar bear fur and other related principles in nature delivered additional concepts for energetic optimization.

1. Introduction

Due to increasing energy demands and environmental concerns, new sustainable, efficient, environmental-friendly and first-of-all safe energy concepts are desirable. One promising strategy is the capture of solar energy via solar thermal collectors where solar radiation is gathered and converted into thermal energy to heat up a medium like water or air to high temperatures [1]. The ITV Denkendorf developed a new concept for energy capture in textile-based buildings by using solar thermal strategies inspired by the polar bear fur [2]. The polar bear (*Ursus maritimus*) is known for its efficient heat insulating properties by means of a thick fur of nearly transparent and hollow hair. The skin underneath the fur is black and absorbs light, which passes through the transparent fur, and conversion into thermal energy takes place. Several air cavities inside the dense underfur ensure an efficient insulation by trapping warm air close to the bear's skin [2–4]. These principles have been used to develop a collector system that is based on a multi-layer arrangement of technical textiles and foil membranes, aiming at transparent heat insulation and efficient solar thermal energy capture in textile-based buildings. The different layers build a channel system consisting of two ethylene tetrafluoroethylene (ETFE) membranes as translucent, but heat insulating top layers and a bottom, black silicone layer for the absorption of light. Light that passes through the transparent ETFE-membranes gets absorbed at the black silicone layer. The emitted heat is trapped inside the system due to the insulating material properties of the ETFE-membranes. Additionally, the two ETFE-membranes are arranged at a distance of 1 cm to each other to provide an air buffer that minimizes the heat loss at the top of the system. Between the lower ETFE-membrane and silicone absorber, an air-permeable polyester spacer fabric textile provides a 1–1.5 cm thick layer for a second air buffer. For the purpose of energy transport, an airflow inside this spacer fabrics layer can be generated by a fan or gas pump. The air takes up thermal energy while passing through the system and can be piped to a thermo-chemical energy storage unit as illustrated in Fig. 1. Underneath the silicon layer a 2 cm thick layer of insulation foam helps minimize heat losses at the bottom of the system. This study focuses particularly on the optimization of the collector system in order to gain the highest possible temperature output. The aim is to increase the air temperature by testing different materials and modifying the system's arrangement. Therefore, we analyzed the

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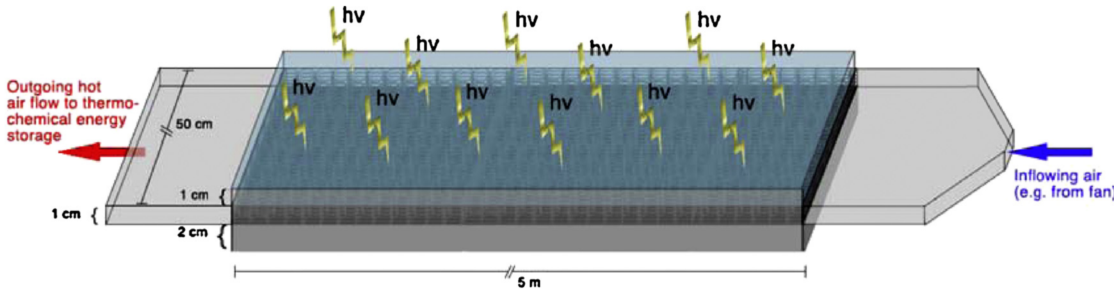

Fig. 1. Schematic illustration of the absorption of solar radiation and heat transport inside the collector.

dependency of parameter changes such as irradiance or airflow velocity on the output temperature while varying between different system arrangements. Measurements were performed under controlled conditions on a test bench as well as under real conditions in nature. Subsequent to this study, a prototype building was set up by the ITV Denkendorf to consider the ideal parameters as investigated in this study. Fig. 2 shows a draft illustrating the functional principles of the proposed building: air from the outside gets sucked into the system by a vacuum gas pump. The air slowly flows through the collector, which forms the building's envelope at the sunlit side of the building, while taking up thermal energy. The hot air can then either be piped directly into the building for heating purposes, exit the building if too much thermal energy has been generated, or be piped into a thermo-chemical energy storage unit.

