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Air Drying in an Industrial Compressor

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Abstract. In many industrial applications where compressed air is used it is necessary to increase the quality of the air by decreasing its humidity. This is done by either a condensation or adsorption dryer in the compressor circuit. In this article, the focus is on an industrial adsorption air dryer. The dryer is briefly described together with its function and a selected range of adsorbents suitable for air drying. The paper further deals with the development of a mathematical model of air humidity adsorption which is based on the Pseudo Gas-side Controlled (PGC) model. This paper contains a detailed description of the model and describes its implementation in MATLAB. Finally, the results of the simulations are discussed.

1 Introduction

Compressed air is used in many industries and, with the expansion of automatization and the use of pneumatic equipment, it could be said that it has become an essential sources of power. In many crucial applications, it is not only the precise pressure, but also the quality of the gas that needs to be maintained. The quality of compressed air is determined by its humidity, i.e. the lower the humidity, the higher the quality. It goes without saying that water condensation and its subsequent leakage from the compressor via the distribution piping or from the equipment itself is not only undesirable in clean and sterile applications such as food processing plants (for example in meat or milk processing where water condensation occurs frequently due to the low temperatures), but it is also unwanted in all industrial plants.

Therefore, condensing or adsorption dryers are used for drying compressed air. Condensation dryers are cheaper, but the air does not reach a sufficiently low relative humidity (given by a low dew point value) and thus cannot prevent condensation at temperatures approaching the freezing point of water. It follows that to achieve high quality compressed air, i.e. to achieve the lowest possible humidity, adsorption drying is required.

According to [1], the adsorption process is characterized by the adhesion of molecules or ions of a given substance, usually called an adsorbate, to a solid or liquid surface, usually called an adsorbent. The adsorbate is usually present in the gaseous or liquid phase. It is a process that affects only the surface of the adsorbent. If the molecules do not adhere to the surface but permeate the volume, it is absorption. The opposite process to adsorption is called desorption. In terms of the long-term reliability of the dryer operation, it is essential to ensure that desorption is efficient enough to avoid the accumulation of water (or adsorbed substances in general) over time, which would ultimately lead to dryer failure and could also cause failure of the following technology. Adsorption occurs commonly in nature and has many industrial applications (for example air drying) [2].

This article provides a brief overview of industrially used adsorbents for air drying, together with a description of the dryer and its role in the compressor circuit. A* 1D

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mathematical model of the cycle is briefly described with a detailed description of the 1D adsorption model. Both models are implemented and numerically solved using MATLAB software. The derived model should be able to predict the outlet moisture content, pressure and temperature of the compressed air after passing through the dryer column which is in the compressor circuit. Thus, this model is able to predict the compressed air properties not only for adsorption but also for desorption that is necessary in order to maintain the long-term reliable operation of the entire circuit.

Nomenclature

A_b	bed cross section area [m^2]
a	volumetric surface are [m^2/m^3]
c	specific heat [J/kg K]
H_A	heat of adsorption [J/kg]
h	convective heat transfer coefficient [W/m^2 K]
h_m	convective heat transfer coefficient [kg/m^2 s]
k	thermal conductivity [W/m K]
$\dot{m}$	mass flow rate [kg/s]
m	mass [kg]
q	average water content [$kg_w/kg_{dry\ adsorbent}$]
T	temperature [°C]
t	time [s]
v	superficial velocity of air [m/s]
w_a	air humidity [kg_w/kg_a]
w_s	equilibrium humidity [kg_w/kg_a]
z	axial position [m]

Greek

ρ	density [kg/m^3]
ε	bed porosity

Subscripts

0	initial condition
a	air side
b	bed
s	adsorbent side
v	water vapor
w	water
z	axial direction

2 Dryer in compressor cycle

As mentioned above, the adsorption dryer is part of the compression circuit, as shown in Fig. 1. A fabric air filter is located at the inlet of the entire circuit to filter particulate matter from the intake air. This is followed by a shut-off damper which prevents the exhaust of pressurized air from the circuit and allows the air supply to the circuit to be regulated. Next comes the compressor, in this case a two-stage screw compressor with intercooling. The compressed air then travels to the oil separator where it is stripped of cooling oil by centrifugal force and then passes through a fine fabric filter. Next comes the cooler. Since the air is hot after being pushed, it must be cooled in the heat exchanger. This exchanger is a plate exchanger, composed of two parts. In one part the hot oil flows and in the other the compressed air from the compressor flows. The heat is dissipated by the ambient air which is driven through the exchanger by a fan.

