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DEHYDRATION OF NATURAL GAS STORED IN UNDERGROUND GAS STORAGES

ODWADNIANIE GAZU NATURALNEGO PRZECHOWYWANEGO W MAGAZYNACH PODZIEMNYCH

Abstract

Due to national strategic reserves and to smooth seasonal and short-term peaks of natural gas consumption it is stored in underground reservoirs. During storage it is being saturated by water vapor from the repository. Before the further distribution gas must be dehydrated to meet the transportation parameters specified by the gas distributors. The paper describes a new energy saving gas-drying technology that uses a supersonic passage of the gas through a nozzle. The goal of this paper is to formulate mathematical-physical model of gas flow in the nozzle. Technical design which solves the problem of unsteady inlet parameters is proposed. Basic geometry and industrial applications are discussed.

Keywords: natural gas, dehydratation, supersonic separation

Streszczenie

Dla potrzeb narodowych rezerw strategicznych, służących wyrównaniu sezonowych i krótkoterminowych wzrostów zużycia, gaz ziemny jest przechowywany w podziemnych zbiornikach. W trakcie przechowywania następuje nasycenie gazu parą wodną ze zbiornika. W celu dostosowania gazu do parametrów transportu określonych przez dystrybutorów, konieczne jest przeprowadzenie dehydracji gazu przed jego dalszym przesyłem. W niniejszym artykule przedstawiono nową, energooszczędną technikę osuszania gazu polegającą na ponaddźwiękowym przepuszczeniu gazu przez dyszę. Celem artykułu jest sformułowanie matematyczno-fizycznego modelu przepływu gazu przez dyszę. Zaproponowano projekt techniczny rozwiązujący problem niestabilności parametrów wlotowych. Omówiono podstawową geometrię i zastosowanie w przemyśle.

Słowa kluczowe: gaz naturalny, odwadnianie, oddzielanie naddźwiękowe

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1. Introduction

There are two basic reasons for storing NG. Firstly, it can decrease dependency on supply. With this in mind national strategic reserves are created. Secondly, by NG storing the maximum capacity of distribution lines can be exploited. Underground Gas Storages (UGS) are the most advantageous option for storing large volumes of gas. Nowadays there are approximately 135 UGSs inside the European Union. Their total maximum technical storage capacity is around 100 bcm. According to the latest update, over 70 bcm of additional storage capacity will come on stream in Europe till 2020 [1]. Next table shows UGS capacities in Poland, Germany and Czech Republic. Capacities of shale gas (SG) in Poland and Czech Republic are not covered in this summary table. Some problems accompanied with SG fracking might be discussed in the lecture.

Table 1

UGS capacities in Poland, Germany and Czech Republic

	UGS present capacities	UGS capatities projected	Present withdrawal rate from UGS	Future projects	NG feeding rate into UGS	Future projects
	$10^6\,m^3$	$10^6\,m^3$	$10^6\,m^3/d$	$10^6\,m^3/d$	$10^6\,m^3/d$	$10^6\,m^3/d$
Czech republic	3277	335	56	0	40	0
Germany	20 301	10 526	437	145	226	74
Poland	1828	1662	40	23	21	10

There are three types of UGSs: (1) Aquifers, (2) Depleted oil/gas fields and (3) Cavern reservoirs (salt or hard rock). Each of these types possesses distinct physical characteristics. The important parameters describing the appropriateness of UGS use are storing capacity, maximal injecting/withdrawing performance and gas contamination during storage. Generally, the allowable pressure of stored gas inside a UGS is up to 20 MPa. The pressure inside increases as the gas is being injected and decreases when gas is withdrawn. The output gas pressure depends on further distribution. Distribution sites from UGS normally begin at 7 MPa. The temperature of the gas usually ranges from 20–35°C. The exact temperature varies with the location of the UGS and with the time of year.

During storage the gas becomes saturated by water vapors. In the case of depleted oil field UGSs, vapors of higher hydrocarbons also contaminate the stored gas. The distribution specification sets the allowable water concentration and higher hydrocarbons. In Europe the concentration of water and higher hydrocarbons is specified by their dew point temperature (T_{dew}). T_{dew} for water is −7°C for NG at 4 MPa and the T_{dew} for hydrocarbons is 0°C for NG at the operating pressures [3].

