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# Optimization and testing on an adsorption dishwasher

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**OPTIMZATION AND TESTING ON AN ADSORPTION DISHWASHER**

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**Abstract**

This paper reports experimental testing of an adsorption dishwasher employing different desiccants, such as 13X zeolite, microporous silica gel and SAPO-34 zeolite. Thermodynamic comparison of the selected adsorbents was carried out on the basis of the experimental measurement of the main thermo-physical parameters, such as specific heat, adsorption equilibrium curves and sorption enthalpy.

A sensitivity analysis on the adsorption dishwasher parameters was carried out adopting full factorial design (FFD) on a modified dishwasher prototype. Finally, the actual energetic performance for the optimized configuration were experimentally evaluated returning a consumed electrical energy of 0.636 kWh, which is 41% lower than that of standard cycle performed by a standard dishwasher with energy label A.

**1.Introduction**

The reversible process of water vapour adsorption on a porous media (e.g. zeolites, silica gel) has been widely applied for a number of heat transformation and storage processes [1-4]. Utilization of an open-cycle adsorption process for efficient dishwashers was previously studied [5], showing that the implementation of a drying adsorption system allows to reduce the energy consumption of about 24% compared with a conventional dishwasher. Practical feasibility of this technology has been demonstrated by numerous patents on the subject [6-9] and even a novel adsorption dishwasher has been recently put on the market [10]. Basically, the developed systems employ a desiccant cartridge that is regenerated during the heating up/washing stage of the dishwasher (desorption phase) and that releases dry and warm air during the subsequent drying stage (adsorption phase).

Majority of the previous studies considered common pelletized 13X zeolite as active dessicant media, due to the relatively high water adsorption capacity (about 30 wt.%), fast ad/desorption kinetics and elevated hydrothermal stability [11]. However, the very high hydrophilic character of 13X zeolite has the disadvantage of a high regeneration temperature (about 300°C), which may expose the constructive materials of the dishwasher to a relevant thermal stress. Moreover, a very

high desorption energy (>4000 kJ/kg) is requested for releasing the water molecules adsorbed into the 13X zeolite cages, which is unfavourable looking at the overall energy balance of the system. Focus of this work is the evaluation of the energy efficiency of a dishwasher employing moderately hydrophilic dessicants, such as microporous silica gel and SAPO-34 zeolite, which are characterized by lower regeneration temperature, lower desorption enthalpy and sufficiently high adsorption capacity. The experimental activity aimed both at the identification of the most promising adsorbent material and at the optimization of the desiccant system parameters. Firstly, thermodynamic analysis and performance evaluation was carried out on the basis of the experimental measurement of the main thermo-physical parameters of selected silica gel and SAPO-34. A commercial pelletized zeolite 13X was also characterized for comparison purposes. Secondly, we describe a set of experimental tests performed on an adsorption dishwasher prototype. A full factorial design (FFD) analysis was carried out to ascertain the design parameters that have the strongest influence and which arrangement affords the best performance in terms of mass of water vapour adsorbed and uptake variations along the operating cycle. Finally, the actual energetic performance for the optimized configuration was experimentally evaluated.

## 2. Operation principle of an adsorption dishwasher

Figure 1 gives a possible operating cycle of an adsorption dishwasher. After the initial pre-washing at ambient temperature, the liquid water is heated up by the electrical resistance R1 and the main washing phase is carried out by distributing the warm water within the washing box. Meanwhile, the wet adsorbent bed is regenerated by the dedicated electrical heater R2. The warm and wet air leaving the cartridge releases heat of condensation within the washing box, so reducing the electrical consumption due to resistance R1 with respect to conventional washers. Both the electrical heaters R1 and R2, then, are switched-off, the cycled liquid water is discharged and a final rinsing stage is carried out by diffusing fresh cold water. During the final drying stage, a fan is started to move the moisture from the washing box to the adsorbent cartridge, where the water vapour is rapidly adsorbed. Within minutes, the air reaches high temperature, due to enthalpy of adsorption. Then, this hot and dry air is sent back inside the washing box, drying efficiently the dishes.
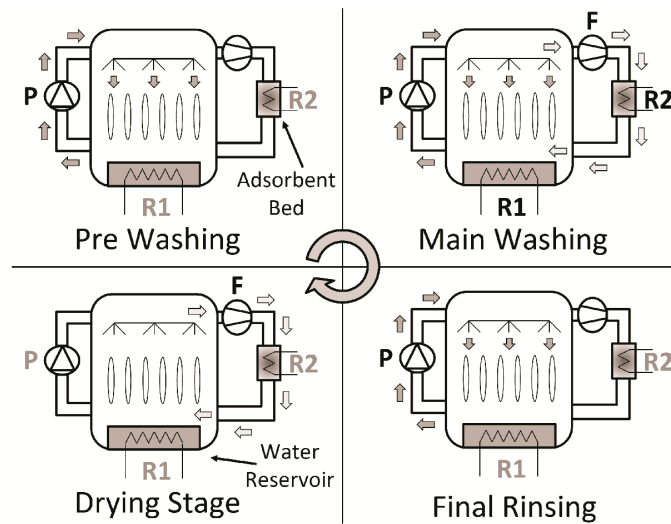
Figure 1. Conceptual schematic and operating principle of an adsorption dishwasher

