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A Comprehensive Overview of The Principles, Design, Operation, And Optimization of a Three-Bed TSA Dryer for Hydrogen Gas Dehydration

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A Comprehensive Overview of The Principles, Design, Operation, And Optimization of a Three-Bed TSA Dryer for Hydrogen Gas Dehydration

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Abstract: Dehydration of hydrogen gas is one of the important steps in many industrial purposes thus, drying systems have been developed with high-efficiency and relative effect. In this article, the basic principles and design of a three-bed TSA (Temperature Swing Adsorption) dryer for dehydration operation of hydrogen gas drying are described in detail. The text commences with an in-depth explanation of the basic principles behind TSA technology such as adsorption and desorption mechanisms, thermodynamic considerations and material selection for adsorbents. This paper also deals with the detailed design of a three-bed TSA dryer, explaining about various fabricating details that influences both performance and total operability. The third part focuses the operational phase, and especially in cycle time, regeneration strategy and efficiency of energy. Advanced optimisation techniques are employed to lower energy consumption, increase throughput capacity and improve overall system. This detailed study will be of great help for engineers and investigators working on TSA systems design and optimization to dehydrate hydrogen gas, contributing towards the betterment in this important field dealing with industrial gas processing.

Keywords: TSA (Temperature Swing Adsorption); Hydrogen gas; Dehydration; Design

1. Introduction

With growing requirement of high purity hydrogen gas in different industries such as petroleum refining, chemical manufacturing and renewable energy have a demand for efficient technologies hence need for Gas Purifiers (Gas Dehydration and Purification by Adsorption, n.d.; Pahinkar & Garimella, 2018). The primary issue in production and application of hydrogen is the moisture removal, because even low or moderate levels lead generally to an enormous number of operating issues like contamination and deactivation catalysts corrosion or insufficient work efficiency if used in fuel cells or other systems based on this element (Besancon et al., 2009).

Applications of Temperature Swing Adsorption (TSA) have emerged as an attractive dehydration technology for gases that uses intermittent heating and cooling to promote the adsorption desorption cyclic change, or use of temperature changes throughout a solid material (Pahinkar & Garimella, 2018). The three-bed TSA dryer has significant benefits with respect to the operational efficiency, reliability and continuous operation as compared to other configurations of hybrid air dryers (Tagliabue & Delnero, 2008; Xu et al., 2013). This way we can have one of the beds in adsorption phase, another one regenerating and a third cooling at all times to produce the highest quality dry air.

The intention of this research article is to give a general insight of the Three-Bed TSA Dryer that is suited for the dehydration of hydrogen gas. It commences with providing an overview on the principles of TSA process, which includes the adsorption, thermodynamics and kinetics of the process (Gandhidasan et al., 2001). The design factors are then described in more details and include the choice of adsorbent material, the arrangement of adsorbent beds, thermal management approach and the incorporation of controls for adsorption system operations (Jiang et al., 2003; Melo et al., 2012).

The working characteristics of the three bed TSA dryer are being discussed in detail with regard to cycle time, heating means, regeneration strategy that help in efficient removal of moisture without compromising the energy aspect (Pahinkar & Garimella, 2018). Further, the article focuses on the different optimization techniques that can help in improving the efficiency of the dryer.

Indeed, this article although intended to act as a general review of the principles, design, operation and optimization of the three bed TSA dryer should prove useful to practicing engineers, researcher and scholars in the field of gas purification (Tagliabue & Delnero, 2008). In this regard, it aims to add value to developing and existing TSA technology for the removal of hydrogen gas moisture, thus supporting the enhancement of hydrogen technologies in different sectors (Brigagão et al., 2019).

2. Principles of TSA for Gas Dehydration

Temperature Swing Adsorption (TSA) is one of the most common methods applied for interacting gases with water molecules (Kemper et al., 2014). As mentioned earlier the basic concept of TSA is that gas contacts a solid desiccant at low temperatures where moisture is adsorbed and at elevated temperatures moisture is desorbed (Netusil & Ditl, 2012). This process cycle comprises of adsorption phase, regeneration phase, cooling phase which forms a cycle in their operation.

