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Integrated development and modeling of heat pipe solar collectors

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Abstract

Heat pipe solar collectors have a high potential regarding both state-of-the-art collector development and new collector concepts and applications. However, they still suffer from several drawbacks. To overcome those drawbacks and exploit the potential an integrated, holistic development approach is proposed. The integrated approach takes three aspects of integration – system, disciplines and life cycle – into account resulting in a high complexity. To handle complexity strong development methods are required. Promising techniques are given by the methods of Multidisciplinary Design Optimization (MDO). Two concepts of integrated collector designs are already presented, further to be optimized by MDO.

Keywords: heat pipe; solar collector; integrated development; multidisciplinary design optimization

1. Potential and challenges of heat pipe solar collectors

The application of heat pipes to solar collectors has several advantages. Besides the high heat transfer ability of the heat pipe itself, heat pipe collectors can show a lower stagnation temperature of the solar fluid than direct flow collectors. This is due to the operation limits of heat pipes that prevent the further increase in heat transfer and therefore the overheating of the solar fluid. In the case of a dry connection of the heat pipe to the manifold exchanging the pipes without draining the collector circuit is possible. Thereby an easy and cost-effective maintenance is ensured. As the solar fluid only flows through the manifold but not through the absorber heat pipe collectors have the potential for a low pressure drop and minor leakage risk. Furthermore, their design allows a high degree of modularity. This supports cost-effective installation and flexible design. Especially for new applications such as building integrated devices those advantages are of high interest and underline the potential of this technology.

Despite those advantages up to now heat pipe collectors only account for a minor market share. State-of-the-art heat pipe collectors show drawbacks which currently lower their efficiency and durability and restrict their application. For instance, one major drawback has to be seen in the high thermal resistance of the heat pipe connection to the absorber or to the manifold of state-of-the-art collectors, which results in a reduced efficiency [1].

Moreover, the European research project QAiST [2] has revealed a relatively low long term stability of heat pipe collectors. Furthermore, noncondensible gases are introduced into the heat pipes by improper filling procedures or by chemical reactions between the working fluid and the container material [3], resulting in deviating power outputs. In addition, current heat pipe design restricts collectors to inclined or only quasi horizontal (> 0°) orientation, lowering the degree of design flexibility and thus acceptance by architects.

The presented advantages and drawbacks of heat pipe collectors underline the need and potential regarding the optimization of state-of-the-art heat pipe collectors as well as the development of innovative collector concepts.

2. Integrated development approach

The presented drawbacks of state-of-the-art heat pipe collectors base on different problems in construction, manufacturing, installation or utilization phase. However, due to interactions a sequential optimization often does not results in an overall optimal design. Therefore, to overcome current problems and exploit the potential an integrated, holistic development approach is proposed.

2.1. The three aspects of integration

The integrated development approach proposed takes three different aspects of integration into account: system, disciplines and life cycle.

2.1.1. System

In a system-oriented development each component or subsystem is optimized in a way so that the overall system acts optimal. This incorporates that each component has to be developed with regard to its future inclusion and function within the system and its interactions with other subsystems. For façade solar collectors according to Munari Probst & Roecker [4] a good system integration requires the functional, constructive and formal (aesthetic) integration of the collector into the façade.

Considering the presented drawbacks the integrated development approach pursued especially aims at an improved aesthetic integration of the collector into the façade as well as an improved integration of the heat pipe into the collector regarding both design and operation. For this purpose especially the connections of the heat pipe to the absorber and to the manifold are reconsidered. Already during the development of the heat pipe the future connection to the absorber and manifold is taken into account. Furthermore, an improved heat pipe collector concept requires an optimization of heat pipe and solar collector operation or their interactions, respectively. As one design variable may influence the design of several systems and subsystems, for achieving an optimal design all incorporated systems have to be taken into account during development. An important example is the inclination angle, affecting heat pipe operation, collector operation (IAM) and architectural design.