## 3.Experimental

Three different commercial materials were selected in order to evaluate the most promising for application in the drying stage of a dishwasher. In particular a commercial pelletized zeolite 13X was selected as reference material, which was already employed by Hauer and Fischer [5] for the same application. The other two selected materials were the Silica Gel Siogel, by Oker Chemie, and the SAPO-34 AQSOA FAM02, by Mitsubishi Plastics Incorporation. The former one is a microporous silica gel, produced for desiccant purposes and suitable for adsorption cooling [12], whereas the latter one is a SAPO-34, having the common Chabazite framework, characterized by a high capacity of adsorption and widely studied for adsorption heat transformers [13-15]. Furthermore, in order to carry out the optimization of the desiccant system parameters, a prototype of dishwasher was suitably set up. The prototype was based on a standard dishwasher model modified for operation with an adsorbent bed. The control was also modified to obtain a standard test cycle with different final rinsing temperatures (from 35°C to 60°C, in 5°C steps). The circuit for drying was externally installed. A connection was provided on the upper surface of the dishwasher for connecting a centrifugal fan (ebm-papst RLF 100-11/18/2HP-182) flowing the moisture to the adsorbent bed. The dry air leaving the adsorbent bed was then sent back inside the tank through an opening in the bottom.

The air flow rate was regulated using an external controller acting on the fan speed. A measure of the flow rates was performed using a hot wire anemometer (Delta-Ohm) located beyond the adsorbent bed. Temperature, relative humidity and static pressure values were recorded (Sensirion Evaluation Kit EK-H4) upstream and downstream from the adsorbent bed. Finally a full factorial

design sensitivity analysis was applied to the adsorption dishwasher prototype operation to ascertain the optimal configuration.

## 4. Evaluation of the performance of the selected adsorbent material

### 4.1. Definition of the operating conditions

During desorption phase, the air stream flowing through the adsorbent bed can be considered having a 100% of relative humidity, $p/p_s=1$, at a temperature close to that of the water inside the chamber at $T_{ads}=45°C$. This leads to an absolute vapour pressure of $p_{ads}=9.5$ kPa. The regeneration temperature was selected as $T_{des}=150°C$ for the silica gel and SAPO-34 and 250°C for the zeolite 13X. The adsorption takes place at the end of the washing phase, again with a water vapour saturated air stream, at temperature of about 40°C and vapour pressure $p_{des}=7.3$ kPa.

### 4.2. Thermo-physical properties of the adsorbent materials

The adsorption equilibrium properties of each sample were measured under the above defined boundaries by means of a thermo-gravimetric system based on a micro balance Cahn C2000, available at the laboratories of the CNR ITAE. The system works under a static atmosphere of saturated vapour generated by a thermostated water reservoir. The procedure consists of a preliminary drying of the sample under continuous evacuation (vacuum level: $1*10^{-4}$ kPa). Drying temperature was 300°C for zeolite 13X and 150°C for silica gel and SAPO-34, as recommended in standardized procedure proposed in [16]. Afterwards, a known water vapour pressure is imposed over the sample by connecting the measuring chamber with the water reservoir. Subsequently, a number of equilibrium points are taken by measuring the sample weight variation corresponding to pressure or temperature changes. Water uptake was calculated as $w=(m_w - m_0)/m_0$, where $m_0$ is the dry weight after preliminary degassing and $m_w$ is the saturated weight at equilibrium. Figure 2 shows the adsorption/desorption isotherms ($T_{ads}=40°C$, $T_{des}=150$ or 250°C) measured for the three samples investigated, allowing the possibility of evaluating the water uptake spread between the adsorption and desorption stages.
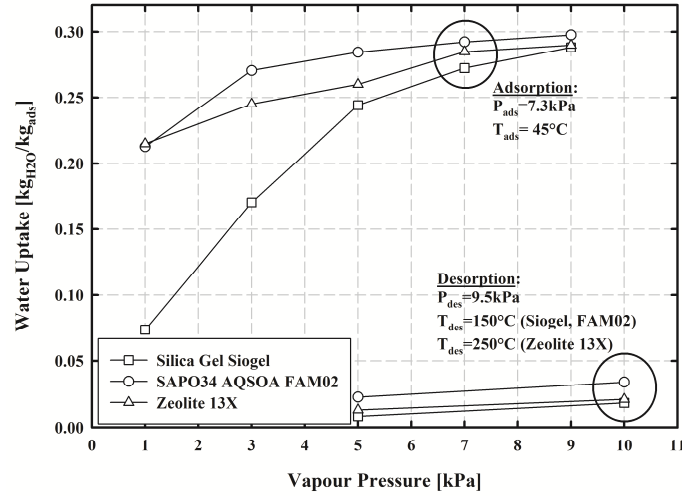
Figure 2: Equilibrium curves of the investigated materials around the operational zones