The cooling of the compressed air causes some of the humidity to condense and therefore the heat exchanger can also be considered as a condensation dryer. This means that the performance of the adsorption dryer is largely influenced by the performance of the heat exchanger, which is dependent on the temperature of the ambient air. The more water condenses in the exchanger, the more water will be removed in the next part of the cycle, the separator, and the less moisture will need to be removed in the adsorption dryer itself.

Finally, the compressed gas goes into the adsorption dryer where it is dried to the desired humidity. After leaving the dryer, when the air has the desired properties, it is distributed through pipes for final use.

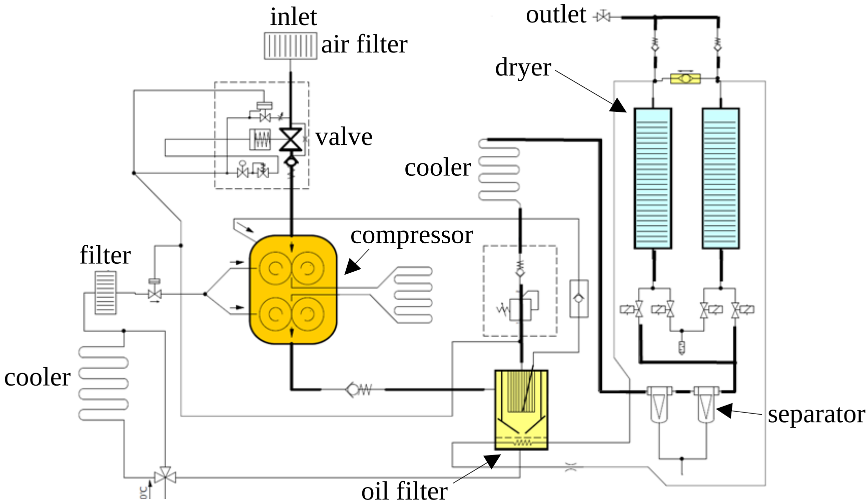

Fig. 1. Compressor circuit

3 Air dryers

According to [3], there are three basic types of air dryers: chemical, refrigeration and adsorption dryers. However, for all types of dryers, the air must be properly cooled and free of condensate before entering, meaning that the already condensed humidity must be removed in a moisture separator.

3.1 Chemical air dryers

Chemical air dryers contain materials that bind to the air or absorb moisture from the air when in close contact. There are two types: one that uses a spray in the form of pellets or granules, and the other type uses liquid ethylene glycol that absorbs water vapour. The glycol is regenerated (i.e. dried) in the plant using fuel gas or steam as the heating medium. The released moisture is discharged into the atmosphere. The regenerated glycol is recirculated by a pump through a water-cooled cooler which lowers the temperature of the glycol before it returns to the drying vessel [3].

3.2 Refrigeration air dryers

Refrigerated air dryers are used in the air system before and after compression. In the pre-compression system, the air must be cooled to a lower temperature for a given final dew point pressure in the duct. This requires more cooling capacity for the same end result. Two systems are used for cooling the air after compression. The flow in smaller and medium sized systems is predominantly air flow through directly cooled coils. Larger systems cool water that circulates through coils and cools the air. Such a system can reach a lower dew point [3].

3.3 Adsorption air dryers

According to [3], adsorption is the ability of some extremely porous materials to hold vapour in their pores, until the desiccant is heated or exposed to a drier gas. The material is always in a solid state and undergoes alternating cycles of drying and regeneration (there is no change in its composition). The most frequently used materials for air drying are activated alumina and silica gel, and molecular sieves are also sometimes used. Adsorption is suitable for achieving the lowest feasible humidity values.

The reverse process is called regeneration and is crucial in terms of long-term reliable operation of the dryer. Regeneration is used to remove the adsorbed humidity and is usually carried out by diverting some of the already dried air through a pressure reducing valve or orifice, thereby reducing the pressure to atmospheric levels and subsequently removing part of the adsorbed moisture. This air along with the recovered moisture from the saturated drying bed is discharged into the atmosphere. To increase the efficiency of the regeneration process, the drying air is often heated before it passes through the drying bed, or the bed itself is heated: the air then removes much more moisture from the system.

For our simulations, both silica gel and activated aluminium F-200 are used as adsorbents. The former is used so that we can validate the mathematical model with experimental data from literature, the latter is modelled because it is used in the compressor circuit's adsorption unit. We assume that these adsorbents are poured into the dryer in the form of beads.