A system-oriented development first of all requires the definition of the system considered or its boundaries, respectively, which for sure is one of the major development decisions. In the case of a building integrated solar collector, the overall system could be defined as the whole building, comprising auxiliary heating devices (e.g. oil or gas burner), the solar collector and its subsystems, the storage as well as the roof, balcony or façade. However, the complexity of this system would be quite high. As the currently existing drawbacks primarily concern the collector itself as well as its building integration, the system considered afterwards is restricted to the façade, the collector and its subsystems.

2.1.2. *Disciplines*

The optimization of a solar collector in a pure component development first of all aims at the maximization of its efficiency or the minimization of the resulting costs per yield. However, in applied research and development focusing on a holistic approach additional aspects have to be taken into account. For instance, a chosen design of a solar collector should not only result in a high efficiency but also in a low pressure drop and a high or sufficient robustness to withstand wind or snow load. Moreover, the environmental impact has to be minimized. In the case of façade integration even social aspects such as the social acceptance or the influence of transparent façade collectors on the working atmosphere in offices have to be considered. Not least legal and normative aspects have to be taken into account. Thus, integrated development must also aim at the integration of all corresponding disciplines and their development objectives into the development process resulting in a multicriteria optimization.

2.1.3. *Life cycle*

The third aspect of integration concerns the life cycle. For all systems and subsystems and all disciplines the whole life cycle should be taken into account. This means, that for instance for the economic analysis not only manufacturing costs but also installation costs, costs of operation and maintenance as well as recycling costs have to be considered.

Fig. 1 illustrates the three aspects of integration. Even if the degree of integration is reduced (e.g. only consideration of parts of the life cycle and parts of the system) it becomes obvious that an integrated development exhibits a high degree of complexity. Thus, to reduce or rather handle complexity strong development methods are required. Promising techniques are given by the methods of Multidisciplinary Design Optimization (MDO).

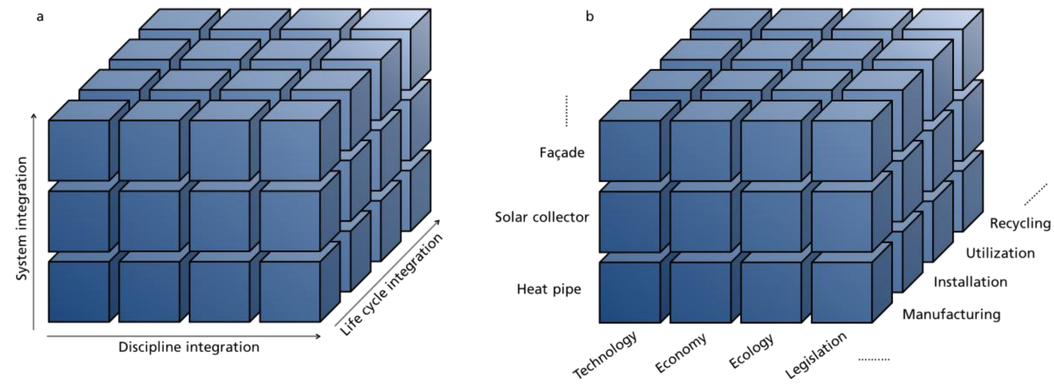

Fig. 1. (a) The three aspects of integration: system, disciplines and life cycle; (b) example (based on sustainability structure of Fraunhofer IBP).

2.2. Multidisciplinary Design Optimization (MDO) of heat pipe façade collectors

Multidisciplinary Design Optimization (MDO) is a field of research that studies the application of optimization techniques for the design of systems that involve a number of disciplines or subsystems [5]. The optimization methods thereby allow the simultaneous optimization of all relevant disciplines [6]. Furthermore, special optimization algorithms as e.g. the Pareto optimization allow a multicriteria optimization.