Table 1 summarizes the resulting adsorption spreads of each sample, highlighting that the adsorbents allow a similar water uptake spread ($\Delta w$=0.26-0.29 $g_{H2O}/g_{ads}$), under the specific conditions investigated.

Table 1: Performance of the selected materials

| Material | Zeolite 13X | Silica Gel Siogel | SAPO34 AQSOA FAM02 |
|---|---|---|---|
| Desorption Uptake [$kg_{H2O}/kg_{ads}$] | 0.02 | 0.02 | 0.03 |
| Adsorption Uptake [$kg_{H2O}/kg_{ads}$] | 0.29 | 0.28 | 0.32 |
| Differential Uptake [$kg_{H2O}/kg_{ads}$] | 0.27 | 0.26 | 0.29 |
| Integrated Heat of Adsorption [$kJ/kg_{H2O}$] | 3197.1 | 2911.8 | 2816.6 |
| $Q_{lat}$ [$kJ/kg_{ads}$] | 863.22 | 732.32 | 844.43 |
| $Q_{cond}$ [$kJ/kg_{ads}$] | 696.33 | 670.54 | 747.91 |
| $Q_{sens}$ [$kJ/kg_{ads}$] | 276.36 | 131.08 | 143.62 |
| $COP_{max}$ | 1.61 | 1.78 | 1.76 |
| $COP_{min}$ | 1.37 | 1.62 | 1.61 |

The differential heat of adsorption was evaluated according to the theory developed by Bering et al. [17] as:

$$\Delta H_{ads} = \lambda + \Delta F - T\Delta S \tag{1}$$

where $\lambda$ [$kJ/kgH_2O$] represents the condensation/evaporation enthalpy, which varies with temperature, $\Delta F$ [$kJ/kg_{H2O}$], known as "adsorption potential", is defined as the difference in chemical potentials of the adsorbate in the state of bulk liquid and in the adsorbed state and $\Delta S$ [$kJ/(kg_{H2O}$ K)] is the differential entropy of adsorption. As reported in [17], the third term in the right-hand side of eq. 1 can be expressed as:

$$T\Delta S = T\alpha'(\partial(\Delta F)/(\partial w))_T \tag{2}$$

where $\alpha'$ [1/K] is the coefficient of thermal expansion of the water. This term accounts for the stronger binding forces of the adsorbed water compared to its liquid state.

Usually the two last terms on the right side of the equation are brought together, defining the so called binding enthalpy:

$$\Delta H_{bind} = \Delta F - T\Delta S \qquad (3)$$

The binding enthalpy can be calculated starting from the adsorption equilibrium data measured for the selected materials as [18]:

