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Performance Comparison of Heat Regeneration Modes in Adsorption Dryers for Ultra-Low Dew Point Compressed Air Production

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Keywords：compressed air; moisture; adsorption dryer; heat regeneration, pressure-dew point

ABSTRACT

The importance of having compressed air free from moisture in engineering applications is well known. Heat regeneration-based adsorption dryers are commonly used to achieve ultra-low dew points. This study focuses on three types of heat regeneration modes for adsorption dryers: internal heating mode, external heating mode, and compressed air heating mode. The study compares these modes by using established calculation schemes and evaluating their specific energy requirements in terms of electrical energy and dried regeneration air.

The study found that internal heating regeneration had the lowest specific energy requirement in terms of electrical energy, while compressor air heating regeneration had no electrical energy requirement. However, external heating regeneration had the highest specific energy requirement. The study also concluded that the energy and capital cost for the three modes were comparable at specific conditions of 35°C feed air temperature and 8 bar absolute feed air pressure of product air. The study's findings can be utilized to develop a system comparison tool for practical applications.

Furthermore, the study found that heat mode adsorption dryers were suitable for specific ranges of feed air temperature, operating pressure of process air, and pressure dew point of product dry air. Heat regeneration mode adsorption dryers were also found to be most suitable for strongly adsorbed species, with recoverable desorbate at high concentrations, but not suitable for rapid cycling.

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INTRODUCTION

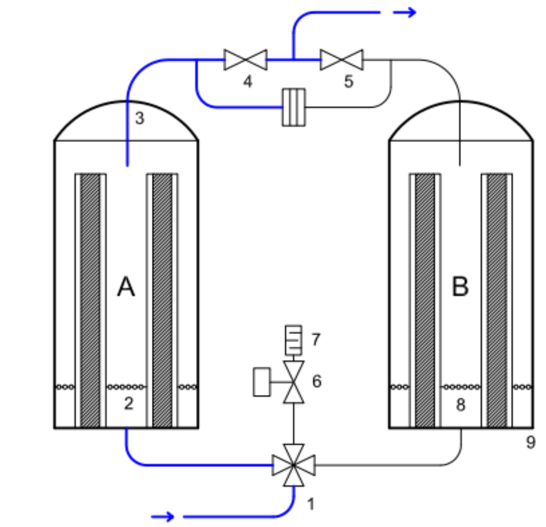
Compressed air has become a popular choice in various industrial sectors such as agriculture, textiles, chemicals, automobiles, construction, and electronics. However, the presence of water vapor in compressed air can cause several problems, including rust, blockages in orifices, and scale formation in air passages, leading to increased pumping power and energy consumption. In addition, moisture in compressed air can cause operational issues such as freezing of outdoor air lines and malfunctioning of processes. To address these issues, moisture is typically removed through a drying process, and the dryness of compressed air is often measured by the pressure dew point temperature (PDPT), with the desired level chosen based on process requirements. The appropriate drying method is selected based on the process air flow rate at the correct pressure and the acceptable level of moisture for the chosen application. (Kannan et al.,2020).

The adsorption drying method is commonly used to attain a high level of dryness in the product air stream, typically reaching a pressure dew point of -70°C.(Sureshkannan et al.,2019). The transfer of heat in desiccant beds under real-world conditions happens through various mechanisms, including conduction of heat through solid desiccant particles, convection within the void space, and radiation on the surface of the desiccant (Kannan et al.,2017,2021). Obtaining temperature variation data is crucial when studying adsorption, and it can be primarily obtained through the energy balance equations of the entire system. The energy balance equations consider the total heat gained by the desiccant particles, the heat gained by moisture in the desiccant bed, and how both factors contribute to heat gain in the flowing air. Numerous studies provide various energy balance correlations, such as the one given by Kwapinski et al. (2010) which accounts for the radial and axial thermal conductivities within the adsorption bed when describing the energy balance. In their study, Béttega et al. (2011) utilized a pseudo-homogeneous approach to calculate thermal conductivity and found that thermal conductivity profiles had a significant impact on the behavior of the adsorption system. Additionally, an important aspect of the adsorption process was predicting the cyclic steady state (CSS). Several methods have been formulated to predict the CSS value by many researchers. In most of the methods, repeated simulations were used to determine CSS between the operating limits and is computationally demanding (Kadoli et al.,2011; Thomas et al.,1998). The literature review has shown that the process of removing moisture from desiccants involves a complex mechanism of heat and mass transfer, making theoretical analysis difficult. Energy consumption is a crucial factor in the selection of a heat regeneration system for an adsorption dryer as it directly affects operating costs. However, there is no literature available that compares the energy consumption and implementation costs of different regeneration methods. Therefore, this study aims to investigate the essential characteristics of various heat-based regeneration methods for adsorption dryers and provide a comparative analysis of their performance and cost for practical purposes, using reproducible data for varying performance ranges.(Sureshkannan et al.,2022).