The water content of NG at saturation is dependent on the temperature and pressure. With increasing pressure of gas the water content decreases and with increasing temperature water content in gas increases.

2. Problems with water in the gas

If the temperature of pipeline walls or storage tanks would decrease below the T_{dew} of water vapors present in a gas the water starts to condensate on those cold surfaces and following problems could appear.

- NG in combination with liquid water can form the methane hydrate. Methane hydrate is a solid in which a large amount of methane is trapped within the crystal structure of water, forming a solid similar to ice. The hydrate production from a unit amount of water is higher than the ice formation. Hydrates formed by cooling may plug the valves, fittings or even pipelines.
- NG dissolved in condensed water is corrosive, especially when it contains CO_2 or H_2S.
- Condensed water in the pipeline cause slug flow and erosion.
- Water vapor increases the volume and decreases the heating value of the gas.
- NG with presence of water vapor cannot be operated on cryogenic plants.

3. Dehydration methods

3.1. Absorption

The most widely method used for industrial dehydration of NG is absorption. Absorption is usually performed using triethyleneglycol sorbent (TEG). Absorption proceeds at low temperatures and the absorbed water is boiled out from TEG during regeneration in reboiler at high temperatures.

The industrial absorption dehydration process proceeds in a glycol contactor (a tray column or packet bed). In a contactor a countercurrent flow of wet NG and TEG is arranged. During the contact, the TEG is enriched by H_2O and flows out of the bottom part of the contactor. Enriched TEG then continues into the internal heat exchanger, which is incorporated at the top of the still column. It then flows into the flash drum, where the flash gases are released and separated from the stream. TEG then runs to the cold side of the TEG/TEG heat exchanger. Just afterwards, the warmed TEG is filtered and sprayed into the still column. From there, the TEG runs into the reboiler. In the reboiler H_2O is boiled out of TEG. Regeneration energy is around 282 kJ for liter of TEG. The temperature inside should not exceed 208°C due to the decomposition temperature of TEG. Regenerated (lean) TEG is then pumped back through the hot side of the TEG/TEG and NG/TEG heat exchanger into the top of the contactor. The entire method is depicted in Fig. 1 [8].

The circulation rate (l_{TEG} / kg_{H2O}) and purity of the regenerated TEG are the main limiting factors determining the output T_{dew} of NG. The circulation rate ranges around 40 times the amount of water to be removed. The minimal TEG concentration should be above 95 weight %, but recommended value is higher. However to obtain TEG concentration above 99% enhanced TEG regenerations have to be implemented. The simplest regeneration enhancing method is gas stripping. Proprietary designs DRIZO®, licensed by Poser-NAT, and COLDFINGER®, licensed by Gas Conditioners International, have been patented as an alternative to traditional stripping gas units. The Drizo regeneration system utilizes
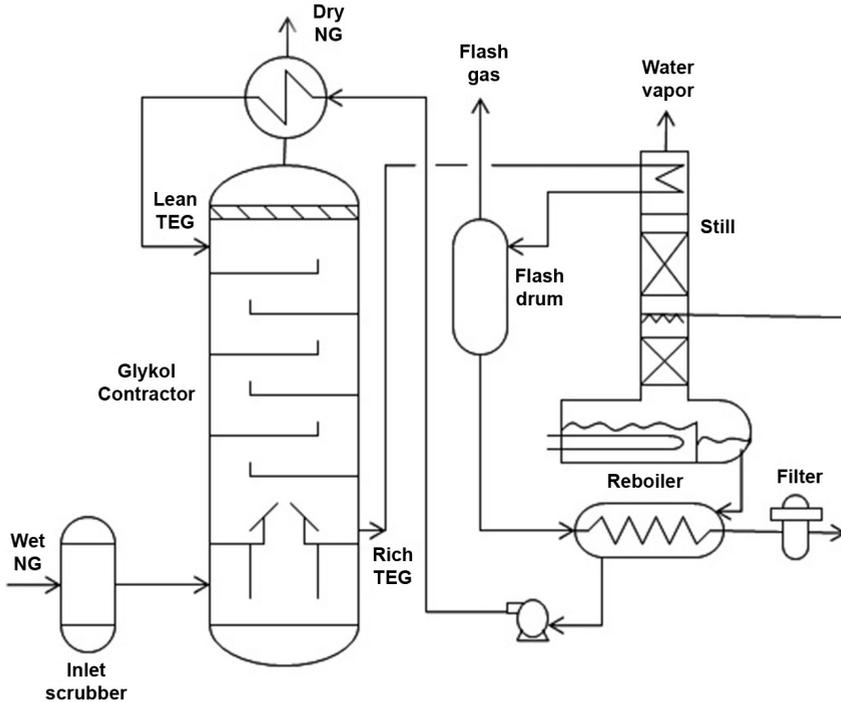
Fig. 1. TEG absorption dehydration scheme