$$\Delta F = RT \ln\left(\frac{p_{H_2O}}{p_s}\right) \qquad (4)$$

The evaluated differential heat of adsorption at 45°C is represented in the figure 3 for each of the tested materials.
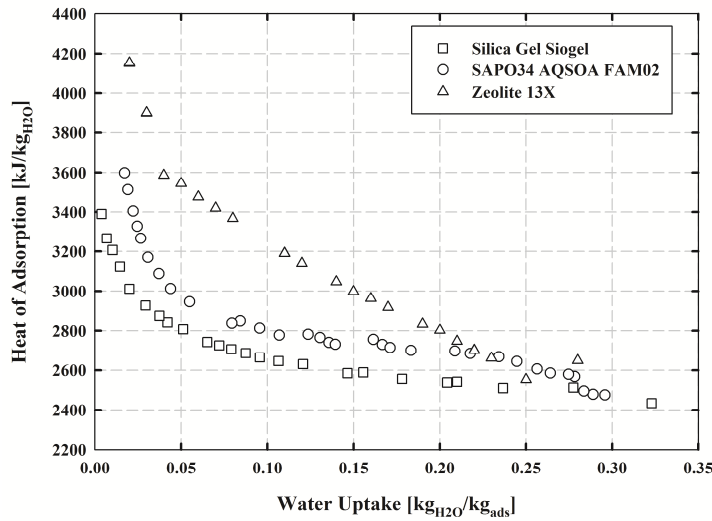


Figure 3: Heat of adsorption of the adsorbent materials

As expected, the zeolite 13X shows a higher value, due to its highly hydrophilic behaviour, on the contrary, the silica gel shows a weaker bonding to the water vapour molecules. The SAPO-34 AQSOA FAM02 lies between the other two materials, closer to the silica gel, as it shows a partial hydrophilic behaviour, as suggested by [13]. Moreover, 2600 kJ/kg$_{H2O}$ is the evaporation enthalpy at 100°C. This represents the lower limit for the differential heat of adsorption.

The integral heat of adsorption was then calculated for the chosen materials, taking into account the uptakes between adsorption and desorption phases. The obtained values are also reported in Table 4. The specific heat of the three selected materials in anhydrous state was directly measured as a function of temperature, by means of a calorimeter (Mettler DSC 27HP). The experimental method involves the preliminary drying of the sample crucible loaded with few milligrams of adsorbent material in a vacuum oven for several hours. Afterwards, the crucible is quickly closed by a

mechanical pressed cover, so obtaining the dry sample to be loaded into the calorimeter for measurement.

Figure 4 shows the results of the specific heat measurement carried out in the temperature range 40-240°C. Obviously, the experimental outcomes show a linear increasing of the value of the specific heat with increasing of temperature. So that, an average value between the maximum and minimum temperature of interest was evaluated for each sample. The lowest specific heats were obtained for the silica gel Siogel, whereas, the highest were obtained for the zeolite 13X. The specific heat of the SAPO-34 AQSOA FAM02 lies between the other two. All measured values are in accordance to literature data [11,19].
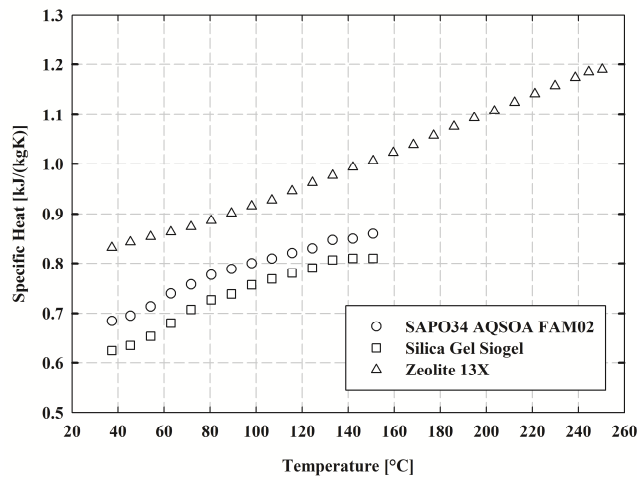


Figure 4: Specific heats of the investigated adsorbent materials

*4.3.Thermodynamic analysis*

Starting from the outcomes of the previous characterization of the three materials, the evaluation of the achievable thermodynamic performance according to the operating conditions of the dishwasher was carried out.

As already reported in [5] the thermal COP was selected as a parameter for comparing the thermodynamic performance achievable by the three selected materials. It is defined as the ratio between the useful heat and the required heat which drives the process.