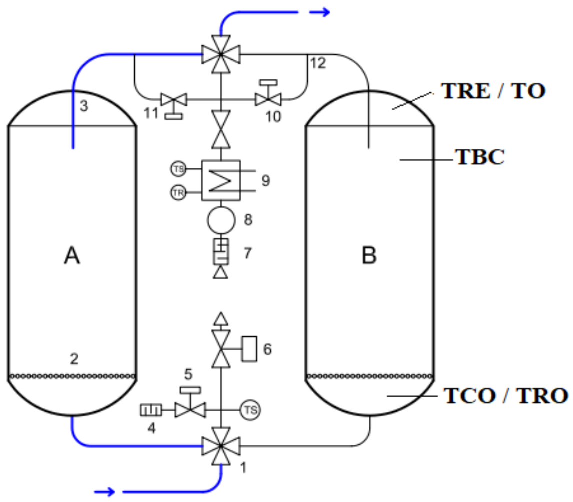
MATERIALS AND METHODS

The heat regeneration of an adsorption dryer can be achieved through three different modes: internal heat, external heat, and compressor heat. The internal heat method involves using a portion of the dry compressed air flow and an internal electrical heating system for regeneration. The external heat method involves drawing in ambient air with a blower and using external electrical heating to regenerate the dryer. The compressor heat method, on the other hand, utilizes the heat generated during compression from the compressor system to carry out the regeneration process.

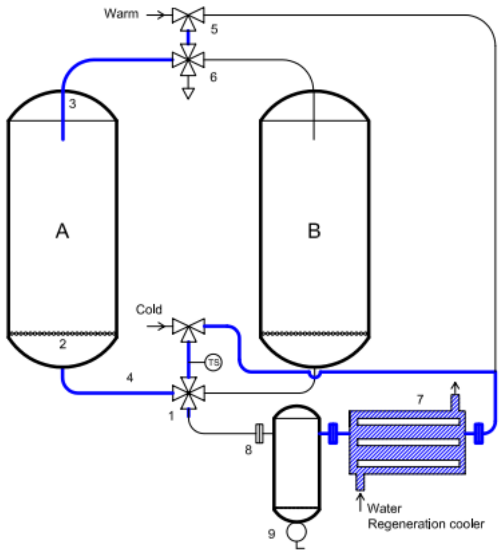
Layout design of three modes of heat regeneration-based adsorption dryer



(a)Regeneration by internal heat



(b)Regeneration by external heat



(c)Regeneration by compressor heat

Fig.1 Schematic diagram of adsorption system heat regeneration modes

There are three modes of heat regeneration available for the desiccant in an adsorption dryer. The internal heat regeneration mode is illustrated in Figure 1(a), which includes flat sieves and wire mesh at the entry and exit of the adsorber vessel to prevent desiccant carryover into the downstream pipe. The two adsorber vessels are connected at the entry and exit and a by-pass valve with an orifice is used to switch the feed stream from adsorption to regeneration. During regeneration, a portion of the dried air is diverted to the offline vessel, which is maintained at atmospheric pressure and heated simultaneously. Valves with a muffler are used to control the regeneration time and pressure build-up time. The regeneration process involves both heat and cold stages. The desiccant bed is heated gradually to reach the regeneration temperature and expel moisture from the saturated desiccant. Once the right temperature is reached, the exhaust valve is opened and a portion of dried air flows through the desiccant bed and towards the atmosphere with the aid of gravity. After regeneration, the adsorber vessel is brought to the same pressure before vessel switching. The exhaust valve is closed to ease pressure build-up in the vessel, and the vessel is switched over from regeneration to adsorption mode after pressure equalization.

