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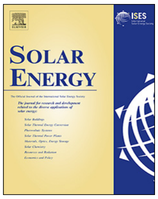

Experimental and theoretical investigations on temperature limitation in solar thermal collectors with heat pipes: Effect of superheating on the maximum temperature

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ABSTRACT

Heat pipes in solar thermal collectors enable to reduce the temperature loads in the solar circuit during stagnation periods by exploiting their dry-out limit. With this approach vapour formation in the solar circuit can be completely avoided, which is essential to reduce costs of solar thermal systems by simplified and more reliable solar circuits. The design of "deactivating" collector heat pipes with a desired maximum temperature requires a comprehensive understanding of the heat transfer processes in the heat pipe, in particular when dry-out takes place. We developed a model, which allows calculating the maximum fluid temperature in the collector for various working fluids. Compared to existing approaches, the effect of superheated vapour in the heat pipe during stagnation is additionally considered. The paper describes the theoretical model in detail and its extensive experimental validation. The results show that the model is able to predict the maximum fluid temperature with an accuracy better than 5 K. Based on parametric studies with different working fluids, we analyse and discuss the temperature limitation and its effect on the collector performance.

1. Introduction

Heat pipes in solar thermal collectors are state-of-the-art devices for the heat transfer from the absorber plate to the solar circuit (see Fig. 1). This technology is well-established for evacuated tube collectors, for flat plate collectors it has been only demonstrated in research projects up to now (e.g. by Jack et al., 2014). Solar thermal collectors with heat pipes provide in comparison to direct-flow collectors simpler hydraulic connections as well as the possibility of avoiding stagnation loads by thermally decoupling the absorber plate from the solar circuit.

If the heat transfer by two-phase flow inside the heat pipe is suppressed beginning from a defined temperature, the maximum temperature in the solar fluid can be limited to reduce thermal loads (see Fig. 2). By using this thermo-physical effect, which is called dry-out limitation, the collectors' internal heat transfer coefficient U_{int} can significantly decrease in dependence on the operating temperature. Based on this technology, evacuated tubes with an inherently safe temperature limitation to 160 °C are already distributed by the German company NARVA Lichtquellen GmbH & Co. KG (Mientkewitz and Zabel, 2010). By further reducing the temperature to about 120 °C, vapour formation in the solar circuit can be completely avoided. Thus, the costs of solar thermal systems can be reduced significantly by simplification and more reliability in general.

Within the research project "Cost effective and reliable solar systems with novel heat pipe collectors" we focus on the optimization of the heat pipe's heat transfer ability as well as on the hydraulic connection with the solar circuit both for flat plate and evacuated tube collectors (Föste et al., 2015). Further, we investigate the dry-out behaviour of collector heat pipes with different working fluids by experiments and theoretical models. In order to correctly design heat pipe collectors preventing overheating, the heat transfer processes need to be described comprehensively. The paper presents a new model, which extends a previous one already developed at ISFH (Jack, 2016) by taking superheating effects into consideration and enables an accurate prediction of the maximum fluid temperature.

2. Operating states of collector heat pipes

In the operating range, the heat transfer in the heat pipe takes place by evaporation, vapour transport from the evaporator to the condenser, condensation and backflow of the condensate to the evaporator. This cycle is carried out in the two-phase region of the specific heat pipe

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Nomenclature

Symbol	quantity [unit]
A	area [m^2]
d_i	inner tube diameter [m]
f_B	wetting factor [W/m^2]
G	global radiation [W/m^2]
g	gravity [m/s^2]
l	length [m]
$\dot{m}$	mass flow rate [kg/h]
m_{fluid}	mass of working fluid [kg]
p	pressure [bar]
$\dot{Q}$	heat flow rate [W]
T	temperature [°C]
U	internal heat transfer coefficient [W/m^2 K]
V	volume [m^3]
v	specific volume [m^3/kg]
x_g	vapour content [–]
x	variable of heat pipe length [m]
z	film width of condensate [m]
α	inclination angle (0° = horizontal) [°]
Δh	evaporation enthalpy [kJ/kg]
ΔT	temperature difference [K]
δ	film thickness [m]
ρ	density [kg/m^3]
η	efficiency [–]
η_c	dynamic viscosity of condensate [Pa s]