The required heat corresponds to the heat of desorption, which is defined as follows:

$$Q_{des} = Q_{lat} + Q_{sens,des} \tag{5}$$

where, $Q_{lat}$ is the total heat needed for the desorption phase, obtained by integration of the heat of adsorption, while the second term on the right side is the sensible heat needed to heat up the adsorbent bed, from the adsorption to the desorption temperature. The two terms are defined by the following equations:

$$Q_{lat} = \int_{w_{des}}^{w_{ads}} \Delta H_{ads} dw \tag{6}$$

$$Q_{sens,des} = c_{p/sorb,eff} \Delta T \tag{7}$$

where, $c_{p/sorb,eff}$ is the effective specific heat of the adsorbent bed, defined as:

$$c_{p/sorb,eff} = c_{p/sorb} + c_{p/water} \left( \frac{w_{des} + w_{ads}}{2} \right) \tag{8}$$

The useful heat is defined as follows:

$$Q_{useful} = Q_{lat} + Q_{sens,des} + Q_{cond} \tag{9}$$

Where the heat of condensation of the desorbed vapour contained in the air stream flowing to the cold dishes is defined as:

$$Q_{cond} = \lambda \left( w_{ads} - w_{des} \right) \tag{10}$$

Obviously not all the sensible heat stored during the desorption phase can be recovered during adsorption, because of the expected heat losses. So that, two different thermal COP could be defined: the maximum thermal COP (COP$_{max}$) ideally reached when all the sensible heat between desorption and adsorption phases can be recovered, and the minimum thermal COP (COP$_{min}$) obtained when all the sensible heat of the adsorbent bed is dissipated before starting the adsorption phase, which means that the initial bed temperature corresponds to the adsorption temperature. Table 1 resumes the evaluated thermal COPs.

The obtained results demonstrate higher values of COP both for Siogel and SAPO-34 AQSOA FAM02, if compared to the standard 13X zeolite. This increasing in achievable performance could be explained taking into account not only the lower enthalpy of ad/desorption of Siogel and SAPO-34 AQSOA FAM02 but also the higher specific heat of the 13X zeolite and the temperature needed to successfully regenerate the material, which lead to a really high sensible heat for heating up the zeolite, about twice than the other two materials.

Another important performance parameter to be defined is the electric COP which is defined as the ratio between the useful heat and the electricity consumed both for regeneration phase and to run the fan. It can be expected an achieved value noticeably lower than the ideal COP evaluated for the material, due to heat losses and to the electric consumption for the fan.

Starting from the outcomes of the analysis of the thermodynamic performance achievable by the adsorbent materials tested, the silica gel Siogel was selected as the most promising one. In fact, although the similar performance achievable by the SAPO-34 AQSOA FAM02, the silica gel sounds more attractive from the economic point of view, about one order of magnitude of difference.

Actually, some possible drawbacks related to this choice should be mentioned and taken into account for further activities. First of all, the dynamic performance of the silica gel has to be considered, as suggested by Hauer [20], to verify whether it is suitable for the given application or not. In principle, the relatively long cycle time of a dishwasher (few hours) should avoid this limitation. Moreover, a point to be discussed is the hydrothermal stability of such a kind of material, which is subjected to stressful working conditions, e.g. high temperatures and high relative humidity. It is, up to now, an open issue, because of the lack of quick ageing systems able to reproduce the above mentioned working conditions on small scale.

## 5. Sensitivity analysis on the system

The purpose of our set of experiments was to ascertain a functional arrangement characterized by the highest adsorbed water vapour at the end of a cycle.

Due to the numerous parameters influencing the system's operation, the experiments were performed using a two-level full factorial design (FFD), which is a known statistical method used to evaluate the effects and interactions of different independent variables on a dependent variable [21,22] .

The investigated parameters are listed in Table 2. This results in the configurations in Figure 5. The experimental procedure consisted of a preliminary regeneration of the adsorbent bed in oven to measure the mass of the anhydrous adsorbent contained. Afterwards, the dry adsorbent bed, consisting in 13X zeolite, is installed inside the machine and a complete washing cycle is launched. Overall duration of the cycle was about 90 min. A final rinsing temperature of 45°C was adopted during the tests. The drying stage after the washing cycle included: i) turning the fan on (for 60 min) after completely draining the tank; ii) removing and weighing the bed to measure the weight after the drying stage; iii) regenerating again the adsorbent.

