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Research Paper

Development and examination of switchable heat pipes

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HIGHLIGHTS

- A thermal switch concept for intelligent temperature control is presented.
- Heat dissipation through a heat pipe is passively regulated.
- Switching is performed by a shape memory alloy actuator.
- Experimental investigations demonstrate a high potential for future applications.
- The computational model of the switch is able to predict the system's behavior.

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ABSTRACT

The well-directed transmission of heat flux enables an efficient and demand-actuated temperature control of technical systems. By the combination of heat pipes and shape memory alloy actuators, an adaptive, passively working switch concept is developed and implemented, which automatically activates the heat flux through the heat pipe when reaching a certain temperature limit. Furthermore, the created numerical calculation model provides the opportunity to theoretically describe the behavior of the designed system. Measurements show the proof of the concept and validate the model for further optimizations of switchable heat pipes to be applied in various technical applications.

1. Introduction

The heat pipe as a two-phase heat transfer device offers the possibility of passive heat exchange and features remarkable thermal properties. Due to its great thermal conductivity the heat pipe is a highly efficient tool for a wide range of applications and has been subject of several recent studies [1–4]. Established fields of application are thermal control of computer systems, solar cells or nuclear power reactors, to name but a few [5–7]. However, there are still numerous potential applications of industrial cooling facilities as for instance machine tools which are not considered yet. As a result of the increasing demands on accuracy and efficiency in machining operations thermal management solutions using heat pipes gain in importance in order to prevent thermoelastic deformations of machine parts and optimize the energy input [8].

As for electric vehicles active temperature control of the battery is necessary, because the ideal operating temperature ranges from 20 °C to 35 °C and considerable reduction of performance and operating life already starts at 45 °C [9,10]. Usual requirements for mobile applications like the occurrence of different ambient temperatures lead to scenarios of complex heat flux distribution and in combination with the need to reduce weight and installation space demand integrated thermal management systems.

The objective of this study is to propose and evaluate a concept for a self-actuated device to perform a switch operation allowing for the transfer of the heat flux from the heat source to the heat sink only after exceeding a certain critical temperature. Experimental and numerical results are compared and discussed in order to determine criteria for further development and industrial application of the concept.

As shown in Fig. 1, a heat pipe is a hermetically sealed vessel containing a wick structure and a working fluid on the inside. Heat applied to the evaporator region causes the fluid to vaporize. Due to the resulting pressure difference in the pipe the vapor flows toward the condenser region, where it condenses. The released latent heat of condensation is absorbed by the provided heat sink. The capillary pressure generated by the wick structure forces the working fluid to flow back to the evaporation section. In this way a continuous transport of latent heat is accomplished. Beyond the very low thermal resistance, advantages of the use of heat pipes as thermoconductive structures are the noiseless working principle as well as the large quantities of heat that can be transported over a considerable distance with no additional power input to the system [11]. Following this, adding the feature of switchability can give way

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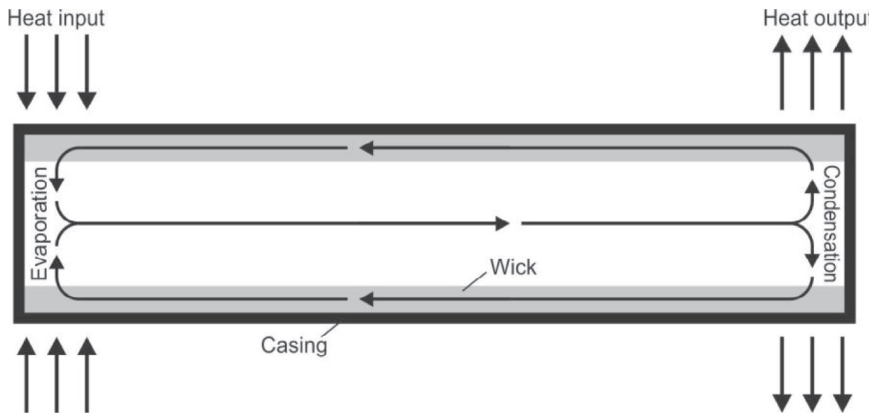

Fig. 1. Schematic diagram of a heat pipe.

for energy savings by selective tempering and demand-actuated provision of cooling capacity which will prove beneficial especially when it comes to local variable heat loads.