Prior to this study a simplified computational fluid dynamics-simulation (CFD-simulation) was modeled for making predictions about the possible temperature gain of the proposed system. For the model the finite volume method was used, which is based on Euler and Navier–Stokes equations. The system was modeled using the software Star-ccm+ by CD-adapco. Three-layer combinations of the proposed collector system were simulated, varying between different material arrangements. For the upper layer, material properties of ETFE-foil and PTFE (polytetrafluoroethylene) coated glass fiber fabric were simulated, while for the bottom layer of the system, material properties for high absorption (black surface) as well as for low emissivity/high reflectance were modeled. The air gap width between the upper and bottom layer as well as the airflow velocity inside the system were varied for the simulation. The second layer of ETFE-foil on top of the system as well as different spacer fabric textiles inside the airflow channel were not considered in the model. The geometry of the airflow channel was set to 10 m in length and 1 m in width. The radiation intensity was kept constant at 800 W/m^2. Further assumptions were made in the model such as: solar radiation with a constant 90° angle of incidence, zero diffuse radiation from the environment, a constant ambient temperature of 25 °C, still air conditions, a laminar airflow inside the system ($Re = 1773$) and a perfect insulated bottom of the system. The results of the CFD-simulation represent the system's steady state after an infinite running time under constant conditions. The highest air temperatures could be observed when choosing an airflow velocity of 0.7 m/s and a system arrangement consisting of an upper ETFE-membrane, an air gap width of 0.02 m and a black bottom layer. The results of this combination are represented in Fig. 3 and show that the air temperature after an airflow distance of 10 m amounts to 100 °C. Fig. 3a compares the temperature courses along the system's upper ETFE-membrane, the airflow channel (working fluid) and the black bottom layer depending on the airflow distance. Fig. 3b shows the simulated temperature distribution along the three collector layers depending on the airflow distance in form of a 2-D heat transfer model. It is expected that the output air temperature under real conditions will be lower than the simulated temperature, which is based on several simplifications that

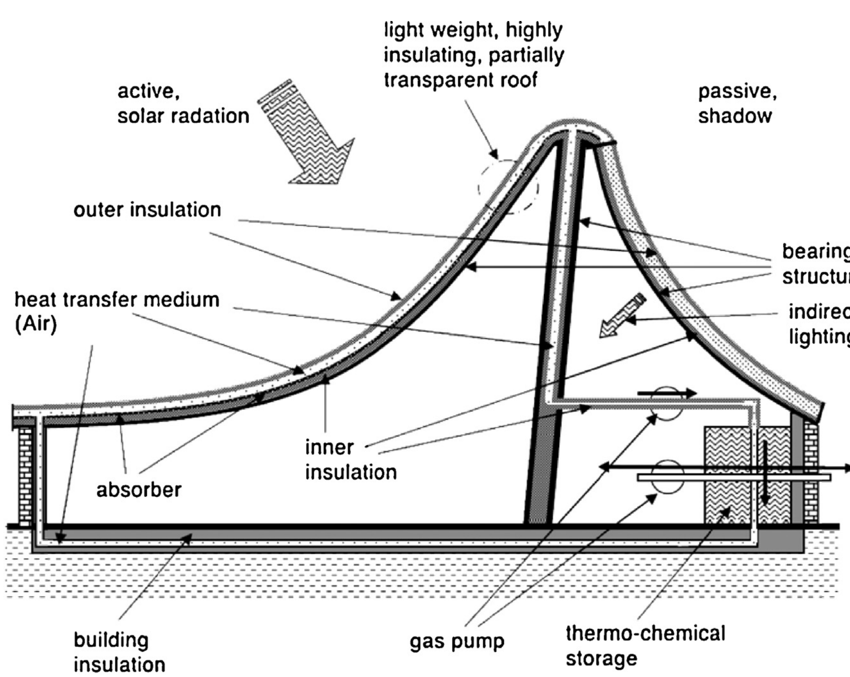

Fig. 2. Illustration of the prototype building's architecture and functional principle.
Source: Reproduced with permission [5]. 2010, Institute of Textile Technology and Process Engineering Denkendorf.