Subscripts

abs	absorber
amb	ambient
aperture	aperture area
c	condensate
cond	condenser
evap	evaporator
fluid	working fluid
g	gas
gain	heat gain
heat	electrical heat
HP	heat pipe
i	control variable (evap, trans, cond)
l	liquid phase
loss	thermal losses
sat	saturation
stag	stagnation
trans	transport zone
v	vapour phase

working fluid (see Fig. 3, (1)). If the temperature at the evaporator is furtherly increased, the two-phase equilibrium is shifted towards the vapour-phase. At the point where the remaining amount of liquid is not sufficient to fully moisten the evaporator zone, the bottom of the evaporator dries out – the so called dry-out limit is reached (see Fig. 3, (2)). At higher evaporator temperature the dried section of the evaporator becomes larger, thus the heat transfer rate of the heat pipe decreases. This dry section of the evaporator is filled with superheated vapour, which is not saturated anymore. During a stagnation period of a solar thermal collector, this superheated region extends over the complete evaporator (see Fig. 3, (3)). For typical collector heat pipes, the evaporator represents about 90% of the whole inner pipe volume. Thus, the heat pipe pressure is mainly determined by the pressure prevailing in the superheated evaporator. As a result, a downsized heat pipe cycle between the transport zone and the condenser takes place until the working fluid is completely evaporated (see Fig. 3, (4)). This effect leads to higher temperatures in the condenser zone than expected if only the dry-out limit is considered. To design deactivating heat pipes, which limit the temperature in the fluid circuit of solar collectors to a desired maximum, it is essential to theoretically describe this effect in detail.

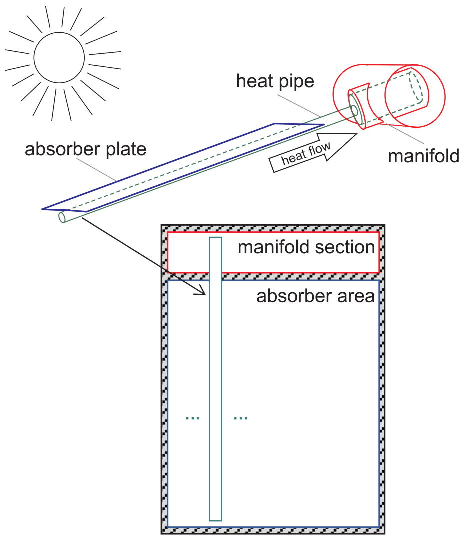

Fig. 1. Schematic drawing of a solar collector configuration with a heat pipe as an additional component between absorber plate and manifold.

Most of the literature deals with calculation models for heat pipes or two phase thermosyphons with untypical dimensions for solar application i.e. Rösler et al. (1987). The great difference between condenser volume and evaporator is very unusual for the most common applications of heat pipes. Furthermore these investigations are mainly focused on the heat pipes' operating range (state 1) and on the maximum heat pipe power (corresponding to state 2). Using the dry-out effect for a defined process limitation is on the contrary not discussed. Rather the avoidance of this situation takes a central role in literature. Existing approaches, described i.e. by Faghri (1995), Riffat et al. (2002) or Golobič and Gašperšič (1993), cannot be used to design a suitable power limitation of collector heat pipes.

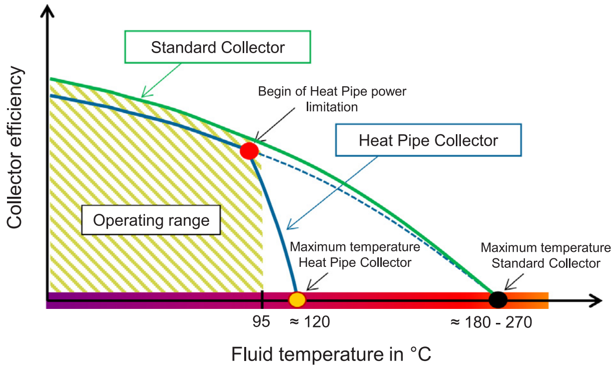

Fig. 2. Characteristic efficiency curve of a heat pipe collector with power shut off (maximum fluid temperature of 120 °C) compared to a standard collector (maximum fluid temperature of 180 – 270 °C, depending on the collector technology).