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Thermal stratification in small solar domestic storage tanks caused by draw-offs

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Abstract

Storage tanks with different cold water inlet devices for small Solar Domestic Hot Water (SDHW) systems are compared. The objective of the investigation is to reveal the impact of the cold water inlet device on the thermal stratification in two marketed tanks and to evaluate the possible enhancement in the annual system performance of small solar heating systems. Two different marketed inlet designs are compared, one connected to a small curved plate placed above the inlet tube, the other one connected to a much larger flat plate. The cold domestic water enters the stores in vertical direction from the bottom of the tanks. Temperature measurements were carried out for different operating conditions. It was shown that the thermal stratification inside the two tanks depends differently on the flow rate, the draw-off volume, as well as the initial temperature in the storage tank. To carry out system simulations, a multi-node storage model was used and expanded by an additional input variable to model the mixing behaviour depending on the operating conditions. The inlet device with a comparatively large plate compared to the less favourable design results in an increase of the solar fraction of about 1–3%-points in annual system simulations with a solar fraction of about 60% and fairly large domestic hot water flow rates. This corresponds to a reduction of the auxiliary energy supply of the solar heating system of about 3–7% (58–155 MJ/year) for the investigated solar domestic hot water system.

Keywords: Storage tank; Thermal stratification; Draw-off; Inlet device; Mixing; Domestic hot water; Pressure drop; Richardson number; TRNSYS simulations; Performance reduction rate

1. Introduction

The influence of the thermal stratification in the storage tank on the performance of a solar heating system has been studied intensively since the 1970s. For increasing thermal stratification, an increasing thermal performance of the system was found. Storage discharge efficiencies were defined, depending on the tank geometry, inlet pipe diameters, flow rates and temperatures (for example Lavan and Thompson, 1977; Sharp and Loehrke, 1979). Most of the annual performance predictions in the past were based on short-term test periods and statistical analysis to predict the degree of mixing

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Nomenclature

A_{col}	collector area (m^2)
f	solar fraction
g	gravity (m/s^2)
h	absolute height (m)
H	relative height
L	characteristic length (m)
$\dot{m}$	mass flow rate (kg/s)
Q	heat (MJ)
r_{pr}	performance reduction rate
Δt_{sim}	simulation time step
λ	conductivity
r_{en}	entrainment rate
Re	Reynolds number
Ri	Richardson number
T	temperature (°C)
V	volume (ℓ)
ρ	density (kg/m^3)
subscripts	
aux	auxiliary
eff	effective
max	maximum
in	in
DHW	domestic hot water
rel	relative

during draw-offs. Further, the reference conditions varied from study to study. Therefore, large variations in performance prediction can be found in the literature.

Detailed theoretical investigations of annual system simulations showed the potential of performance enhancement due to increased thermal stratification due to well designed cold water inlet devices for hot water tanks. In previous studies to these investigations, Andersen and Furbo (1999) showed that thermal destratification can cause a decrease of the net utilized solar energy by up to 23% due do mixing during draw-off, if 51% of the storage tank is mixed during each draw-off applied during the entire simulation. This mixing rate was found for measurements in a marketed solar tank carried out with an initial storage temperatures of 30 °C at the bottom of the store and a flow rate of 0.33 l/s (20 l/min). Knudsen (2002) showed that the net utilized solar energy of small solar heating systems decreases by about 10–16% if the storage tank is mixed in the lower 40% of the storage tank during each draw-off compared to the case that no mixing occurs, depending on the hot water tank design.

In the present study, the degree of mixing for the draw-offs is defined as a function of flow-rates, as well as inlet and storage temperatures. The influence of two different inlet designs on the degree of mixing is evaluated and modelled with the simulation tool TRNSYS (Klein et al., 1998). The water enters the stores in vertical direction from the bottom. The investigations are focused on small SDHW systems with a collector area of 2.5 m^2 and a mean domestic hot water consumption of 100 l/day (T_{DHW} = 45 °C).

In the following, measurements are presented, carried out with thermocouples placed in different heights inside the storage tank. The experimental results are then used for parameter identification purposes, as well as validation of the simulation models. After a description of the experiments in Section 2, modifications of a simulation model for a TRNSYS standard storage tank, TYPE 140 (Drück, 2000), are described in Section 3. In Section 4 measured and calculated curves of the thermal stratification are shown. Finally, annual simulation results of a small solar heating system are presented in Section 5.

2. Experiments

2.1. Experimental set-up

Schemes of the two investigated storage tanks are shown in Figs. 1 and 2. The volume of the water content in the storage tanks is 144 l and 183 l, respectively. In tank I, coil heat exchangers are used in the bottom and top part to transfer solar heat as well as auxiliary energy into the tank, whereas in tank II a mantle heat exchanger is applied to transfer the heat from the solar collector loop into the storage tank. Details about the tank parameters are given in Table 1.

The inlet design of tank I is composed of a curved plate in the shape of a half ball above the inlet pipe, with the same diameter as the pipe (Fig. 1b and c). The second inlet device consists of a flat plate placed above the inlet pipe with a plate/pipe-diameter ratio of about 5 (Fig. 2b and c). Copper-constantan thermocouples (type TT) were placed at 12 positions (tank I) and 17 positions (tank II) in different heights of the storage tank (accuracy of the temperature measurements: about 0.5 K). The maximum error of the measurements of temperature differences in the tank could be reduced to 0.2 K by calibrations. This leads to an overall measurement error far below the differences of calculated and measured values as described in Section 4. Thus, the accuracy of the measurement equipment is sufficient regarding the impact of measurement errors on identified parameters.

The flow meter type *aqua metro, type V2020A1*, was used. Both, flow rates and temperatures were measured