Originally developed in the field of aerospace engineering, the application of MDO has been extended to several other engineering disciplines (e.g. automobile [6], building design [7], etc.). With the heat pipe solar façade collector clearly being a multidisciplinary system (see Fig. 2) the application and adaption of these methods to heat pipe solar façade collector development represents an adequate and interesting approach.

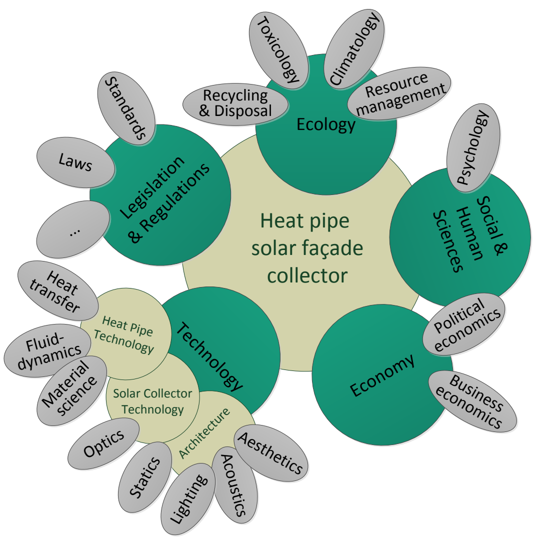

Fig. 2. Examples of disciplines influencing the development of a heat pipe solar façade collector.

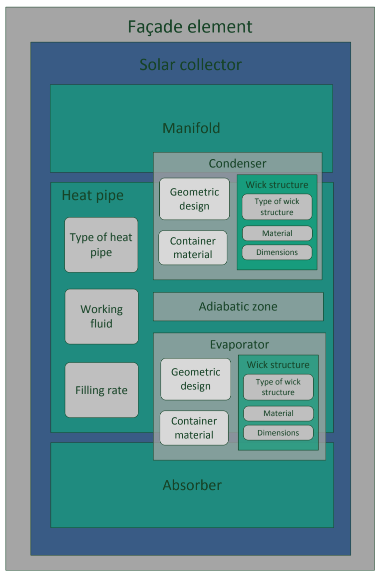

Fig. 3. Scheme of the nested black box model structure.

To successfully transfer MDO to building design, Geyer [7] developed methods which enabled the consideration of qualitative development goals such as flexibility or aesthetics within the optimization process. The implementation of MDO to solar façade collector design will require an adequate approach.

Even if MDO bases on mathematical optimization algorithms, it is clearly more than this. Already the first step of the MDO process – the summary, structuring and selection of the influencing factors taken into account, the resulting requirements, criteria, optimization objectives and constraints as well as the definition of the design variables and fix parameters – represents an important and challenging development task. For selecting reasonable objectives and constraints the structured assessment of all relevant development criteria is helpful. In

Fig. 4 an extract of a summary of possible technological and economic criteria for heat pipe façade collector development organized in a tree diagram is presented.

The maybe biggest challenge lies in development of the criteria analysis models the optimization bases on. To support the development process properly an early and continuous application of MDO is preferable. Therefore, models in different levels of detail are required which furthermore are flexible for alteration. Moreover, to support system integration the models should be suitable for both looking at the whole system and a specific subsystem in detail. To fulfill these needs, a "nested black box model structure" based on object-oriented programming is chosen. A simple example of the nested structure is shown in Fig. 3. Due to the chosen model structure the collector can be modeled at different system levels and with different level of detail. When the collector is investigated from an overall perspective subsystems can be considered as black boxes with defined input and output parameters, which are independent of the internal level of detail of the model. This means that for instance the collector efficiency can be modeled by the efficiency curve with parameters being derived from measurements (black boxes) or physical calculations of different detail. Moreover, the chosen model structure enables the representation of all interfaces and interactions between the subsystems so that a holistic optimization can be pursued. To further ensure the development of the collector from a holistic point of view, some subsystems are modeled as overlapping systems. Within the collector model an enhanced model of the solar heat pipe is being developed.