The schematic diagram of the external heat mode adsorption dryer for regeneration is presented in Figure 1(b). This type of dryer utilizes an external heater and a blowing system that requires a small amount of already dried air for purging. The regeneration air is drawn from the atmosphere and heated by an external heater. Two 4/2-way valves and an external heater mounted in line with a blower are used in the process. During regeneration, the exhaust valve is opened and then closed during pressure build-up time after regeneration. The blower-assisted regeneration process requires a minimum quantity of dried air for the purging operation. After regeneration, the hot blower air, which is humidified by the removed moisture, exits the adsorber vessel via valve and valve. The cooling stage starts when the thermostat detects that the heating stage is complete. The heater is switched off, and fresh cold air is supplied through the same path. The desiccant bed and adsorber vessel are cooled down, and the cooling phase ends after the set period. Then, the exhaust valve closes, and the pressure build-up phase follows before switching over of the vessel takes place. Finally, the regenerated adsorber vessel is depressurized to atmospheric pressure via a muffler fitted at the exit, and the process is completed.

The adsorption dryer in Fig.1(c) is regenerated by compressor heat mode, using a closed loop design with two adsorber vessels for continuous operation. This system includes two 4/2-way valves for switching between adsorption and regeneration, as well as two 3/2-way valves in the piping. It also features a water-cooled heat exchanger and cyclone separator. Due to the closed loop design, the regeneration air in this system is more humid than in other modes, which requires a higher regeneration temperature to reach a specific pressure dew point.

Experimental design for system evaluation

The objective of the authors was to evaluate various types of adsorption dryers by analyzing their essential features and utilizing fundamental parameters to reach an unbiased assessment. In previous work by the authors [9-10], they developed principal calculation schemes for adsorption dryers, which form the foundation for a rational comparison between systems. The evaluation takes into account significant process variables, including operating pressure (3-16 bar), feed air temperature (25°C-45°C), and product air pressure dew point (-40°C). The authors utilized a compressed air cost parameter of Rs.1000 per 1000 m^3 to determine the characteristic cost of compressed air for adsorption dryers.

Regeneration energy establishment

In order to perform regeneration experiments, an electric heater is utilized to supply heat energy. This energy is sufficient to raise the bed temperature to the required regeneration temperature (TRE). As the desorption process takes place, the temperature of the adsorber gradually increases from the inlet to the outlet. Once the temperature at the outlet of the bed reaches a certain level, it indicates that the temperature has migrated throughout the entire bed, and triggers the switch-off of the heating phase. This specific temperature at which the switch-off occurs is referred to as the switching off temperature (TRO).

The amount of air required for regeneration is determined by calculating the LMTD (Logarithmic Mean Temperature Difference) for both the desorption and cooling stages. The LMTD-Desorption is calculated by utilizing the regeneration temperature (TRE), switching off temperature (TRO), and the temperature of the desiccant bed (TBC), as specified in equation (1).

$$LMTD_{Desorption} = \frac{T_{RO} - T_{BC}}{ln\frac{T_{RO} - T_{BC}}{T_{RE} - T_{RO}}} \quad (1)$$

Considering the regeneration temperature (TRE), the entry temperature (TO) and the outlet temperature of cooling air (TCO), LMTD (log-mean temperature difference) for cooling are calculated as described by equation (2).

$$LMTD_{Cooling} = \frac{T_{RE} - T_{CO}}{ln\frac{T_{RE} - T_O}{T_{CO} - T_O}} \quad (2)$$

In the cooling phase, the desiccant bed and adsorber vessel are cooled to a low temperature. To determine the energy needed to heat the desiccant material, the specific heat value is utilized, and equation (3) is employed for the calculation.

$$Q_{dr}=m_{dr}\times C_{dr}\times (T_{RE}-T_O) \quad (3)$$

Equation (4) is used to calculate the amount of heat needed to eliminate the moisture that has been adsorbed by the desiccant, and this is achieved by multiplying the heat of adsorption (QH) by the moisture load (hc).

$$Q_{H2O}=h_c\times Q_H \quad (4)$$

To determine the quantity of heat required to heat the adsorber vessel to the necessary regeneration temperature, equation (5) can be utilized.