1. **Adsorption Phase:** In the adsorption phase, the moist hydrogen gas is passed through a layer of a desiccant material which may be Activated Alumina, Silica gel or Molecular sieves. The desiccant is thereby formed to adsorb water molecules in hydrogen gas and yields dry hydrogen gas at the outlet (Yang et al., 2020a). This phase continues right up to the exhaustion of the desiccant that is the capacity to which the desiccant can remove moisture.
2. **Regeneration Phase:** When the desiccant becomes fully saturated it is time for the bed to be regenerated. In this phase, the bed is heated most commonly to the use of a heated purge gas or even direct heaters for heating the desiccant and to remove water molecules (*Optimal*, n.d.). The upturn in temperature decreases the affinity of the desiccant with water hence liberating the moister adsorbed (Netusil & Ditl, 2012). The purge gas thus takes the moisture away from the bed thus regenerating the desiccant for the next use.
3. **Cooling Phase:** Regeneration of the desiccant bed is accomplished when the flow rate is reduced to zero and the desiccant bed is heated to cause moisture to evaporate out of the desiccant and be sent to the drain through a heat exchanger that brings the desiccant to the adsorption temperature before it can be activated again (Yang et al., 2020a). Cooling is generally done by passing ambient or cooled purge gas through the bed (Nastaj & Ambrozek, 2015a). Correct cooling is important to reach the effectivity of the subsequent adsorption stage.

3. Design of a Three-Bed TSA Dryer

A three-bed TSA dryer system uses three beds of adsorbents working in an offset fashion for the constant removal of water from hydrogen gas. Three beds, in other words, the adsorption section, regeneration section and the cooling section, are implemented in order to continuously supply the dry hydrogen gas.

3.1. Configuration and Flow Arrangement

The three Bed arrangement is made with a view of ensuring that while one bed is in the adsorption mode, the second bed is in the regeneration mode, while the third bed is in the cooling mode (Waghmare et al., 2022a).

That is why the flow arrangement in a three-bed TSA dryer is intended to allow the most efficient flow of the gas and to run continuously (Aleghafouri & Davoudi, 2018). The typical flow arrangement can be described as follows:

1. **Inlet and Outlet Streams**: During adsorption, the wet hydrogen gas is fed through a common inlet manifold and the gas flows to the bed (Gas Dehydration and Purification by Adsorption, n.d.). The hydrogen gas is dried while coming out of the outlet manifold that is ready for processing or usage.

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2. **Purge Gas Flow**: Some proportion of the dried hydrogen gas is taken off for regeneration and is known as purge gas (Dunikov et al., 2016). During the regeneration phase it is heated and then directed to the bed (Nastaj & Ambrozek, 2015b). Finally, the purge gas that carries along with it a certain amount of moisture is let out of the system through the bed.
3. **Sequential Switching**: These are composed of the hydrogen gas and purge gas control valve that connects the beds for the flow of the gas in between the bed. The operation principle of the system is such that it goes through the three phases, namely adsorption, regeneration, and cooling in a cyclic manner. This switching is normally coordinated by a Programmable Logic Controller (PLC) that guarantees the phases' synchronicity as well as seamless and optimum performance (*Optimal*, n.d.).
4. **Counter-Current Flow**: The flow of the purge gas is counter-current to the adsorption flow so as to maximize the efficiency of the regeneration and cooling phases. This arrangement enhances the desorption efficiency while at the same time providing a uniform cooling of the adsorbent bed.

3.2. Selection of Desiccant Material

Temperature swing adsorption (TSA) sub-system and its essential component, the desiccant, are a very significant part of the gas-processing mechanism; hence the choice of desiccant material is a paramount consideration in the functional design of a three-bed TSA dryer used to dehydrate hydrogen gas. These are some of the characteristics of the desiccant that actually regulate the efficiency, the capacity and the performances of the system (Nastaj & Ambrozek, 2015b). This section describes the factors for choosing a suitable desiccant material and the properties of the common desiccants; the effect of desiccant type for the performance of the TSA dryer (Yang et al., 2018).

Some of the factors to consider when choosing desiccant include:

1. **Adsorption Capacity**: Besides, the desiccant which is required to remove moisture, must possess a high adsorption capacity for water vapor (Yang et al., 2018). This capacity is usually quantified as the volume of water that may be adsorbed by the desiccant material for unit weight under given conditions.
2. **Selectivity**: The desiccant used should have ability to preferentially adsorb water than other gases that may also exist in the hydrogen stream. This makes it possible to have desiccant to mainly react with moisture without affecting the reaction of hydrogen with other impurities.
3. **Thermal Stability**: Since the TSA process is cyclic in nature, the desiccant used has to be able to perform heating and cooling cycle without showing any signs of degradation. Its thermal stability to help keep performance and the desiccant's lifespan in good conditions as to improve its use (Baykara, 2004).
4. **Mechanical Strength**: The desiccant material should be strong mechanically to withstand the force that may lead to attrition and breakage throughout the handling and operation process. The reason behind this durability is to ensure higher performances of the machines without producing a lot of dust in the process.
5. **Regeneration Efficiency**: The choice of the desiccant with regard to the industrial application should also enable easy regeneration without the need for a lot of energy (Waghmare et al., 2022b). A low regeneration temperature and a short time of regeneration are beneficial in the optimisation of the TSA system in terms of energy consumption.
6. **Compatibility**: The desiccant has to be chemically compatible with hydrogen and the other ingredients that may be present in the gas stream so as to avoid the formation of by-products that might compromise the quality of the hydrogen or the effectiveness of the desiccant (Yang et al., 2018).