Table 2: Variables and levels investigated

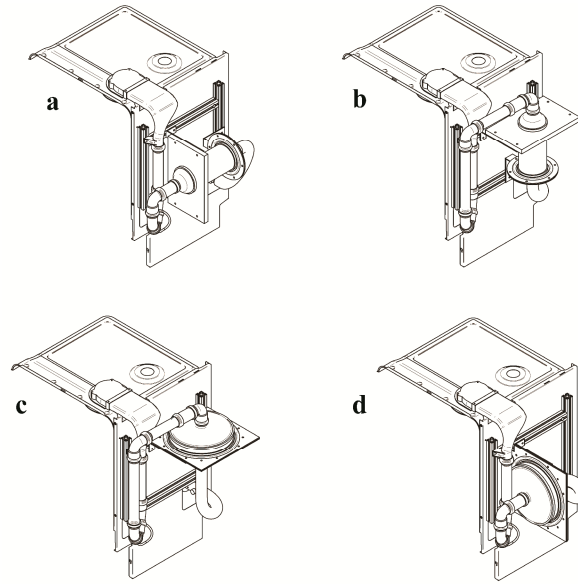|   |   | Low level (-) | High level (+) |
|---|---|---|---|
| **A** | Bed geometry | D/h= 10cm/20cm = 0.5 | D/h= 24cm/4cm=6 |
| **B** | Particle size[a] | Fine (d=2 mm) | Coarse (d=5 mm) |
| **C** | Fan speed | 630 rpm | 2250 rpm |
| **D** | Bed orientation | Horizontal | Vertical |
| a: the value is the average of the grains diameters | | | |

Figure 5: Experimental apparatus in different configurations for the FFD. a) D/h=0.5, horizontal; b) D/h=0.5, vertical; c) D/h=6, vertical; d) D/h=6, horizontal.

Performance achieved in the 16 tests of the FFD are shown in Table 3. The flow rates ranged from a minimum of 7m$^3$/h to a maximum of 28 m$^3$/h. The best drying performance was achieved in run 16, even if taking into account the uncertainties of Table 3, the obtained results for run 14 were quite similar to the results of the run 16. Figure 6 shows the trends of the temperatures and relative humidity at the zeolite bed inlet and outlet for the run 16. During the washing cycle the bed is cooled down to a temperature of approximately 28°C. Within 4 to 7 minutes of the fan starting, the adsorbent material rapidly reached temperature peak at >100°C. The zeolite cooled down again immediately later, reaching 50°C after approximately 1 hour.
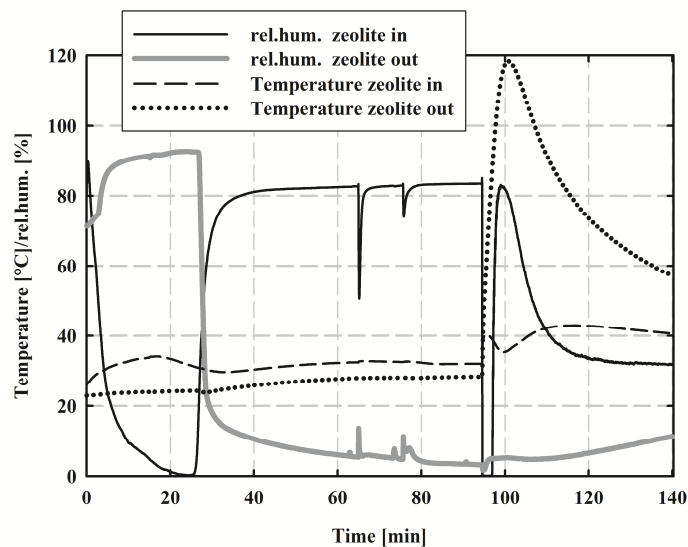


Figure 6: Temperature and relative humidity trends in run 16

The sensitivity analysis indicated that the parameters and the interactions among them influenced the system's performance as shown in Table 3 and Fig. 7 after application of the Yates algorithm on the measured uptakes. In Table 3, the effects are the weights of the single parameter and higher order interactions on the uptake change.

Table 3: Results of the FFD

| Run | A | B | C | D | $\Delta w$ [%] | Effects | VAR |
|-----|-----|---|------|------------|------------|--------|------|
| 1 | 0.5 | 2 | 630 | horizontal | 3.7±0.86 | 10.27% | Mean |
| 2 | 6 | 2 | 630 | horizontal | 5.7±0.63 | 2.37% | A |
| 3 | 0.5 | 5 | 630 | horizontal | 7.1±0.85 | 2.74% | B |
| 4 | 6 | 5 | 630 | horizontal | 8.3±0.62 | -1.10% | AB |
| 5 | 0.5 | 2 | 2250 | horizontal | 10.5±0.96 | 7.62% | C |
| 6 | 6 | 2 | 2250 | horizontal | 14.0±0.69 | -0.15% | AC |
| 7 | 0.5 | 5 | 2250 | horizontal | 16.1±0.91 | -0.29% | BC |
| 8 | 6 | 5 | 2250 | horizontal | 14.5±0.67 | -0.36% | ABC |
| 9 | 0.5 | 2 | 630 | vertical | 2.9±0.85 | 0.56% | D |
| 10 | 6 | 2 | 630 | vertical | 7.5±0.77 | 1.13% | AD |
| 11 | 0.5 | 5 | 630 | vertical | 7.0±0.84 | -0.32% | BD |
| 12 | 6 | 5 | 630 | vertical | 9.5±0.77 | 0.38% | ABD |
| 13 | 0.5 | 2 | 2250 | vertical | 11.6±0.92 | 0.04% | CD |
| 14 | 6 | 2 | 2250 | vertical | 15.4±0.83 | 0.13% | ACD |
| 15 | 0.5 | 5 | 2250 | vertical | 13.7±0.89 | -0.34% | BCD |
| 16 | 6 | 5 | 2250 | vertical | 16.8±0.82 | 0.72% | ABCD |