$$Q_{vessel}=m_{vessel}\times C_{vessel} \times \Delta T_{log} \quad (5)$$

Equation (6) is used to calculate the total energy needed, which is obtained by adding up the heat duty for the desiccant (Qdr), the moisture loading (QH2O), and the adsorber vessel (Qst).

$$Q_s=Q_{dr}+ Q_{H2O}+ Q_{vessel} \quad (6)$$

Equation (7) is used for theoretical calculations to determine the value of Qrad for an adsorber tower, which depends on its position and the LMTD-Desorption. Typically, Qrad is estimated to be between 4 to 8 percent of the total calculated energy (QS) to account for heat loss through radiation. However, a general tolerance of 2 to 5 percent is added as a safety factor.

$$Q_{tot}=Q_s+Q_{ra}+ (2\text{-}5\%)\ Q_{rad} \quad (7)$$

Economic Analysis of heat regeneration-based adsorption dryer

The calculation systems for the heat regeneration mode of an adsorption dryer have been previously established and serve as a basis for evaluation. The developed regression equation is used to conduct an objective study of the dryer. Equation (8) is used to calculate the energy cost per 1000 m3, which serves as a common and uniform parameter.

$$C_{o,1000} = C_{oh} \times \frac{1000}{V_e} \quad (8)$$

For a dryer comparison taking investment into account, capital costs is to be included and are calculated using the equation (9).

$$C = \frac{z \times (1+z)^n}{(1+z)^{n-1}} \times A \quad (9)$$

The cost of operating a dryer, which takes into account the running time and differential flows at the exit, is calculated using equation (10). The capital cost is spread out over the yearly service life and expressed as capital amortization per hour.

$$C_h = C \times \frac{t_{Bh}}{t_{Ba}} \quad (10)$$

RESULTS AND DISCUSSION

The regeneration characteristics in the three modes are affected by several factors, such as desorption temperature, switch-off temperature, logarithmic temperature difference during desorption and cooling. By determining the ideal values for these factors, the cost of energy required for regeneration can be calculated. To assess the system's performance, a standard range is used for all modes, which includes a compressed air output of 1000 to 5000 m3/hr, an operating pressure of 3 to 16 bar, and a feed air temperature of 25 to 45°C.

System evaluation data

An analysis is conducted on the system evaluation data that pertains to the air requirement for regeneration at a pressure dew point of -40°C for three modes of heat regeneration.

In the testing, it was found that the regeneration process takes a shorter amount of time for internal heat regeneration compared to external heat regeneration and compressor heat regeneration. Specifically, the regeneration process takes 96%, 82%, and 40% of the time required for adsorption in the cases of internal heat regeneration, external heat regeneration, and compressor heat regeneration, respectively. Additionally, the duration of heating during the regeneration process is highest for internal heat regeneration at 65% of the time needed for adsorption, followed by external heat regeneration at 54%, and compressor heat regeneration at 27%. On the other hand, the cooling time during the regeneration process is shortest for external heat regeneration at 11% of the time taken for adsorption, followed by compressor heat regeneration at 13%, and internal heat regeneration at 31%.

In addition to the information provided earlier, it was observed that the duration of the flushing time during the regeneration process is 18% of the time required for adsorption in the case of external heat regeneration. Moreover, the holding time during the regeneration process is longer for compressor heat regeneration at 60% of the time taken for adsorption, while for external heat regeneration, it is 18%. Finally, the duration of the pressure build-up time is minimal, only 4% of the time required for adsorption in the case of both external heat regeneration and compressor heat regeneration.

Internal heat regeneration involves the use of 5% of the product air for purging during the heating phase and an extra 4% for purging during the cooling phase. Consequently, the energy required for regeneration amounts to 0.697 kW/m^3/min of product air.

According to the performance results, the external heat regeneration method requires 0.61 kW/m^3/min of heating power requirement, while internal heat regeneration method requires 0.27 kW/m^3/min of heating power requirement for regeneration. Moreover, when using internal heat regeneration method, 5% of the produced product air is diverted as purge air for regeneration, resulting in moisture-free product air with a volume percentage of 95%. When using external heat regeneration method, only 1.5% of the product air is diverted for regeneration, resulting in moisture-free product air with a volume percentage of 98.5%. In compressor heat regeneration mode, 100% of moisture-free product air is produced.