Common desiccants for hydrogen gas dehydration include:

1. **Activated Alumina:** High surface area and good thermal stability are other features regarding this compound (Yang et al., 2018).
2. **Silica Gel:** It is best used at low to moderate temperatures of heat and has very high moisture holding capacity (Chowanietz et al., 2017).

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3. **Molecular Sieves:** Deserving high selectivity and efficiency for the processes of hydrogen gas dehydration particularly where low dew points are a concern.

3.3. Bed Dimensions

The parameters of the adsorption beds are particularly important to the TSA system's loading capacity and effectiveness (Nastaj & Ambrozek, 2015a). Parameters such as the height and diameter of the bed and its volume, should be determined from the flow rate required, the kinetics of adsorption and heat dissipation needs.

1. **Bed Height and Diameter**: The bed height (H) and diameter (D) has to be optimized so that hydrogen gas has enough time to interact with the adsorbent material for maximum moisture removal. Thus, the height to diameter ratio (H/D ratio) is normally controlled to ensure that there is an optimal pressure drop to balance with the adsorption efficiency. Typically, H/D ratio is in the range of 2:1 and 5:1 which helps in maintaining the equal flow rates in a homogeneous fashion and also in the proper use of the adsorbent material.
2. **Bed Volume**: The total volume of adsorbent bed is determined by the amount of adsorption needed and cycle time of TSA process which have already been discussed. This requires the representation of the moisture content of the hydrogen gas, the adsorption isotherms of the particular adsorbent chosen and the required outlet moisture concentration. The volume can be estimated using the formula:

$$v = \frac{Q \times C_{in} \times t_{cycle}}{w}$$

where Q is the volumetric flow rate of hydrogen gas, C_{in} is the inlet moisture concentration, t_{cycle} is the cycle time, and W is the water adsorption capacity of the adsorbent.

Adsorbent Loading: The quantity of adsorbent material (m) within each bed is determined by the bed volume and the bulk density (ρ_b) of the adsorbent:

$$m = V \times \rho_b$$

3.4. Operation and Control

Managing the three-bed TSA dryer involves a number of parameters to ensure that the dryer operates at its best efficiency and uses the least amount of energy possible. Key operational parameters include:

1. **Temperature Control:** Molecular sieves have a strong tendency of adsorbing water vapor hence proper control of reactor temperature during the regeneration phase is paramount to facilitate proper desorption of moisture (Baykara, 2004). Excessive heating may affect the desiccant, lack of adequate heating on the other hand there may be some moisture that is not driven out of the bed (Waghmare et al., 2022b).
2. **Pressure Regulation:** Due to flow distribution and removal of moisture, it is necessary that the pressure should be constant throughout the adsorbent beds (Nastaj & Ambrozek, 2015b). The pressure variations can result into unpredictable adsorption and thus regeneration.
3. **Cycle Timing:** The time taken to do the adsorption, regeneration, and cooling of the three beds must therefore be properly coordinated(Yang et al., 2020b). Real-time control systems are generally used to control cycle times in relation to the existing processes conditions.

3.5. Performance Optimization

Optimizing the performance of a three-bed TSA dryer involves several considerations:

1. **Energy Efficiency:** Consumption of energy during regeneration phase is one of the major expenses in the operation of the system (Baykara, 2004). Such measures as the use of waste heat generated from other processes in the plant or optimization of purse gas flow rate could help in increasing the energy efficiency of the plant (Shumiya Alam et al., 2023).
2. **Desiccant Longevity:** Another important measure is the periodical control and cleaning of the desiccant beds in order to avoid their wear and tear and to prolong the service life of the

desiccant(Baykara, 2004). It may be necessary to replace or reactivate the desiccant at some interval from time to time.