Besides its application as optimization method MDO can also be implemented for design exploration [7]. Applied as a design exploration tool, MDO can deliver important information about the design space and help handling complexity.

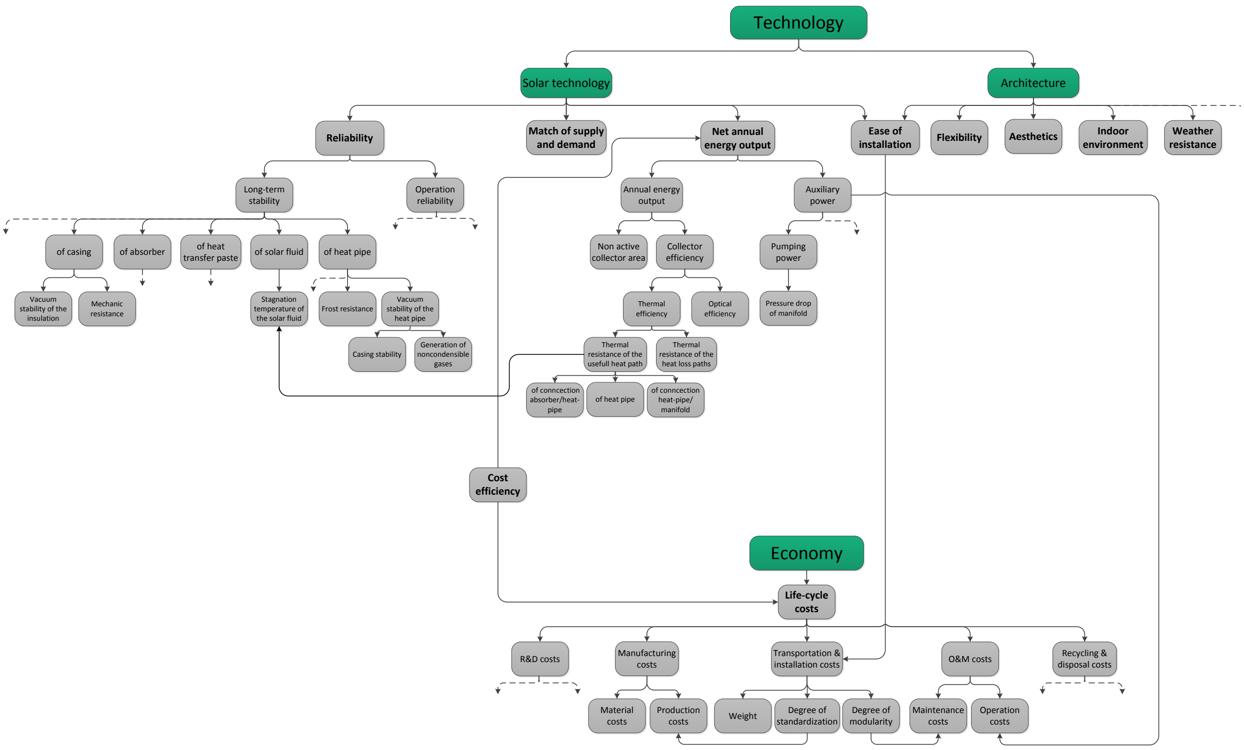

Fig. 4. Tree diagram of possible technological and economic criteria for heat pipe façade collector development (extract).

3. Examples of integrated heat pipe collector designs

Even if MDO is a powerful tool, it won't be possible (or reasonable) to develop a model which incorporates all possible solutions for a heat pipe collector. Before starting the MDO process, the basic structure of the collector design must already be given. This also means that by setting up the basic collector design some design decisions are already made (e.g. evacuated tube or flat-plate). The process of setting up the basic structure can also be supported by development methods (e.g. TRIZ "theory of inventive problem solving") [8].