Based on the findings, it can be observed that the operating pressure of the product air for internal and external heat regeneration methods remains at 7.74 bar when using an 8 bar pressure feed air, while for compressor heat regeneration, it is 7.43 bar. The operating pressure loss is 7.3% for both internal and external heat regeneration methods, whereas for compressor heat regeneration, it is 15.6%. Additionally, the characteristic specific energy consumption with respect to electrical energy is 0.176 kW/m^3/min for internal heat regeneration and 0.342 kW/m^3/min for external heat regeneration.

Effect of temperature on pressure dew point of product air in all three modes

The relationship between the pressure dew point temperature of the product air and the desorption temperature and switching off temperature of the TSA system is illustrated in Figure 3. It appears that there is an inverse correlation between the desorption temperature and pressure dew point temperature. For a pressure dew point temperature of -40°C in the product air, the appropriate pair value of desorption temperature and switching off temperature is 180°C and 130°C, respectively. During the desorption process, the temperature inside the adsorber gradually moves towards the outlet. The speed of this temperature migration is similar at different levels of regeneration temperature, which can be attributed to the heat capacity ratio of the gas phase to the solid phase. Once the temperature at the outlet of the adsorber changes, it signals the completion of temperature migration and triggers the end of the heating phase. Any deviation from the appropriate pair value of temperature can significantly impact the pressure dew point of the product air.

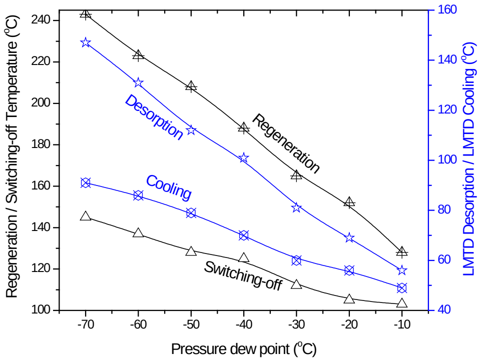


Fig.3 Variation of PDPT corresponding to temperature

The logarithmic temperature variations of desorption and cooling with respect to the pressure dew point temperature are depicted in Figure 3. The LMTD-Desorption value is obtained using equations that involve the switching off temperature, desiccant bed temperature, and desorption temperature. On the other hand, LMTD-Cooling is computed using equations that consider the desorption temperature, inlet temperature, and cooling air outlet temperature. The pair values of LMTD-Desorption, ranging from 55°C to 145°C, correspond to product air dew point temperatures ranging from -10°C to -70°C. To ensure that the humidity on the dry side of the adsorber bed is kept to a minimum, the cooling air outlet temperature should not exceed 70-80°C. During the cooling phase, the desiccant material and the adsorber tower are cooled to a low operating temperature. The cooling phase ends after a specified period, as given by the corresponding equation.

Energy cost diagrams

Figure 4 presents the energy cost per 1000 m^3 of adsorption dryers, and it is evident that heat mode regeneration is more cost-effective than heatless regeneration mode at higher operating pressures. This is due to the pressure-dependent secondary relative humidity, which generates a favourable load factor, leading to the best correlation between volume flow rate from the inlet to the working state. On the other hand, for a fixed volume flow rate of feed air at a constant inlet temperature, the energy cost is lowest for heatless regeneration, followed by external heat regeneration and compressor heat regeneration methods, respectively.

Moreover, the energy cost required for internal heat regeneration mode decreases dramatically after 6.5 bar operating pressure, making it the most cost-effective option for higher operating pressures. This suggests that choosing the appropriate regeneration mode for adsorption dryers requires careful consideration of the operating pressure and the characteristics of the feed air. Additionally, these findings are based on basic data and can serve as a valuable reference for the design and selection of adsorption dryers.

