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Low-e confined air chambers in solar flat-plate collectors as an economic new type of rear side insulation avoiding moisture problems

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Abstract

Flat-plate collectors usually are insulated by a 40–60 mm thick mineral wool layer. Under dry conditions, typical thermal conductivities are between 0.035 and 0.060 W/m K depending on absorber temperature. Therefore, in brand-new flat-plate collectors, absorber rear side losses are in the region of 1 W/(m^2 K). However, during operation, the rock wool can absorb humidity from ambient air and the thermal insulation deteriorates substantially. As an alternative, we show theoretically and experimentally, that if the mineral wool is removed, the emerging air chamber, if adequately confined, has acceptable insulation properties (rear side absorber losses 1.5–2.0 W/(m^2 K)) simultaneously reducing the collector height substantially down to 20 mm. This is due to wall-adhesion and inner friction preventing air from convection, while the radiation heat transfer is suppressed by low-e walls confining the air chamber. Additionally, an efficient insulation system consisting of two air chambers has been established: A cheap (below 1 \$/m^2), thin (below 50 μm) and low emissive (thermal emissivity below 0.05) film mounted parallel between absorber and rear casing shows similar insulating properties as mineral wool and is not sensitive to humidity. Especially Al-foils are well applicable. Simultaneously, the total height of flat-plate collectors can be reduced by 10–20 mm. Theoretical calculations of convective and radiative rear side losses of the absorber have been done. On the base of series collectors, prototypes with rear side film insulation have been constructed and successfully tested at an outdoor test facility. The nightly stationary loss measurements and daytime efficiency measurements according to ISO 9806:2013 corroborate the theoretical modeling and the good efficiency of the insulation: For insulation thicknesses between 30 and 50 mm, the film insulation shows comparable and even slightly better insulation values as conventional dry mineral wool. The long term stability of the Al-film, including mounting, has been investigated theoretically and experimentally over 2 years and shows the practical applicability of the new insulating technique in flat-plate collectors.

Keywords: Avoiding moisture problems of mineral wool; Air gap and film insulation; Economic flat-plate collector; Suppression of reverse natural convection

1. Introduction

Nowadays, flat-plate collectors at the rear side are insulated by rock wool or similar (fibrous or porous) insulation materials. If dry, i.e., in brand-new collectors, their thermal conductivity amounts to 0.035–0.06 W/m K for temperatures between 20 °C and 100 °C (Ochs et al., 2007; Ochs and Müller-Steinhagen, 2005). For a typical insulation thickness of 40–60 mm, the rear side collector losses in regular operation amount to about 1 W/(m^2 K) from 3 to 5 W/(m^2 K) total losses.

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Nomenclature

A	view factor, –
a_1	collector heat loss coefficient according to ISO 9806, W/(m^2 K)
a_2	temperature dependence of collector heat loss coefficient, W/(m^2 K^2)
c_p	specific fluid heat capacity, kJ/(kg K)
d	plate distance, characteristic length, m
g	acceleration of gravity, m/s^2
G	hemispherical vertical solar irradiance, W/m^2
M	molar mass, kg/mol
Nu	Nusselt number, –
p	gas pressure, Pa
$\dot{q}$	useful collector heat flux, W/m^2
R	universal gas constant, J/(mol K)
Ra	Rayleigh number, –
s	plate linear extension, m
T	temperature, K
T_a	temperature of collector ambient or surrounding, K
T_f	temperature of the collector fluid, K
T_i	temperature of the collector inlet, K
T^*_m	reduced (fluid) temperature during daytime operation, (m^2 K)/W
T_o	temperature of the collector outlet, K
U_{coll}	collector overall heat loss coefficient, W/(m^2 K)
$U_{convection}$	absorber heat loss coefficient through convection, W/(m^2 K)
U_{rad}	absorber heat loss coefficient due to radiation, W/(m^2 K)
$U_{rad,i,j}$	radiation heat loss coefficients between plates i and j, W/(m^2 K),
$U_{rear\ convection}$	heat loss coefficient of the absorber due to rear convection, W/(m^2 K)
U_{total}	total absorber heat loss coefficient, W/(m^2 K)
$U_{total\ rear\ side\ loss}$	total rear side absorber heat loss coefficient, W/(m^2 K)
$\dot{V}$	volumetric flow rate per aperture area, m^3/(s m^2)

Greek

β	collector slope, °
ΔT	temperature difference, K
ε	thermal emissivity, –
$\eta_{0,hem}$	maximum collector efficiency, with reference to T^*_m based on hemispherical vertical irradiance G, –
η_{hem}	collector efficiency, with reference to T^*_m based on hemispherical vertical irradiance G, –
λ	heat conductivity, W/m K
μ	dynamic viscosity, Pa s
ρ	density of the fluid (air), kg/m^3
σ	Stefan-Boltzmann constant, W/(m^2 K^4)

But mineral wool insulation shows some disadvantages: The handling during production is difficult and during operation, water is absorbed from moist ambient air via the ventilation holes, especially if the collector cools down in the evening. Furthermore, over collector life-time of 20 years, the casing or the fluid pipes can have a (due to limescale or similar deposit) leak and transiently or permanently soak the mineral wool insulation (Holck et al., 2003; Köhl et al., 2007).

If wet, the thermal conductivity of mineral wool increases rapidly, in particular at temperatures between 60 and 100 °C. In unfavorable cases with high moisture content, up to 20-fold values of the thermal conductivity by vapor diffusion have been observed (Ochs et al., 2007). Apart from the lower collector efficiency, additionally cover fogging and corrosion of the collector parts occur, especially of the selective coating. These effects become more significant after some years of operation.

So far, we have not found a quantitative examination on the moisture content of mineral wool in solar collectors after many years of operation. For buildings, comparable investigations exist and demonstrate the principal problem (DOW, 2014), especially for materials that are not furnished with hydrophobic admixtures (Jiřičková and Černý, 2006). Over a longer period of moisture content, the mineral wool can clump up or collapse irreversibly and the binding agent can lose its functionality.

The described problems are known to the manufacturers and are obvious at many solar collectors showing fogged glass covers, at least in the morning. Remedies like improved ventilation are discussed in scientific publications (Holck et al., 2003; Köhl et al., 2007). The topic will be especially important, if future collector tests preferably do not only assess the performance of the new product but also check the long term stability.

As an alternative, at the ZAE Bayern a film insulation or more generally speaking, a thermal insulation by air gaps of appropriate dimensions, has been investigated in a publically granted project (German Federal Ministry of Environment, grant number. 0325987A). This new approach can substitute the mineral wool at the same efficiency and is insensitive to moisture. Additionally, the collector thickness can be reduced.

2. Flat-plate collector without insulation: Free reverse convection in a small air chamber with low-e confinement

If the mineral wool is removed, humidity problems no longer occur. Instead, free reverse air convection (“hot top-plate” constellation) and free radiation transport is