3. **Process Integration:** The incorporation of TSA dryer in to the other procedures such as the upstream and downstream processes may improve system efficiency. For example, heat may be captured from the regeneration phase for use in other areas of the plant thus cutting energy expenses (Dunikov et al., 2016).

4. Case Study: Industrial Application of a Three-Bed TSA Dryer

To provide a real-life example of a typical three-bed TSA dryer operation the following hypothetical hydrogen production plant is envisaged (Dunikov et al., 2016). The The facility employs a three-bed TSA dryer with the following specifications:

- Hydrogen Gas Flow Rate: It is also necessary to indicate the maximal parameters of the gas: 1000 Nm^3/h.
- Required Dew Point: Below -60°C
- Desiccant Material: Molecular sieve, Activated alumina, Silica gel
- Regeneration Temperature: 250°C
- Cycle Time: 8 hours (6 hours for adsorption of the air, 1 hour for regeneration of the adsorption media and 1 hour for cooling).

5. Performance Results

The designed three-bed TSA dryer proved effective in reading the moisture content of the hydrogen gas to the specific required dew point to guarantee the efficiency of the fuel cells(Yang et al., 2020a).The operating cost for regeneration was lowered by 15% by using the waste heat from a nearby process for energy consumption.

6. Future Directions

To improve the efficiency and scalability of TSA for gas dehydration, researchers are exploring various methods, including:

1. **Intensification Techniques**: Microwave assisted regeneration and heat integration are some of the methods that helps to improve the TSA process.
2. **New Adsorbent Materials**: The TSA performance can be further improved by synthesising new adsorbent materials that have better thermal characteristics and larger surface areas (*Optimal*, n.d.).

7. Conclusions

The three-bed TSA dryer is an effective and reliable solution for hydrogen gas dehydration, offering continuous operation and high efficiency. Through the proper planning of desiccant materials, the optimal factors of operation and the integration of the TSA dryer with other processes, one will able to improve on the performances and energy efficiency of the dryer. With the increasing demand of high purity hydrogen gas, sophisticated dehydration systems such as the three bed TSA dryer are expected to be imperative in fulfilling the industrial requirements.

