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Comparison of modelled heat transfer and fluid dynamics of a flat plate solar air heating collector towards experimental data

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Abstract

Research concerning the field of Liquid Heating Collectors (SLHCs) cannot be directly transferred to the large area of applications for Solar Air Heating Collectors (SAHC). Larger cross sections for transporting the air are necessary. This results in rather complicated fluid distributions within the products. In this paper we combine simulation and experimental techniques providing a high level of detail. Highly resolved three dimensional fluid dynamic simulations contain all the relevant heat transfer mechanisms in a plate SAHC: Heat conduction, convection patterns and radiation are modelled in the two air gaps. In all solid materials of the collector only heat conduction has to be accounted for. For the exchange of heat between the two air zones the heat transfer through the absorber is modelled. Nevertheless careful simplification is needed to be able to concentrate on the important details. Furthermore we shed light on numerical instabilities observed in the air gap between absorber and glass in the simulated example.

A consistent numerical description is given, concluding, that Computational Fluid Dynamics (CFD) is an appropriate tool for design and optimisation of SAHC concepts. The effects of collector tilting, insulation level and heat transfer surface increase have been assessed as a prove of applicability. The performance of these models will finally be compared to the experimental data obtained using a high-precision SAHC testing facility. For the experimental data base refined local measurement techniques, which meet highest accuracy requirements, are developed and employed.

Keywords: Computational Fluid Dynamics (CFD); Flat plate Solar Air Heating Collector (SAHC); Heat loss; Solar thermal

1. Introduction

1.1. General background

Solar Air Heating Collectors (SAHC) have some interesting potential benefits (no danger of frost, no health and environmental dangers due to leakages) in comparison to Liquid Heating Collectors (SLHC) and are potentially cheaper in acquisition and maintenance (Stryi-Hipp et al., 2008; Thoma et al., 2010, 2011b). Draw-backs are on the other hand induced by the lower heat transfer capacity (Welz et al., 2014). Those boundary conditions make it even more crucial to gain a detailed understanding for performance evaluations (Stryi-Hipp et al., 2011). Recently, their primary field of application is providing industrial process heat (e.g. drying processes). Heating of working

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Nomenclature

α	absorptivity, absorptance (–)
β	thermal expansion coefficient (K^{-1})
ΔT	temperature difference (°C)
$\dot{m}$	mass flow rate ($kg\ s^{-1}$)
$\dot{Q}$	useful power extracted from collector (W)
$\dot{V}$	volumetric flow rate ($m^3\ s^{-1}$)
ϵ	emissivity (–)
κ	thermal diffusivity ($m^2\ s^{-1}$)
λ	thermal conductivity ($W\ m^{-1}\ K^{-1}$)
μ	dynamic viscosity ($kg\ m^{-1}\ s^{-1}$)
ν	kinematic viscosity ($m^2\ s^{-1}$)
ω	specific dissipation rate ($1\ s^{-3}$)
ρ	density ($kg\ m^{-3}$)
τ	transmissivity, transmittance (–)
ϑ	temperature (°C)
G	solar irradiation ($W\ m^{-2}$)
g	gravitational constant ($9.81\ m\ s^{-2}$)
h	heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
k	turbulent kinetic energy ($m^2\ s^{-2}$)
P	absolute pressure (Pa)
p	static pressure (Pa)
R_D	gas constant of water vapour ($J\ kg^{-1}\ K^{-1}$)
R_L	gas constant of air ($J\ kg^{-1}\ K^{-1}$)
rH	(relative) humidity (%)
T	temperature (K)

u, v	velocity, air speed ($m\ s^{-1}$)
x_W	water content (kg H_2O/kg dry air)
y	height of air-gap (m)
c_p, c_f	specific heat capacity ($J\ kg^{-1}\ K^{-1}$)
CFD	Computational Fluid Dynamics
MLR	multi linear regression
Pr	Prandtl number (–)
Ra	Rayleigh number (–)
SST	shear stress transport

Subscripts

(*eff*, *n*)	effective, normal radiation
(*m*, *th*)	volume flow weighted mean
abs	absorber
amb, *a*	ambient, surrounding
crit	critical
exp	experimental value
ext	external
fc	forced convection
in, *i*	inlet
out, *e*	exit, outlet
pe	downstream air
pi	upstream air
s	atmospheric, sky
sim	simulated value

and living areas, where controlled ventilation is established (like halls and office buildings) is also gaining increasing attention.

Research concerning the field of water driven collectors, however, cannot be directly transferred to the large area of applications for air collectors. Computational Fluid Dynamics simulation (CFD) is well established. Its application to the field of solar collectors, however, only partly. Convective processes are covered in early papers (Eames and Norton, 1993a,b) and numerical CFD simulations have been presented by Selmi et al. (2008). Some simulation results are available for CPC collectors in recent years (Buttinger et al., 2007; Welz et al., 2014). Geometrical variations have been numerically studied in various articles including variations of channel depth (Sun et al., 2010) and absorber plate structures (El-Sebaii et al., 2011; Promvonge et al., 2011). Special numerical topics like artificial roughness studies have been addressed in recent years and presented in a comprehensive review (Hans et al., 2009). Further review articles are available for general thermodynamic, heat and fluid flow analysis (Saxena et al., 2015; Yadav and Bhagoria, 2013; Tagliafico et al., 2014).

In the current paper we present numerical and experimental results for a commercially available SAHC. For both, computational and the laboratory work, innovative approaches have been taken. Thus, the state-of-the-art in the field of SAHCs used in the applied methods has been extended in this work.

The experimental work covers global and local measurement techniques performed at the Test Lab Solar Thermal Systems of the Fraunhofer Institute for Solar Energy Systems (ISE) in Freiburg. The collectors were designed in a way which allowed for rapid changing between different technical layouts (e.g. different glasses). The measurements can be used to extract boundary conditions for the highly resolved numerical simulations. Starting 2003 a test rig (Thoma et al., 2011a,b) for the assessment of solar collectors was designed at *Fraunhofer ISE*. The test rig consists of several parts for assessing different physical quantities which have impact on the calorimetric performance of SAHCs. Some of these measuring components have been specifically developed in the lab (Thoma et al., 2010).

New methods (e.g. three dimensional ultra sonic anemometry for assessing wind vector dependencies) and advanced data processing (e.g. MLR multi linear regression) for the characterisation of SAHCs are developed leading to increased inter-comparability of technological variants. Those empirical results are compared to highly resolved three dimensional fluid dynamic simulations with ANSYS FLUENT done by AIT containing all relevant heat transfer mechanisms (Reichl et al., 2013; Zauner