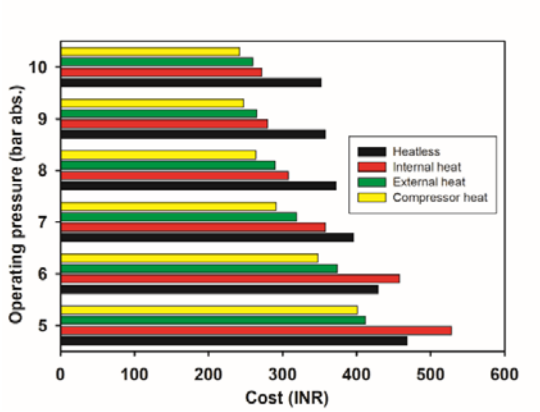


Fig.4 Energy cost referred to Q=3000 m^3/hr and T_i=35°C

Figure 5 presents the energy cost per 1000 m^3 plotted against a constant pressure and volume but varying feed temperatures. The graph indicates that adsorption dryers with heatless regeneration mode are more cost-effective at higher inlet temperatures than those with regeneration by heat mode. This is evident from all curves on the graph, which show that the energy required for regeneration increases with higher inlet temperatures in the case of regeneration by heat mode. This is due to the fact that the higher inlet temperature affects the secondary relative humidity, resulting in an unfavorable load factor.

In contrast, heatless regeneration mode does not depend on temperature and, therefore, its energy cost remains relatively constant with varying inlet temperatures. Consequently, based on the graph in Figure 5, it is recommended to use heatless regeneration mode for adsorption dryers at higher inlet temperatures to achieve the most cost-effective operation. This information is important for industries and businesses that rely on adsorption dryers for their operations, as it helps them make informed decisions on which regeneration mode to use based on their specific needs and operating conditions.

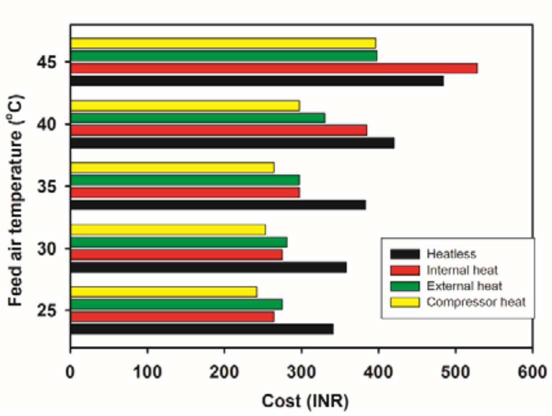


Fig.5 Energy cost referred to Q=3000 m^3/hr and p=8 bar abs

The plot in Figure 6 displays the capital and energy costs of adsorption dryers per 1000 m^3 against varying volume flow rate at a constant feed pressure and temperature. As per the plot, the heatless regeneration mode adsorption dryer is cheaper to produce than a regeneration by heat mode adsorption dryer owing to their respective designs. However, the capital and energy expenses of these dryers move in opposite directions, which means that while the production cost may be low for one, its operational cost may be high, and vice versa. The results used for dryer comparison in the plot are based on basic data, which emphasizes the importance of additional data and analysis to obtain an accurate representation of the cost differences between different dryer types. Additionally, the plot shows that although the heatless regeneration mode adsorption dryers are cheaper to produce, they are more expensive in terms of both capital and energy costs when compared to regeneration by heat mode dryers. Therefore, when considering the costs of adsorption dryers, it is essential to account for both capital and energy expenses to ensure that the most cost-effective dryer is chosen for a given application.

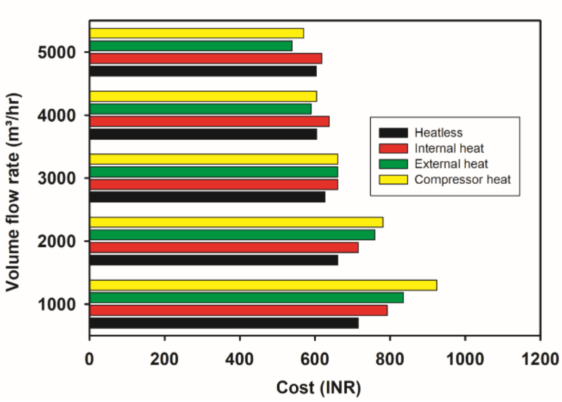


Fig.6 Energy and capital cost referred to T_i=35°C and p=8 bar abs.

CONCLUSIONS

From the performance studies of three types of heat regeneration-based adsorption dryers, the following conclusions were drawn:

• Regeneration by heat mode adsorption dryers is most suitable for strongly adsorbed species, with desorbate being recovered at high concentrations. However, it is unsuitable for rapid cycling, limiting the adsorbent's maximum efficiency.