4 Mathematical model of adsorption

The mathematical model of air drying is based on the law of conservation of mass and the law of conservation of energy. These equations are applied to both the adsorbent and the adsorbate. The conservation law of mass for the adsorbate yields the following equation:

$$\frac{\partial w_a}{\partial t} = - \frac{\dot{m}_a}{\rho_a \varepsilon A_b}\frac{\partial w_a}{\partial z} - \frac{h_m a}{\rho_a \varepsilon}(w_a - w_s) \tag{1}$$

The law of conservation of mass for the adsorbent can be written as follows:

$$\frac{\partial q}{\partial t} = \frac{\dot{m}_a}{m_s}(w_{a,\,z} - w_{a,\,z+dz}) \tag{2}$$

Furthermore, the energy equation for the adsorbate can be expressed in the form:

$$\frac{\partial T_a}{\partial t} = - \frac{\dot{m}_a}{\rho_b \varepsilon A_b}\frac{\partial T_a}{\partial z} + \left[\frac{ha}{\rho_a c_a \varepsilon} + \frac{c_V h_m a}{\rho_a \varepsilon}(w_a - w_s)\right](T_s - T_a) \tag{3}$$

Finally, we can write the energy equation for the adsorbent as:

$$k_b \frac{\partial^2 T_s}{\partial z^2} + H_A h_m a(w_a - w_s) + ha\,(T_a - T_s) = c_s \rho_s (1-\varepsilon)\frac{\partial T_s}{\partial t} \tag{4}$$

These equations [4], are suitable for modelling adsorption using the first-order Pseudo Gas-side Controlled (PGC) model, which is suitable for emphasizing the physical characteristics of the adsorption mechanism [5]. Moreover, for the mathematical modelling of adsorption, it is necessary to know the adsorption isotherm model in addition to the equations mentioned above. In principle and according to [6], the models can be divided into:

- a model based on the potential theory of Polanyi

- a single-layer chemical model of adsorption
- a multilayer physical model of adsorption
- an ion exchange model

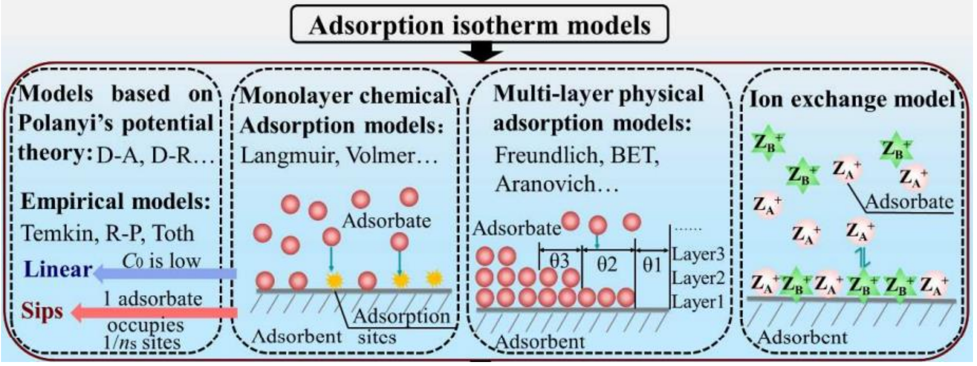

Fig. 2. Adsorption isotherm models [6]

These models are compared in Fig. 2. Another important equation in the mathematical model is the adsorption isotherm. According to [6], the isotherm represents the relationship between the equilibrium concentration of the adsorbate and the equilibrium amount of adsorption at a given temperature. Using isotherms, information about adsorption such as the adsorption mechanism, maximum adsorbent capacity as well as adsorbent properties can be investigated. In principle, we can have three mechanisms of adsorption [6]:

- monolayer chemical
- multilayer physical
- ion exchange

For our mathematical model, the adsorption isotherm from [7] was used for the silica gel. This adsorption isotherm is an empirically generated polynomial in which the relative humidity is calculated from the adsorbent saturation. For the activated alumina, the same polynomial was derived using a data sheet from the adsorbent manufacturer (BASF). Thus, in both cases empirical models of the adsorption isotherm are used.

