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Grey-box modelling and *in situ* experimental identification of desiccant rotors

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HIGHLIGHTS

► Grey-box modelling of a silica gel desiccant rotor was performed for a DEC system.
► An original method was used to experimentally identify the physical parameters.
► Accurate predictions have been obtained with the one-dimensional model.
► The identified desiccant mass was 30–40% lower than its theoretical value.
► The identified specific heat was 1.5–2 times higher than its theoretical value.

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ABSTRACT

This work focuses on grey-box modelling of desiccant rotors. The main objective is to enhance the accuracy of the desiccant wheel model at off-design conditions, including unbalanced flows and variable rotational speed, by introducing tuneable parameters which can be experimentally identified. In order to perform parameters' identification on full-scale Desiccant Evaporative Cooling (DEC) units, an *ad hoc* measurement apparatus has been developed and tested, along with a suitable identification procedure. The core of the measurement apparatus consists of a set of eight sensors which allow measuring the process air temperature profile at the dehumidifier wheel outlet. The apparatus was installed in an experimental DEC setup. With the support of numerical modelling, a methodology to identify the physical parameters of the desiccant wheel has been developed. The method is based on a one-dimensional physical model of the generic rotor channel. The results show that the recorded temperature profiles in a few operating conditions are sufficient to identify the model's tuneable parameters and that the model's output is valid over a different and wide range of operating conditions. Moreover, the influence of tuneable parameters on the model predicted temperature profile and the comparison of the experimentally identified parameters with their theoretical expected values are discussed. Finally, it is concluded that the accuracy of the one-dimensional model can be improved when its physical parameters are experimentally identified rather than estimated on the basis of literature data. Therefore, grey-box models of commercial wheels would be very helpful in cases where numerical simulations are employed for the design and control optimization of real life DEC systems.

1. Introduction

Desiccant and evaporative cooling (DEC) systems are gaining popularity due to the possibility to use environmental benign low temperature heat sources, such as solar energy and waste heat. Different system concepts have been investigated, from both the theoretical and experimental perspective. Henning et al. [1] have investigated the combined use of co-generation, electricity driven heat pump and DEC systems in Mediterranean climates for tertiary uses. The case study treated of an office building in Palermo, Italy, and reported electricity savings in the range of 25–34% depending on the desiccant system configuration used. Mazzei et al. [2] have studied hybrid systems using desiccant rotors with electricity driven heat pumps. The condensation heat rejected by the heat pump is used to pre-heat the regeneration air, which is finally heated up to the necessary regeneration temperature by a conventional boiler. The study, addressing tertiary uses (supermarkets,

Abbreviations: CHP, combined heat and power; DEC, desiccant and evaporative cooling; HVAC, heating ventilation and air conditioning; PGC, pseudo-gas side controlled (heat and mass transfer coefficients); ETC, experimentally identified (heat and mass) transfer coefficients; GSR, gas side resistance; GSSR, gas and solid side resistance; RPH, revolutions per hour; RMSE, root mean square error.

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public halls) in Rome, Italy, reported operating costs and primary energy savings in the range 25–38% and electricity savings in the range 34–50%. Mavroudaki et al. [3] have explored the applicability of solar assisted desiccant cooling system in Europe. The study envisaged a high potential in central Europe and some parts of southern Europe whereas applicability to Mediterranean coastal sites was said questionable. The main technical barrier at southern latitudes is the high regeneration temperature required in order to neutralize the high latent load. The amount of thermal energy provided by solar varied largely with location, from 25% in London to 93% in Oslo. Gamou et al. [4] have addressed the operational planning optimization for a co-generation system with micro-turbine and desiccant cooling unit, for use in the Japanese tertiary sector (offices and hospitals). The operation status of the plant is determined so as to minimize the hourly cost of purchased energy (natural gas and electricity). The numerical study has shown both energy and operational cost savings in the range of 6–10%. All the mentioned studies used numerical simulations for the assessment of the energy performance of the DEC systems considered. Nevertheless, few is known and published in literature on the effect of the core model, the wheel, on these simulation studies results. Further a review of the different mathematical modelling activities presented in literature for this purpose is given, highlighting the problem of the accuracy against the DEC systems performance analysis. Moreover a novel solution towards the wheel performance identification is presented, along with the comparison with experimental results.

2. Literature review

In DEC units, the desiccant wheel is the heart of the system and its performance, affected by rotor configuration and operating conditions, is not easy to characterize. Not only the influence of temperature and humidity at the inlets of the wheel needs to be carefully assessed, but also the possibility to independently vary flow rates, select the regeneration and dehumidification area ratio, and vary rotational speed shall be considered in order to optimize the design and the control of the whole DEC system. Consequently, the experimental characterization of desiccant rotors requires a large number of test conditions and accurate measurements, which are seldom available to engineers.

