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Numerical simulations of gas–liquid flow in thermal sorption processes

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ABSTRACT

Thermal storage systems, used, e.g., for domestic heating, must be able to compensate the mismatch between supply and demand. The most efficient techniques for thermal storage are based on sorption storage processes. Usually in sorption, the adsorption process occurs in combination with a solid state adsorbent, whereas absorption takes place in a liquid/gas system. During such sorption processes the flow behavior of the carrier medium is crucial for the efficiency of a falling film absorber. In this work the hydrodynamics of the falling liquid film in two geometrical setups, namely on an inclined plane and over two horizontal parallel tubes, is studied. For the simulation the Eulerian–Eulerian model of the software ANSYS CFX and the interFoam application of the open source software OpenFOAM were used. The numerical results of the two geometries were compared with each other and also with existing data from literature to predict the performance of a sorption storage regarding the specific wetted area and the needed height for gravity driven film absorption.

1. Introduction

Solar energy is currently being regarded as one of the most promising substitutes for traditional energy resources. Thermal storage systems are crucial components for such applications because of their ability to compensate the mismatch between supply and demand, e.g., in domestic heating applications. Some existing methods for solar heat storages include water tanks, underground storages with phase changing materials, sorption storages, etc. However, considering domestic heating, the storage system volume becomes important due to place restrictions and due to the mass of the system. The storage density defined as the amount of energy accumulated per unit volume or mass, gives a general relation between different materials. This density depends strongly on the storing meth×od and temperature. For example Hadorn (2007) showed that to store 1850 kWh heat, a volume of 10 m^3 is required for a sorption system, which is considerably smaller compared to a volume of 34 m^3 for sensible heat of water (with a temperature difference of 70 K). Due to the high energy density Hui et al. (2011) described absorption based sorption storages to be most promising for building applications. But there are many challenges to be solved like spraying, tightness, long time vacuum maintaining, choice of the geometry of the heat exchanger, etc.

The thermal sorption includes both, absorption and adsorption, and is defined as the capturing of a gas (sorbate) by a condensed substances (absorbent). Considering storage applications adsorption usually occurs in combination with a solid state adsorbent, e.g., zeolith or silica gel, where absorption takes place in a liquid/gas system. Hui et al. (2011) did an evaluation for different working pairs for an absorption based sorption storage intended as a seasonal storage of solar energy for house heating. According to his study KOH/H_2O seems to be the most economical material combination because of its low price and high storage capacity. There have been different approaches to enhance the storage density of a sorption storage. N'Tsoukpoe et al. (2014) allowed crystallization of LiBr (33 m%) within the storage tank leading to an increase of the storage density by 22%. Quinnella and Davidsona (2012) used a concept of one vessel for storing the $CaCl_2$-solution and the water for the sorption storage. With this approach only one tank was necessary, which can be additionally used as a short term sensible storage. For domestic heating, sorption storages are usually used in combination with solar energy. The process is described in detail in Hui et al. (2011) by evaluating a seasonal storage system of solar energy for house heating using different absorption couples. During summer time the storage is charged by a solar thermal energy system.

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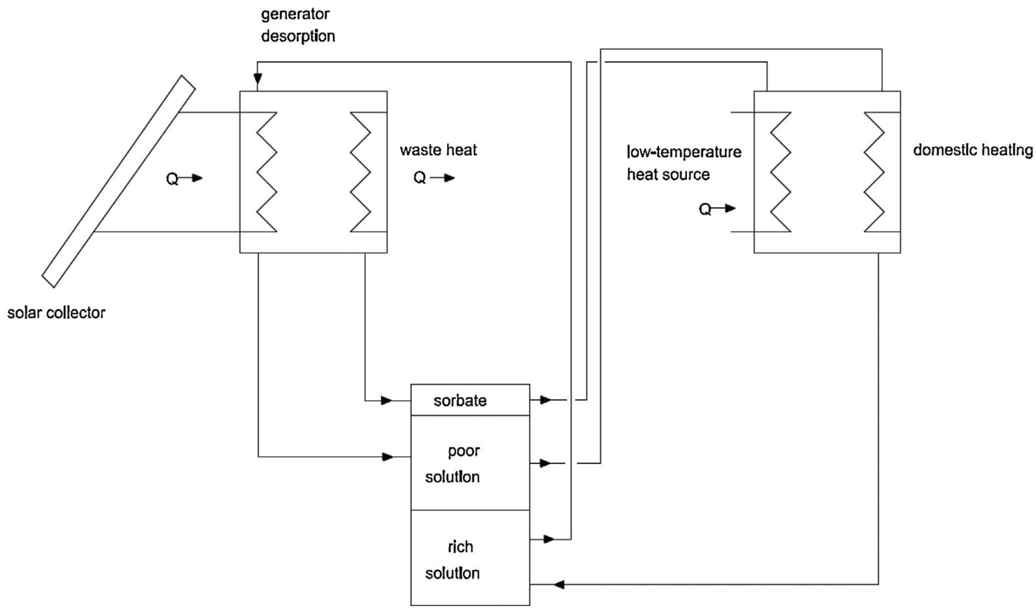

Fig. 1. Sketch of a solar heat system for a seasonal sorption storage.

