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Absorber and Regenerator Models for Liquid Desiccant Air Conditioning Systems: Validation and Comparison using Experimental Data

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ABSTRACT

Solar assisted air conditioning systems using liquid desiccants represent a promising option to decrease high summer energy demand caused by electrically driven vapor compression machines. The main components of liquid desiccant systems are absorbers for dehumidifying and cooling of supply air and regenerators for concentrating the desiccant. However, high efficient and validated reliable components are required and the design and operation have to be adjusted to each respective building design, location, and user demand. Simulation tools can help to optimize component and system design. The present paper presents new developed numerical models for absorbers and regenerators, as well as experimental data of a regenerator prototype. The models have been compared with a finite-difference method model as well as experimental data. The data are gained from the regenerator prototype presented and an absorber presented in the literature.

1. INTRODUCTION

1.1 SYSTEM APPROACH

The energy demand for air-conditioning to provide temperature and humidity control has increased continuously throughout the last decades and is still rising. This increase is found both, in commercial and residential buildings and is largely caused by increased thermal loads, residents' comfort demands, and architectural trends. Since by far most of the air-conditioning systems are electrically driven vapor compression machines, the increase is responsible for a large rise in electricity demand and especially high peak loads. The substitution of these compression machines by thermally driven cooling systems using renewable energy or waste heat is a promising alternative. An overview of different technologies for thermally driven cooling systems can be found in Afonso (2006). In particular, due to a high correlation between solar irradiation and cooling demand for most buildings, the application of solar energy is very attractive.

Considering all the different technologies, the use of liquid desiccants in an open cycle system is a promising solution for solar assisted air-conditioning. The main components of these systems are absorber, regenerator, indirect and/or direct evaporative cooling units and heat recovery stages for both, the desiccant solution and the regeneration air. In the absorber, a hygroscopic solution, e.g. LiCl or $CaCl_2$, is directly brought in contact with fresh air, which it dehumidifies. While absorbing the moisture, the concentration of the hygroscopic solution and thus, its capability to absorb water, decreases. This requires drying of the solution, which can be done in a regenerator, where solar thermal energy is used to drive the process. Solution tanks for concentrated and weak solutions offer the option to operate the system even at times when no solar radiation is available.

1.2 THEORETICAL BACKGROUND

Many investigations worldwide have been dealing with modeling and testing of absorber and regenerator designs and performances. For the absorber, mainly two different designs to provide the heat and mass transfer area have been investigated so far:

- Packed-bed designs
- Plate heat exchanger designs

For regenerating the desiccant solution, mainly two more options have been investigated:

- Multistage boilers
- Collector/regenerator designs

Models for packed-bed absorbers and regenerators with simultaneous heat and mass transfer in an adiabatic process have been developed amongst others in Chengqin et al. (2005). Since flat plate absorbers are usually operated with much lower solution flow rates compared to packed bed systems, the absorption process needs to be cooled internally. Thus, a third fluid has to be considered for flat plate designs. Khan and Sulsona (1998) developed a model for parallel plates using NTU relations. Mesquita (2006) developed a model with variable film thickness.

Models for packed-bed or plate regenerator designs are usually similar to absorber models, however the operating temperatures are much higher and thus, the driving forces. Air collector/regenerator models have been developed for example by Alizadeh and Saman (2002).

1.3 EXPERIMENTAL BACKGROUND

Many research groups around the world have been carrying out experimental investigations on liquid desiccant components and systems, a few system are close to market introduction or are even commercially available.

Fundamental research on heat and mass transfer in packed-bed absorbers and regenerators has been carried out for example by Liu et al. (2006). Gommed and Grossman (2007) presented experimental data of a whole liquid desiccant air conditioning system based on packed-beds. Biel and Röben (2002) developed a compact system, incorporating absorber, regenerator, heat recovery and evaporative cooling in one unit. For both systems, pilot plants are under investigation. Lävemann and Peltzer (2005) developed water cooled plate absorbers (and water heated plate regenerators). A second test system is in operation since 2005. Lowenstein et al. (2006) developed a zero-carry over plate heat exchanger design using extruded plates. In order to increase the storage capacity of the desiccant solution, Kessling et al. (1998) are suggesting to operate the system with a high concentration step between concentrated and diluted solution. For both designs, a wicking material, e.g. cotton or fleece, is attached to the plates to ensure an even distribution of solution on the plates.

1.4 CURRENT INVESTIGATIONS

In order to find suitable designs of absorber and regenerator components as well as the control scheme, simulation tools like TRNSYS can be used. Optimizations of a complete system have been performed in Krause et al. (2006).

In the present paper, experimental and theoretical investigations on absorbers and regenerators for liquid desiccant air conditioning systems are presented. Numerical models have been developed and two regenerator prototypes have been constructed and extensively tested. Test results of the second prototype as well as test results from literature are used to validate the numerical models.