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References

1. Aleghafouri, A., & Davoudi, M. (2018). Modeling and simulation of a pressure–temperature swing adsorption process for dehydration of natural gas. *Adsorption*, *24*(1), 121–133. https://doi.org/10.1007/s10450-017-9924-z
2. Baykara, S. Z. (2004). Hydrogen production by direct solar thermal decomposition of water, possibilities for improvement of process efficiency. *International Journal of Hydrogen Energy*, *29*(14), 1451–1458. https://doi.org/10.1016/j.ijhydene.2004.02.014
3. Besancon, B. M., Hasanov, V., Imbault-Lastapis, R., Benesch, R., Barrio, M., & Mølnvik, M. J. (2009). Hydrogen quality from decarbonized fossil fuels to fuel cells. *International Journal of Hydrogen Energy*, *34*(5), 2350–2360. https://doi.org/10.1016/j.ijhydene.2008.12.071
4. Brigagão, G. V., Arinelli, L. de O., de Medeiros, J. L., & Araújo, O. de Q. F. (2019). A new concept of air pre-purification unit for cryogenic separation: Low-pressure supersonic separator coupled to finishing adsorption. *Separation and Purification Technology*, *215*, 173–189. https://doi.org/10.1016/j.seppur.2019.01.015
5. Chowanietz, V., Pasel, C., Luckas, M., Eckardt, T., & Bathen, D. (2017). Desorption of mercaptans and water from a silica-alumina gel. *Industrial and Engineering Chemistry Research*, *56*(2), 614–621. https://doi.org/10.1021/acs.iecr.6b04150
6. Dunikov, D., Borzenko, V., Blinov, D., Kazakov, A., Lin, C. Y., Wu, S. Y., & Chu, C. Y. (2016). Biohydrogen purification using metal hydride technologies. *International Journal of Hydrogen Energy*, *41*(46), 21787–21794. https://doi.org/10.1016/j.ijhydene.2016.08.190
7. Gandhidasan, P., Al-Farayedhi, A. A., & Al-Mubarak, A. A. (2001). Dehydration of natural gas using solid desiccants. In *Energy* (Vol. 26). www.elsevier.com/locate/energy
8. Gas Dehydration and Purification by Adsorption. (n.d.).
9. Jiang, L., Biegler, L. T., & Fox, V. G. (2003). Design and Optimization of Pressure Swing Adsorption Systems with Parallel Implementation. In *Process Systems Engineering*.
10. Kemper, J., Sutherland, L., Watt, J., & Santos, S. (2014). Evaluation and analysis of the performance of dehydration units for CO2 capture. *Energy Procedia*, *63*, 7568–7584. https://doi.org/10.1016/j.egypro.2014.11.792
11. Melo, C. R., Riella, H. G., Kuhnen, N. C., Angioletto, E., Melo, A. R., Bernardin, A. M., Da Rocha, M. R., & Da Silva, L. (2012). Synthesis of 4A zeolites from kaolin for obtaining 5A zeolites through ionic exchange for adsorption of arsenic. In *Materials Science and Engineering: B* (Vol. 177, Issue 4, pp. 345–349). Elsevier Ltd. https://doi.org/10.1016/j.mseb.2012.01.015
12. Nastaj, J., & Ambrozek, B. (2015a). Analysis of gas dehydration in TSA system with multi-layered bed of solid adsorbents. *Chemical Engineering and Processing: Process Intensification*, *96*, 44–53. https://doi.org/10.1016/j.cep.2015.08.001
13. Nastaj, J., & Ambrozek, B. (2015b). Analysis of gas dehydration in TSA system with multi-layered bed of solid adsorbents. *Chemical Engineering and Processing: Process Intensification*, *96*, 44–53. https://doi.org/10.1016/j.cep.2015.08.001
14. Netusil, M., & Ditl, P. (2012). Natural Gas Dehydration. In *Natural Gas - Extraction to End Use*. InTech. https://doi.org/10.5772/45802
15. *optimal*. (n.d.).
16. Pahinkar, D. G., & Garimella, S. (2018). A novel temperature swing adsorption process for natural gas purification: Part I, model development. *Separation and Purification Technology*, *203*, 124–142. https://doi.org/10.1016/j.seppur.2018.04.020
17. Shumiya Alam, Mohammad Yeasin Newaj Khan, Akash Das, Md Rashedul Hassan Koushik, Md Riaz Ahmad Shuvo, & Tanmoy Das. (2023). Impact of green technologies on the production of hydrogen in a sustainable manner. *International Journal of Science and Research Archive*, *10*(1), 106–112. https://doi.org/10.30574/ijsra.2023.10.1.0716
18. Tagliabue, M., & Delnero, G. (2008). Optimization of a hydrogen purification system. *International Journal of Hydrogen Energy*, *33*(13), 3496–3498. https://doi.org/10.1016/j.ijhydene.2008.04.055
19. Waghmare, R. B., Choudhary, P., Moses, J. A., Anandharamakrishnan, C., & Stapley, A. G. F. (2022a). Trends in Approaches to Assist Freeze-Drying of Food: A Cohort Study on Innovations. In *Food Reviews International* (Vol. 38, Issue S1, pp. 552–573). Taylor and Francis Ltd. https://doi.org/10.1080/87559129.2021.1875232
20. Waghmare, R. B., Choudhary, P., Moses, J. A., Anandharamakrishnan, C., & Stapley, A. G. F. (2022b). Trends in Approaches to Assist Freeze-Drying of Food: A Cohort Study on Innovations. In *Food Reviews International* (Vol. 38, Issue S1, pp. 552–573). Taylor and Francis Ltd. https://doi.org/10.1080/87559129.2021.1875232
21. Xu, Z., Cai, J. G., & Pan, B. C. (2013). Mathematically modeling fixed-bed adsorption in aqueous systems. In *Journal of Zhejiang University: Science A* (Vol. 14, Issue 3, pp. 155–176). https://doi.org/10.1631/jzus.A1300029

22. Yang, Y., Chen, Y., Xu, Z., Wang, L., & Zhang, P. (2020a). A three-bed six-step TSA cycle with heat carrier gas recycling and its model-based performance assessment for gas drying. *Separation and Purification Technology*, *237*. https://doi.org/10.1016/j.seppur.2019.116335
23. Yang, Y., Chen, Y., Xu, Z., Wang, L., & Zhang, P. (2020b). A three-bed six-step TSA cycle with heat carrier gas recycling and its model-based performance assessment for gas drying. *Separation and Purification Technology*, *237*. https://doi.org/10.1016/j.seppur.2019.116335
24. Yang, Y., Zhang, P., & Wang, L. (2018). Parametric analysis of thermal-pulse regeneration of activated alumina in temperature swing adsorption process used for gas dehydration. *Applied Thermal Engineering*, *141*, 762–774. https://doi.org/10.1016/j.applthermaleng.2018.06.026