4.1 Simplification and assumptions

For the mathematical modelling we use a cylindrical dryer with a height of 0.8m and a diameter of 0.13m. A non-isothermal, adiabatic adsorption model is chosen for the simulation. The following assumptions were considered in the derivation of the model:

- Pressure drop in the column is neglected
- Moist air contains water vapour as the only adsorbable component
- The particles of the adsorbent are round and have a uniform diameter
- Uniform porosity is assumed at all points in the column
- Heat transfer is considered only in the column height direction, i.e. the walls are considered to be adiabatic
- No chemical processes take place in the column

4.2 Implementation and numerical solution

The mathematical model was implemented and numerically solved in MATLAB. The air dryer column was divided into a defined number of layers (see Fig. 3) and for each layer the system of differential equations mentioned above was applied using the central difference scheme for numerical solution of the first and second derivative, which in general form yields:

$$f'(z) = \frac{f(z+h) - f(z-h)}{2h} \tag{5}$$

$$f''(z) = \frac{f(z+h) - 2f(z) + f(z-h)}{h^2} \tag{6}$$

where *h* is the height of the layer and *z* is the axial coordinate of the column. This yields a large system of ODEs that was solved using the commonly used *ode45*, i.e. the explicit Runge-Kutta method with variable time-step.

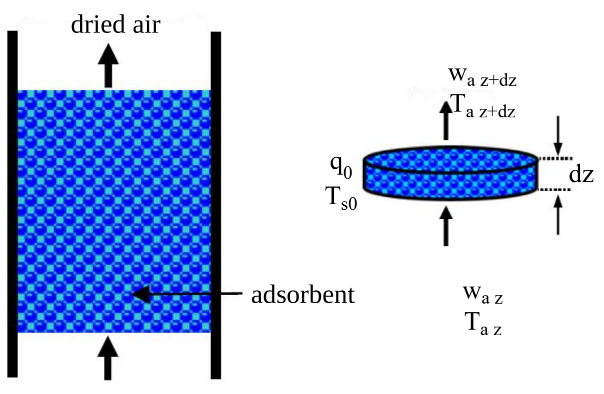

Fig. 3. Discretization of adsorber column [7]

The base equations are accompanied by auxiliary equations (for example for saturation water pressure, etc.) and also by boundary and initial conditions. These conditions are summarized below:

$$T_a\,(z, t=0) = T_{a0},\quad T_s\,(z, t=0) = T_{s0},\quad w_a\,(z, t=0) = w_{a0},\quad q\,(z, t=0) = q_0 \tag{7}$$

$$T_a\,(z=0, t) = T_{a,\,in},\quad w_a\,(z=0, t) = w_{a,\,in},\quad \left.\frac{\partial T_s}{\partial z}\right|_{z=0} = \left.\frac{\partial T_s}{\partial z}\right|_{z=L} = 0 \tag{8}$$

5 Adsorbents

In connection with the mathematical modelling of adsorption, we conducted a review of adsorbents commonly used in industrial applications. Only adsorbents suitable for air drying are listed here. According to [5], adsorbents can be used in several forms, as powder, small pellets, or granules. The most important property of an adsorbent is porosity which is associated with high surface area. Another important property of adsorbents is mechanical and wear resistance. Last but not least, the adsorbent should allow easy regeneration. Many adsorbents are amorphous and contain networks of interconnected pores. The types of pores are shown schematically in Fig. 4. In adsorption, water molecules must first penetrate the film of liquid occurring on the surface of the adsorbent particle. Then they pass through the macropores to the micropores where the molecules are adsorbed.

According to [8], silica gel and activated alumina are generally suitable for adsorption of moisture from humid air.

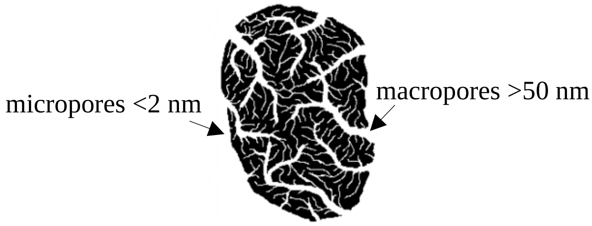

Fig. 4. Types of pore in adsorbent [5]

5.1 Silica gel

Silica gel is the most widely used adsorbent in industrial applications. Its main advantage is its high adsorption capacity and easy regeneration, meaning low regeneration temperature [8]. It is prepared by coagulation of colloidal silicic acid, which leads to the formation of porous and nanocrystalline granules of various sizes. The surface area of the granules ranges from 250-900 m^2/g [5].

5.2 Activated alumina

Activated alumina is a synthetic porous crystalline gel with a surface area ranging from 200 to 300 m^2/g [5]. Activated alumina has a higher capacity for water than silica gel at elevated temperatures, on the other hand has lower adsorption for elevated relative humidity (as seen in Fig. 5). Activated alumina has a low adsorption heat for water and other polar substances [8]. However, the disadvantage of this adsorbent is its higher regeneration temperature.