$M_v$ = mass of adsorbed water vapor, $M_z$ = mass of adsorbent bed; w=uptake of bed after adsorption

A Student's distribution was applied to the effects for the identification of the significant factors or interactions. Considering a 95% confidence interval based on the trend of Student's t-test (4 variables, 8 degrees of freedom), the parameters with a non-negligible effect on the system are the bed geometry and the particle size of the zeolite, each with a weight of approximately 2.5%, and by the fan speed, which has a weight >7%. A better drying performance can be achieved by using beds with high D/h ratios, zeolite with a coarse particle size and high fan speed corresponding to high air flow rates.
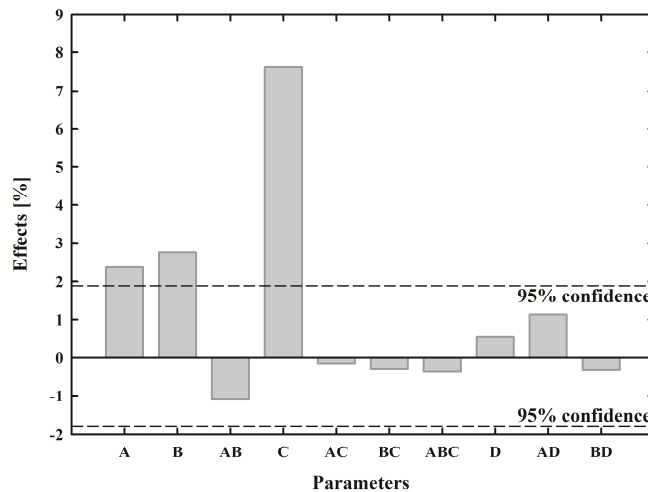


Figure 7: Results of the FFD

In the tests characterized by the lowest fan speed, there was condensation in the piping; this phenomenon was particularly evident for the arrangements with vertical axis. The problem of condensation was negligible with the fan turned at maximum speed. The adsorbent with grains of 5 mm diameter performed better during the drying cycle, probably due to the larger interparticle porosity and lower pressure drops. The bed geometry to adopt is the one where the diameter is greater than the height. Assuming the same volume, the solution where D/h=0.5 causes greater pressure drops, preventing the part of the adsorbent bed closest to its outlet from adsorbing water vapour. This effect is amplified when finer zeolite grains are used. The configurations characterized by the use of coarse zeolite and maximum air flow rate enabled several of the dishes that are usually critical in terms of the drying cycle to be dried completely.

## 6.Testing of the optimized prototype

Starting from the outcomes deriving both from the system and material optimization, a prototype of the dishwasher was built and tested. The adsorbent bed was loaded with silica gel Siogel, having a particle size of 1 - 3 mm. Moreover the bed geometry was designed with the optimized ratio D/h of 6 and the fan speed was set to 2250rpm. A preliminary test was carried out in order to evaluate the performance achievable by the real system. Accordingly, 1.16 kg of adsorbent material were regenerated into an oven at 150°C for 1 hour. Afterwards it was inserted into the bed, performing the washing cycle, and after 60 minutes of drying 190 g of water vapour were adsorbed onto the material ($\Delta w=16.3\pm0.91\%$), so that the achievable drying performance was confirmed. Subsequently, an electrical resistance (1200W rated but partially supplied) was added to the prototype and installed within the bed for desorption during the washing phase and the estimation of the drying performance and the energy consumption. The fan was activated together with the resistance during desorption at the maximal flow rate. Furthermore, starting from the results obtained in the preliminary test, the amount of employed adsorbent material was scaled down to 0.75 kg, as the target of water vapour to be adsorbed within a washing cycle was 120 g.
The drying had duration of 36 minutes starting from the end of washing. Figure 8 shows the trends of the temperatures and powers during the last test. The amount of adsorbed water was 125 g ($\Delta w=16.6\pm0.80\%$) and the consumed electrical energy 0.636 kWh.
The energy consumption of a standard cycle performed by a standard dishwasher with energy label A is 1.08 kWh. Therefore the found configuration permits a reduction of the energy consumption of 41%, confirming that one of the most promising ways to reduce the energy consumption of