2. PROTOTYPE DESIGN

Most solar collectors used for domestic hot water and space heating are water or water/glycol based. If these collectors should be used for air conditioning, too, a regenerator is required, which uses hot water for the regeneration process. Based on previous approaches for water-cooled absorber constructions from Lävemann and Peltzer (2005), two regenerator prototypes designed as plate heat and mass exchanger have been developed and tested. Both prototypes have been extensively tested using different operating conditions. Test results for the first prototype are presented in Krause et al. (2005). Fig. 1 shows a photograph of the second regenerator prototype, which has an improved flow distribution. Test results for this are presented in Fig. 3.

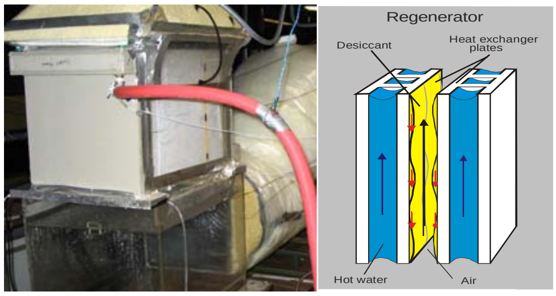

Fig. 1: Photograph of the second regenerator prototype installed in the test rig. The schematic on the right hand side demonstrates the path of air, water and desiccant flows.

3. ABSORBER/REGENERATOR MODEL

A numerical multi-element model has been developed for water cooled/heated absorber/regenerators. The models calculate the enthalpy balances for the water flow, the desiccant film and the air stream for each element along the channels. Both, parallel flow and counter flow conditions can be considered. For each element, heat and mass transfer from the desiccant to the air stream as well as heat transfer through the heat exchanger plates are determined simultaneously. The single enthalpy equations follow approaches from Khan and Sulsona (1998).

The heat transfer coefficients are determined using Reynolds and Nusselt number relationships for laminar and turbulent flow in channels. In order to model different flow

directions of water, air and solution, an iterative procedure including all elements is used.
In order to validate the models, comparisons with measured data are necessary. Since the numerical models are designed as static models, only quasi steady state conditions can be used for the comparison.

3.1 ABSORBER MODEL

For the validation of the absorber model, test data from Kessling (1998) have been used. In the tests, which consist of 14 test sequences with steady-state conditions, the performance of a single plate absorber instead of a multi-plate absorber was tested. Due to this, even distribution of all three fluids could have been assumed. Thus, a quite reliable validation of the theoretical model regarding heat and mass transfer phenomena is possible.
The main results of this comparison are presented in Fig. 2. Since the flow rate of the cooling water was chosen comparably high, and all inlet temperatures are chosen to similar values, outlet temperatures of all fluids are not varying much and are neglected for the comparison. As Fig 2 demonstrates, modeled and experimental outlet mass concentration of the solution show very good agreement. Simulated and tested air humidity follow the same trend, however, the slight difference is caused by uncertainties in the humidity measurement during the tests.

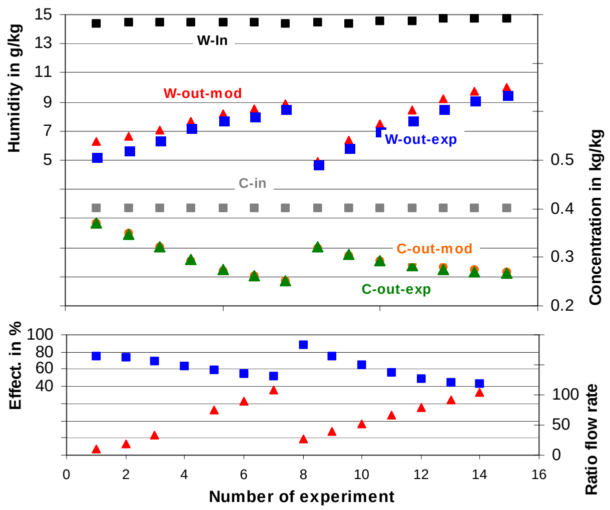

Fig. 2: Comparison of data from the absorber model and 14 sets of experiments gained from Kessling (1998). The top diagram shows air humidity and solution mass concentration (inlet, modeled outlet and experimental outlet conditions), the bottom diagram modeled effectiveness and flow rate ratio between air and solution.

Additionally, the performance of the model has been compared to the finite-difference model from Mesquita et al. (2006). For the same conditions used in the experiments 1 to 7 in Fig. 2, the humidity of the outlet air stream for both models and the experiments together with the inlet humidity are listed in Table 1. It shows that the deviations of the models related to the overall absorbed moisture are in the range of 2-3 %.

TABLE 1: Comparison of the outlet air humidity gained from the presented model and a finite-difference model, cf. Mesquita et al. (2006). The last column represents the flow rate ratio between air and desiccant solution.