Thereby the rich solution (high concentration of the sorbate) is pumped into the generator where the sorbate is vaporized and condensed at its thermodynamic equilibrium. The resulting solutions are afterwards seasonally stored. During winter time, an additional low temperature heat source is needed to power the discharging process. Thereby, the absorbent as well as the sorbate are pumped into the generator. The sorbate is vaporized using the low temperature heat source. The released energy, due condensation in the absorbent at a higher temperature, is used to power the domestic heating system as shown in Fig. 1.

During a charging or discharging process losses can occur, e.g., due to mixing, temperature differences, etc. There have been different approaches to build a sorption storage. Weber and Dorer (2008) used flat plates for the absorption process with NaOH/H_2O. Fumey et al. (2014) used a falling film absorber with NaOH/H_2O. They encountered losses due to mixing within the absorber leading to a lower temperature. N'Tsoukpoe et al. (2009) also used a falling film absorber with LiBr/H_2O. During the desorption process they encountered losses due to the high operation temperature of the desorption process. This process should also be optimized to reduce these losses. Industrial established absorption, e.g., absorption chiller usually uses falling-film absorbers with horizontal tubes as described by Hoffmann (1996). This geometry is already established on an industrial scale and the mathematical simulation methods are already derived by Banasiak and Koziol (2009). Due to the similarity of an absorption chiller process and sorption storages, horizontal tubes could be a suitable geometry for such an application.

The flow behavior of the carrier medium is crucial for the efficiency of a falling film absorber. In order to control the desired saturation of the carrier medium, the following parameters are the most important: local Reynolds number on the liquid surface, liquid film Reynolds number, liquid film thickness, turbulence intensity, duration of dwell. Computational fluid dynamics (CFD) have become a useful tool to simulate two- and multiphase flows with a free surface by applying the volume of fluid (VOF) model (Hirt and Nichols, 1981; Biausser et al., 2004). There are a number of publications about numerical studies of liquid-film two-phase flows. Since one goal of the present study is to create a best possible validated simulation model, a widely used setup for which experimental measurements are available is considered. Such a setup has been found in a gravity driven water film flow down an inclined plane. Ausner (2006) performed experiments of water and multicomponent liquid film flows on a $0.05 \times 0.08\,m^2$ (width × length) inclined plane with different angles and measured surface velocity, liquid spreading and fluid thickness by means of particle-tracking-velocimetry (PTV) and light-induced-fluorescence (LIF). Further measurements of water liquid film flows on various geometries, accompanied also by numerical simulations with the CFD code CFX by ANSYS, Inc., were performed by Hoffmann (2010). With the same geometry, Iso and Chen (2011) present CFD simulations performed on the code FLUENT by ANSYS, Inc. which show the effect of increasing and decreasing liquid flow rates (hysteresis) and the effect of various surface characteristics. Cooke et al. (2013) investigated the mesh influence on the flow behavior of a water film flow on a plane with the dimensions $0.05 \times 0.06\,m^2$ inclined by 60°. Their simulations were performed in OpenFOAM, in particular with the solver interFOAM, by comparing a fine resolution static meshes with an adaptive refined meshes (AMR). The investigations show, that simulations with AMR were more able to replicate experimental data by means of the flow pattern.

Further simulations, which involve a liquid flow over two horizontal cylinders were performed. Jafar (2011) made numerical predictions of the flow field and the heat transfer of a liquid falling film over two horizontal cylinders using the VOF-method in the CFD code FLUENT. The investigation shows that the Reynolds number, nozzle width, cylinder diameter and cylinder separation have a significant effect on the flow field and heat transfer characteristic.

The objective of this paper is to investigate the flow behavior of a sodium hydroxide solution as a carrier medium on an inclined plane, which is the designated geometry of the first experimental plant of a sorption storage.

2. Governing equations and numerical method

Due to the fact that a full scale model of a sorption storage including the mass transfer from vapor to the sodium hydroxide solution is very complex and computational expensive, the investigation presented in this paper are based on a simplified model. Thus, a gravity driven flow down an inclined plane was considered by neglecting species absorption and resulting changes of