• The results showed that the characteristic specific energy requirement for electrical energy in terms of internal heating regeneration, external heating regeneration, and compressor air heating regeneration are 0.176, 0.342, and 0 kW/m^3/min, respectively. Additionally, the characteristic specific energy requirement for dried regeneration air for internal heating, external heating, and compressor air heating are 0.203, 0, and 0 kW/m^3/min, respectively.

• It was concluded that the energy and capital costs for a feed air temperature of 35°C and feed air pressure of 8 bar abs. at a volume flow rate of 3000 m^3/hr were similar for all three modes of heat regeneration.

• The system comparison using reproducible dryer data for various performance ranges can be utilized for practical purposes.

Nomenclature

m3-Cubic metre
CSS-Cyclic steady state
°C-Degree Celsius
Co-Energy cost
TO-Entry air temperature
Qdr-Heat energy required for desiccant bed
Qvessel-Heat energy required to heat adsorber vessel
QH2O-Heat energy required to remove moisture
QH-Heat of adsorption
Qrad -Heat transfer by radiation mode
LMTD-Logarithmic Mean Temperature Difference
mdr-Mass of desiccant material
hc-Moisture load
TCO-Outlet temperature of cooling air
PDPT-Pressure dew point temperature
TRE-Regeneration temperature
Cdr-Specific heat of desiccant material
Cvessel-Specific heat of vessel material
TRO-Switching off temperature
TBC-Temperature of desiccant bed
Qs-Total heat energy required for regeneration

REFERENCES

Bettega, Rodrigo, et al., "Mathematical simulation of radial heat transfer in packed beds by pseudo homogeneous modeling," Particuology,vol.9,no..2,pp.107-113,2011.DOI:https://doi.org/10.1016/j.partic.2010.09.009.

Kadoli, R., and TP Ashok Babu., "Improved utilization of desiccant material in packed bed dehumidifier using composite particles," Renewable energy, vol.36, no.2, pp.732-742,2011.DOI:https://doi.org/10.1016/j.renene.2010.06.038.

Kannan, V. Suresh, T. V. Arjunan, and S. Vijayan., "Drying characteristics of mint leaves (Mentha arvensis) dried in a solid desiccant dehumidifier system," Journal of Food Science and Technology, vol. 58, no.2,pp.777-786,2021.DOI:https://doi.org/10.1007/s13197-020-04595-z.

Kannan, V. Suresh, T. V. Arjunan, and S. Vijayan., "Experimental investigation of temperature swing adsorption system for air dehumidification," Heat and Mass Transfer, vol. 56, no.7,pp. 2093-2105,2020.DOI:https://doi.org/10.1007/s00231-020-02841-w.

Kannan, V., and T. Arjunan., "Optimization of process parameters of pressure-swing adsorption cycle in a silica gel desiccant dehumidification system," J Adv Chem, vol. 13, no.10,pp.6543-6551,2017.

Kwapinski, Witold, et al., "Thermal and flow effects during adsorption in conventional, diluted and annular packed beds," Chemical engineering science, vol. 65, no.14,pp.4250-4260, 2010.DOI: https://doi.org/10.1016/j.ces.2010.04.017.

Sureshkannan, V., et al., "Parametric study on pressure-based packed bed adsorption system for air dehumidification," Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering, vol.235, no.5,pp.1351-1362,2021.DOI: https://doi.org/10.1177%2F09544089211007318.

Sureshkannan, V., S. Vijayan, and V. R. Lenin., "Design and performance analysis of compressed air adsorption dryer with heatless regeneration mode," Heat and Mass Transfer,vol. 58,no.4,pp.631-641,2022.DOI:https://doi.org/10.1007/s00231-021-03136-4.

Venkatachalam, Sureshkannan, and Arjunan Thottipalayam Vellingri., "Optimization of process parameters of adsorption process in solid desiccant dehumidification system using genetic algorithm." □ □ □ □ □ □ □ □ , vol. 40, no.5,pp.547-553,2019.DOI: https://www.airitilibrary.com/Publication/PublicationIndex/02579731.

W John Thomas, FEng, and Barry Crittenden., Adsorption technology and design. Butterworth-Heinemann, 1998.