Number of test	W_{in} in g/kg	$W_{out-exp}$ in g/kg	$W_{out-mod}$ in g/kg	$W_{out-Mesq}$ in g/kg	Flow rate ratio
1	14.4	5.3	6.3	6.1	10.2
2	14.5	5.7	6.6	6.4	19.4
3	14.5	6.4	7.0	6.8	33.8
4	14.5	7.2	7.7	7.4	55.2
5	14.5	7.8	8.2	7.8	74.8
6	14.5	8.0	8.5	8.1	89.0
7	14.4	8.5	8.9	8.4	108.9

3.2 REGENERATOR MODEL

In contrast to the quasi-isothermal absorber performance, significant temperature changes occur within internally heated parallel plate regenerators. Thus, all the temperature curves, solution concentration and air humidity form the basis for the comparison of model and experiments.
Fig. 3 compares the simulation results with test data of the regenerator presented in chapter 2. At points with steady-state conditions, the comparison shows a good agreement between the outlet temperatures of heating water and air for most of the operating points. Additionally, the resulting air humidity shows good agreement with the experimental data, too, only the desiccant mass concentration shows some discrepancy. However, the latter is caused by uncertainties of the non-continuous mass concentration measurement.
In the experiments, even flow of all three fluids over the plates could not be guaranteed. Especially the even distribution of the solution over the plates is very difficult to realize. Thus, since flow development on the plates is not calculated in the model, effects of non-even distribution could only be considered using additional parameters. However, since the non-even distribution could not be measured directly, the effective heat and mass transfer area used for the simulations had been adjusted to the heat and mass transfer in the experiments. Additionally, the heat transfer value through the plastic plates was fitted to the experimental results.
Considering these adjustments, experiments and model show good agreement independent on the operating conditions.

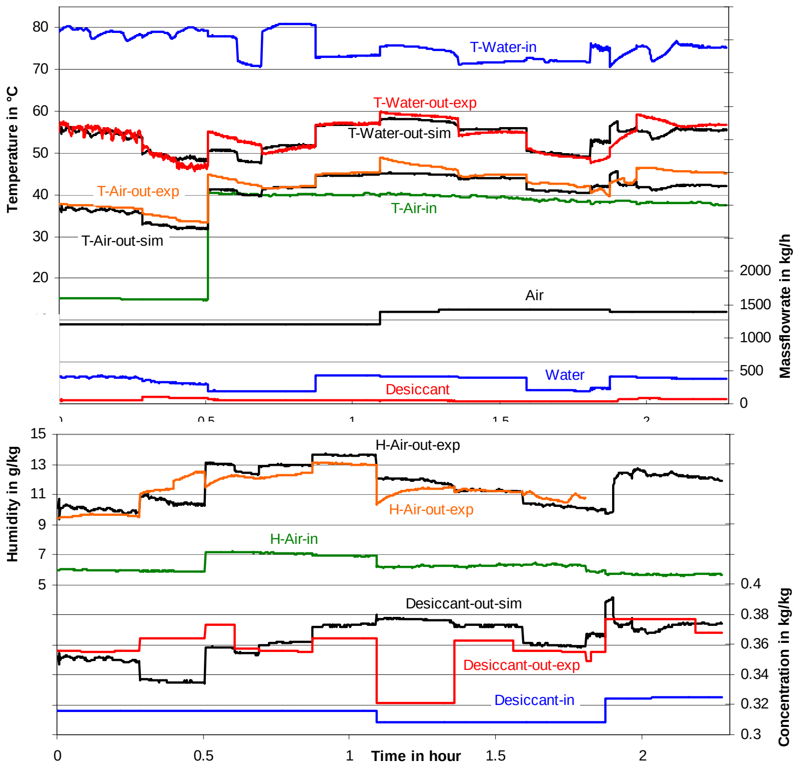

Fig. 3: Simulation and experimental results of the regenerator. The top diagram shows water and air temperatures and the three flow rates, the bottom diagram air humidity and solution mass concentration.

4. RESULTS AND OUTLOOK

Both, experimental and theoretical investigations on heat and mass exchangers for a liquid desiccant air conditioner have been carried out. Two prototypes for regenerators have been build and tested regarding their operational behavior. Additionally, models for regenerators and absorbers have been developed. The regenerator model has been compared to measured data from the second regenerator prototype. The absorber model has been validated with test data from literature as well as a finite-difference model.

The investigations showed that a validation is possible within the limits of the uncertainties of the experimental tests. Both, experiments and simulations demonstrated the option of using the presented design for components of liquid desiccant systems. However, additional construction work is necessary. Additionally, in order to design solar air conditioning plants, simulation studies of a whole system including the building are required.

5. ACKNOWLEDGEMENTS

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