Two examples of integrated innovative heat pipe collector designs were already developed which shall be optimized by MDO. The first concept is an evacuated tube collector suitable for roof or balcony integration or process heat applications. The second collector concept uses plane heat pipe stripes for opaque façade integration (see Fig. 5). To reduce the thermal resistance of the heat pipe connection to the absorber, in both collector concepts a direct selective coating of the heat pipe itself is considered. Moreover, an integrated innovative condenser-manifold design was developed, aiming at a lower thermal resistance and a lower pressure drop in the manifold. Due to fabrication by extrusion processes low manufacturing costs are expected. The developed manifold concept also ensures a high degree of design flexibility as the distance between the tubes or stripes can be chosen individually. This also offers space for architectural designing. The dry manifold connection enables an easy and cost-effective installation and maintenance. To allow a high freedom of orientation and thus ensure a good architectural integration a wick structure will be implemented in the heat pipes which enables the condensate to return to the evaporator against gravity. The flat plate design of the stripe collector further improves the architectural integration. Moreover, different lengths of heat pipe stripes might be connected to one manifold enabling individual design and good area utilization in case of perforated window facades. As the fluid circuit of heat pipe and manifold are separated, no costly individual hydraulic balancing is required. Both collector concepts already ensure a high degree of integration, further being optimized by MDO.

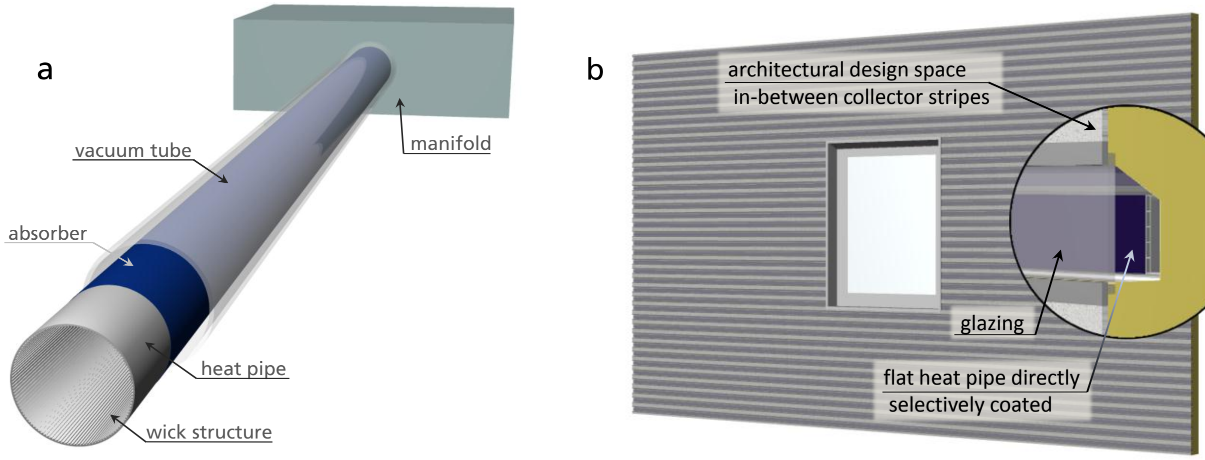

Fig. 5. Examples of integrated collector concepts: (a) evacuated tube heat pipe collector, (b) heat pipe stripe collector.

4. Conclusions

The integrated development approach proposed represents a promising method to overcome current drawbacks of heat pipe solar collectors sustainably and thus exploit their potential successfully. To handle the high complexity of integrated development a structured development supported by development methods is required. Here, the application and adaption of the methods of Multidisciplinary Design Optimization (MDO) to heat pipe solar collector development represents a promising approach.

By rethinking heat pipe design within the integrated collector development two innovative holistic heat pipe façade collector concepts are being developed. While maximizing efficiency and minimizing costs, their design especially aims at a high degree of design flexibility and aesthetic integration, ensuring an increased acceptance by architects and society and thus representing an important step towards growing solar installation.

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