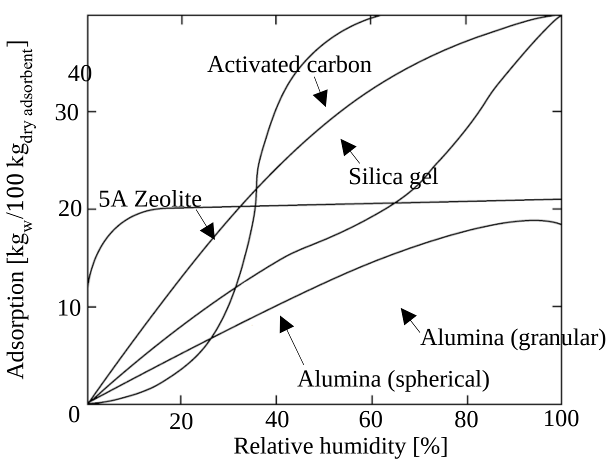

Fig. 5. Adsorption isotherms of water vapour from atmospheric air [8]

6 Results

In this chapter, the results obtained from the mathematical model are presented. First, we compare the results with the experimental data from literature and then we discuss the results for the compressor circuit and the adsorption dryer.

6.1 Comparison with experimental data

The mathematical model was validated using experimental data from [7] which gives measurements of adsorption using silica gel. The comparison shows that the mathematical model corresponds very well to both adsorption (Fig. 6) and desorption (Fig. 7). The agreement is not just for the output humidity of the air, but also for its output temperature. In the graphs below, the orange dots indicate the measurements from [7], in blue you can see the resulting variables over time from the mathematical model.