Various analytical and numerical approaches have been developed in order to examine the thermal behavior of heat pipes. Whereas former investigations focused on the simulation of steady-state vapor flow in heat pipes [12], more comprehensive models have been proposed during the last years. An extensive overview of the different models is given by Faghri [11]. Recent studies cover improved modeling of the thermophysical properties of working fluids [13] as well as the modeling of loop heat pipes [14] and micro flat heat pipes [15]. Analytical models for the design of conventional heat pipes can also be found [16].

Successful attempts to realize variably controllable heat pipes were already introduced in several works during the last years. To only briefly address the concepts most closely linked to the purpose, this article refers to the papers summarized in Table 1. The listed concepts can be categorized into designs that are based on either external or internal working principles on the one hand and either active or passive actuation, which means with or without the necessity for an additional energy source for the switching operation, on the other hand.

Summarized, it can be stated that most realizations of switchable heat pipes are based on specific designs to realize an internal switch. In most cases the thermal switch requires auxiliary power supply or major additional effort and aside from that existing devices were found to be respectively restricted to specific fields of application.

A novel idea which has been suggested is to combine heat pipes and shape memory alloys (SMAs) to reach a passive thermomechanical self-regulating switch including the efficient dissipation of exceeding heat loads. Successfully implemented, this combination is an efficient way of regulating temperature fields as it benefits from the good thermal properties of the heat pipe as well as the temperature-induced phase transitions of the SMA, as illustrated hereafter.

When a SMA is heated, it begins to transform from martensite into the austenite phase. Having manipulated the form of a SMA element by the exposure to an external force the SMA element can be heated beyond the critical temperature to start the structure transformation into the austenite phase and therefore will start to recover its original form, i.e. typically to contract. This transformation is possible even under high applied loads, and therefore results in high actuation energy densities. During the cooling process, the transformation starts to revert to the martensite at the temperature determining this transition. In addition to this so called one-way effect, a two-way SMA can remember its shape at both high and low temperatures. This behavior can also be achieved by making use of an external retraction element resulting in the so-called external two-way shape memory effect.

In recent years, efforts have been made to use SMA elements as actuators in switchable heat pipe systems. Benafan et al. developed a SMA activated heat pipe-based thermal switch for temperature management purposes in space-related applications [23]. Based on a variable length heat pipe and SMA spring elements, a self-regulating system was realized to reject heat from a liquid oxygen tank into space during the lunar night cycle while providing thermal isolation during the day cycle. In this concept various SMA springs are arranged in an antagonistic system with biased springs. When the temperature of the SMA elements falls below the threshold value, the spring stiffness decreases which results in a deflection of the SMA springs so that contact is made between the heat pipe and the oxygen tank. At high temperatures the SMA springs overcome the force of the bias springs and the heat pipe is pulled back to its initial position. In this position no heat transport occurs and the tank remains isolated.

Other studies dealing with the combination of heat pipes and SMA elements can be found in the field of solar technology or automotive engineering and demonstrate the potential of such systems as thermal management solutions [17,22]. At the same time, it is apparent that a deeper examination of the topic is necessary to accomplish a wider application of heat pipe structures with SMA switches.

The aim of this study is to design and evaluate a new concept that allows the self-regulated initiation and interruption of heat flow between a heat source and a heat sink. The present work demonstrates the development of a corresponding concept as well as its theoretical and practical examination. The remarks are based on the

Table 1
Overview over existing variably controllable heat pipe concepts.

Concept	Working principle	Actuation	Reference
Heat pipe with moving plug	Internal	Passive	[17]
Heat pipe with storage tank	Internal	Passive	[18]
Variable conductance heat pipe (VCHP)	Internal	Passive	[19]
Heat pipes with magnetic valve as control element	Internal	Active	[20]
Heat pipes with valve flap as control element	Internal	Active	[20]
VCHP with piston	Internal	Active	[21]
Externally moved heat pipe	External	Passive	[22]
Lunar oxygen tank	External	Passive	[23]
Heat pipes with thermal coupling as control element	External	Active	[20]