The lack of reliable, thorough and readily accessible experimental data has motivated a few experimental works, with the aim to create the correct characterisation base for the wheel models to be used in the DEC systems performance analysis. Kodama et al. [5] have investigated the variation of the outlet air state with increasing rotational speed for a silica gel based desiccant rotor and developed simple equations for the prediction of the process air outlet state at the optimal rotational speed. Enteria et al. [6] have conducted experiments on a 300 mm diameter, 100 mm depth silica gel rotor and provided measurements of the wheel outlet states for low regeneration temperatures (60, 70 and 80 °C) at different flow rates and wheel rotational speeds. Eicker et al.[7] have characterized newly developed rotors composed of different desiccant material, i.e. titanium silicate, lithium chloride, silica gel and silica gel - lithium chloride compound, providing detailed maps for dehumidification capacity, regeneration specific heat input, dehumidification efficiency and enthalpy change of process air at different operating conditions.

Alternatively, the performance of desiccant rotors can be predicted through mathematical modelling on the basis of governing physical equations. Recently, Ge et al. have reviewed more than 20 models [8]. They have different level of complexities: simplified methods, one-dimensional physical models and two-dimensional physical models. Simplified methods include effectiveness method based on the so called F_1 F_2 potentials [9], the ε-NTU method [10] and empirical correlations of the wheel outlet states [11]. In one-dimensional physical models, also known as Gas Side Resistance (GSR), the spatial variations of air and desiccant properties are considered only in the channel axial direction, assuming uniform properties within the desiccant layer thickness [12]. In two-dimensional models, also known as Gas and Solid Side Resistance (GSSR), heat and mass transfer resistance is considered also in the channel wall in the direction normal to airflow. Majumdar [13] has developed a model which accounts for moisture transfer in a microporous felt composed of silica gel particles and inert material, including effective ordinary and Knudsen diffusion for moisture and surface diffusion for the adsorbed phase. Zhang and Niu [14] have applied the GSSR model to the case of the rotary exchanger. Sphaier and Worek [15] have developed a fully normalized system of equations for the GSSR wheel model and investigated the effect of varying the sorbent mass fraction in composite felt for an enthalpy wheel.

On the one hand, two-dimensional physical models are less suitable for system parametric simulations due to their complexity, high computation time and the additional physical parameters involved, including e.g., surface and Knudsen diffusion coefficients. They are mostly used in the optimization of the wheel design, allowing investigating the effect of the channel wall thickness, shape and composition. In order to reduce model complexity and number of parameters, simplified analytical treatment of the solid side resistance was investigated by either applying the integral method in the solid side, supposed isothermal (see Chant [16]), or using *ad hoc* experimental correlations (PGC, Pseudo-Gas Controlled coefficients) for the transfer coefficients, which allow to simplify the model to one-dimensional. Indeed, literature on PGC coefficients addressed packed beds of granular silica rather than corrugated profiles. Heat and mass transfer coefficients for packed beds were provided by Hougen and Marshall [17] and the validity of the PGC model with respect to experimental data was later assessed by Pesaran and Mills [18].

On the other hand, simplified models have also drawbacks. They were derived on the basis of conservation and transfer equations solved through simplified analytical treatment or by analogy with heat regenerators. Moreover, they provide only mixed outlet states, so that experimental verification of the models requires also mixed air temperature and humidity measurements. Finally, empirical correlations, due to the number of independent input parameters (temperature, humidity, and flow rate at the two inlets and the rotational speed), require large volumes of experimental data.

Very little is known about the overall accuracy of the different models, although accuracy in predicting the desiccant wheel performance is of paramount importance for successful design and control of DEC systems. Accuracy against experimental data of the effectiveness method has been reported by a few authors. Stabat and Marchio [9] have compared their model to manufacturer's and experimental data. Neti and Wolf [19] have compared experimental data on a silica gel rotor to the effectiveness method and to numerical solutions obtained by the finite difference method. Recently, Panaras et al. [20] have investigated the experimental performance of a silica gel desiccant rotor with respect to simulated predictions using constant effectiveness values. In general, the reported accuracy cannot be said satisfactory. As an example, humidity ratio deviations between simplified models predictions and manufacturers data can be as large as 1 g kg^{-1}. Considering that the typical dehumidification capacity at low regeneration temperatures and outdoor humidity ratios is about 5 g kg^{-1}, inaccurate models could end up in errors as large as 20%.

However, with the contribution of experimental measurements, accuracy of desiccant wheel models can be improved. In this work,