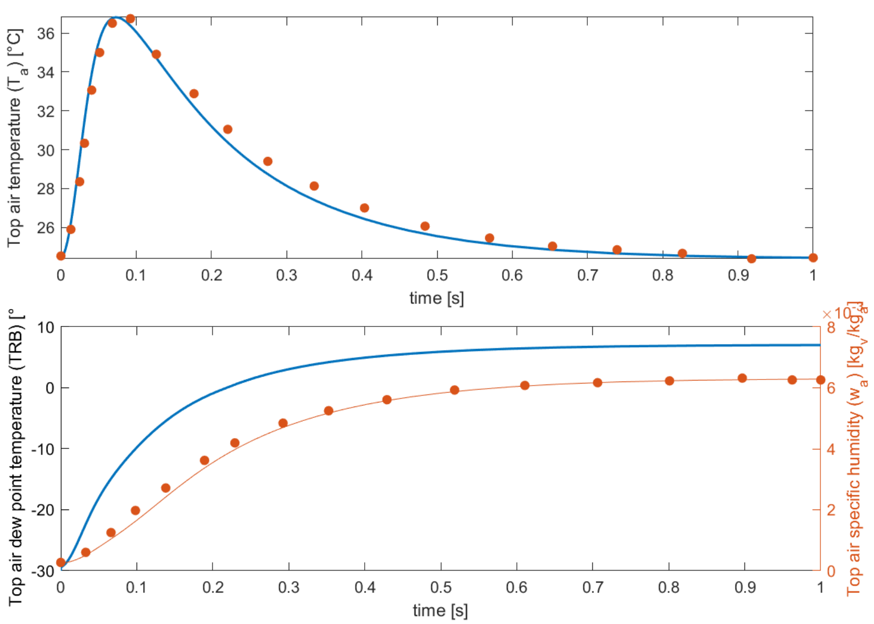

Fig. 6. Comparison of the adsorption process using silica gel

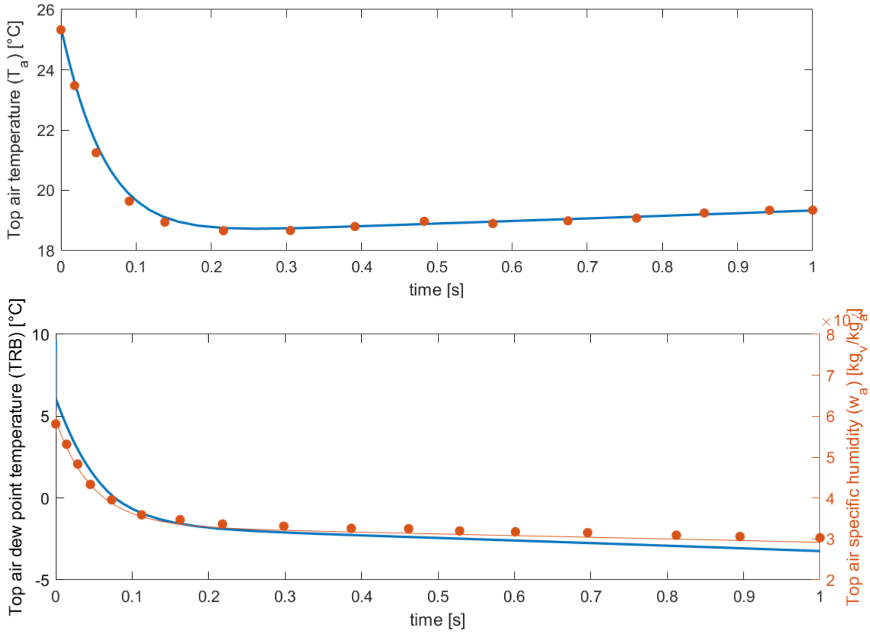

Fig. 7. Comparison of the desorption process

6.2 Results for the adsorption dryer in the compressor circuit

In this subchapter, the results concerning the adsorption dryer in the compressor circuit are presented. In the dryer, the adsorbent is activated alumina, so the adsorbent properties are different from those used in the previous simulation. The resulting outlet humidity and temperature curve is shown in Fig. 8. The orange line in the graph of the output humidity is there because in the mathematical model the output humidity is also plotted using the dew point temperature (blue plot). Since the dew point temperature is pressure dependent, these variables have a different path.

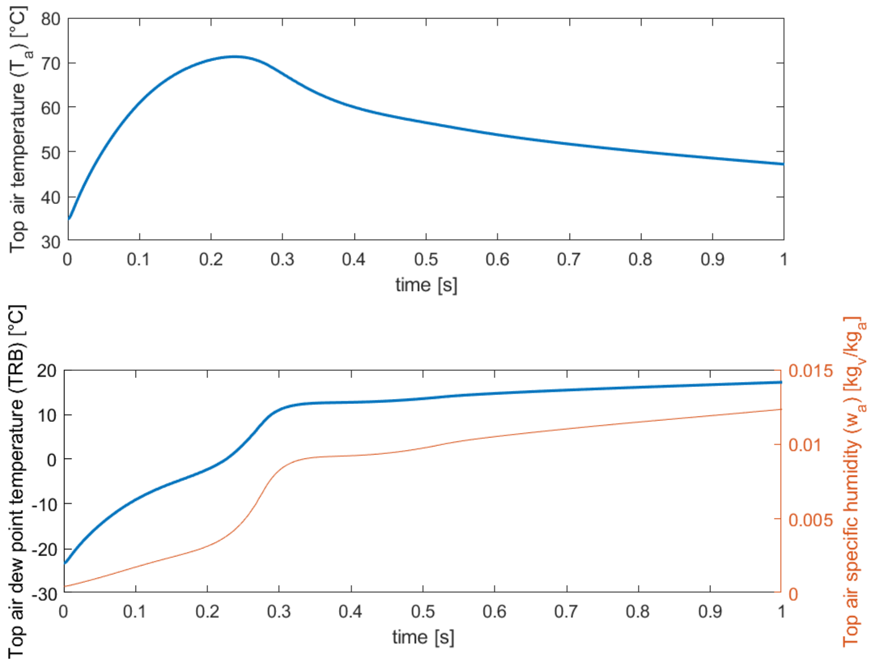

Fig. 8. Plot of the adsorption process

The results were obtained using the mathematical model validated by silica gel; however, this does not necessarily mean that these results are validated too. For that, we would need to perform measurements using activated alumina so that we could validate the equations that we use to model properties of this adsorbent. Unfortunately, no suitable data were found in the literature and thus we cannot proceed with that as of now. Nevertheless, as part of the ongoing project, measurements will be carried out at a later stage. So far it is fair to say that the temperature and humidity curves qualitatively provide the expected results.

7 Conclusion

In conclusion, the proposed mathematical model gives very accurate results when using silica gel as the adsorbent, so it can be assumed that the simplifications and assumptions are valid. However, the model cannot be verified when using activated aluminium as no suitable experimental data in the literature could be found. It is therefore necessary to obtain experimental data from measurements on a real dryer using an adsorbent identical to the one defined in the mathematical model. For this purpose, in the ongoing project aimed at the development of an industrial compressor, we are also building an experimental stand on which the required measurements will be carried out.

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