dishwashers is to include an adsorbent bed which guarantees the possibility of carrying out the drying phase without expense of electric energy.
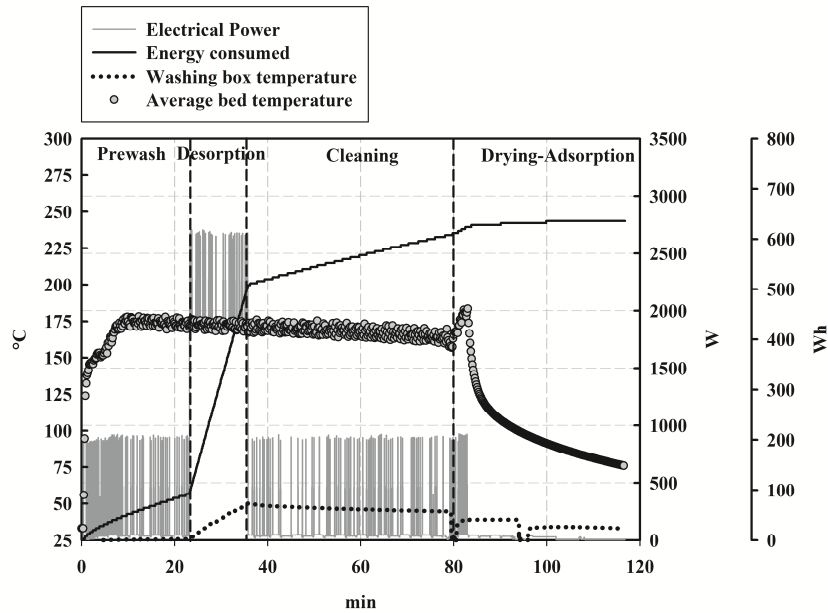


Figure 8: Operation of the prototype loaded with 0.75kg of silica gel Siogel

As already discussed in paragraph 4, the electric COP was evaluated to be about 0.3, which confirms the expected lowering if compared with the theoretical thermal COP.


## 7.Conclusions

Aim of the presented work was the optimization of the performance of a dishwasher by using an optimized adsorbent bed. An investigation on three different commercial adsorbents was oriented to find out the optimal adsorbent material for the drying stage of a dishwasher. The results of the thermodynamic analysis demonstrated higher values of thermal COP both for Siogel and SAPO-34 AQSOA FAM02, if compared to the standard zeolite 13X.

Despite the slightly higher adsorption capacity showed by the SAPO-34 AQSOA FAM02, silica gel Siogel was selected as optimized material, due to its easy commercial availability and really low cost (about 5 €/kg).

An open issue concerns the hydrothermal stability of such material. In fact in the actual working conditions there is a lack of information on the behaviour of the material. Specifically further activities will be oriented to investigate this aspect.

Moreover, the sensitivity analysis on some dishwasher parameters was carried out adopting full factorial design on a prototype unit. The experiments demonstrated that the configuration achieving the best drying performance ($\Delta w=16.8\pm0.82\%$) is characterized by D/h=6, coarse particle size and high moisture flow rate. The tests on the final prototype loaded with silica gel Siogel in the optimal

configuration have shown an electric power consumption of 0.636 kWh, an adsorption of 125 g of water and a reduction of the energy consumption of 41% compared with a standard dishwasher operating with a standard cycle and having energy label A.

**Nomenclature**

T [°C] Temperature

p [Pa] Pressure

w [g/g] Water uptake

Q [kJ/kg] Heat

COP [-] Coefficient of Performance

ΔH [kJ/kg] Differential heat

λ [kJ/kg] Phase transition enthalpy

ΔF [kJ/kg] Adsorption potential

ΔS [kJ/(kg K)] Differential entropy of adsorption

R [kJ/(kg K)] Specific gas constant

cp [kJ/(kg K)] Specific heat

α' [1/K] Coefficient of thermal expansion of the water

Subscripts

ads - adsorption

des - desorption

lat - latent

cond - condensation

sens - sensible

bind - binding

s - saturation

sorb - sorbent

eff - effective

useful - useful