Rys. 1. Schemat odwadniania absorpcyjnego TEG

a recoverable solvent as the stripping medium. The patent operates with iso-octant solvent, but the typical composition is about 60% aromatic hydrocarbons, 30% naphthenes and 10% paraffins. The three-phase solvent water separator is crucial for this method. The Coldfinger regeneration system employs a cooling coil (the "coldfinger") in the vapor space of the surge tank. The cooling that takes place there causes condensation of a high amount of vapors. The condensate is a water rich TEG mixture, which is led to a further separation process [9].

3.2. Adsorption

The second dehydration method is adsorption of H_2O by a solid desiccant. In this method, H_2O is usually adsorbed on a mole sieve, silica gel or alumina. The amount of adsorbed H_2O molecules increases with the pressure of the gas and decreases with its temperature. These facts are taken into account when the process parameters are designed. Adsorption dehydration columns always work periodically. A minimum of two bed systems are used. Typically one bed dries the gas while the other is being regenerated. Regeneration is performed by preheated gas, or by part of dehydrated NG as it is depicted in Fig. 2.

This method is known as temperature swing adsorption (TSA). Regeneration can also be performed by change of pressure − pressure swing adsorption (PSA), but for cases of NG dehydration PSA is not industrially applied.
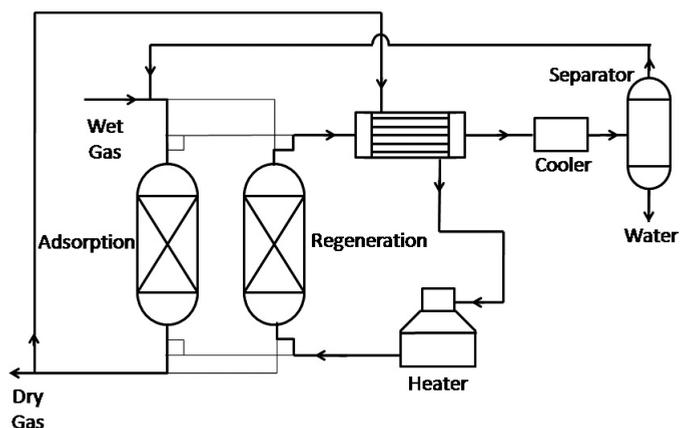
Fig. 2. Scheme of the temperature swing adsorption dehydration process

Rys. 2. Schemat procesu odwadniania adsorpcyjnego przy wahaniach temperatury
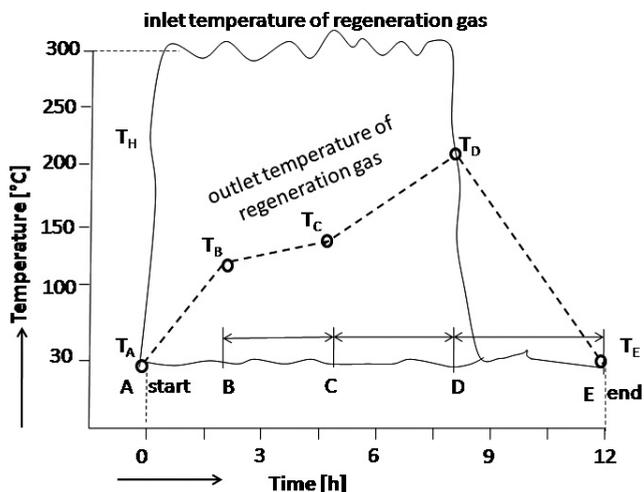

Fig. 3. Typical temperature course for 12 h TSA regeneration of molecular sieves

Rys. 3. Typowe wahania temperatury dla 12-godzinnego odzysku TSA molekuł sitowych

The heater for TSA can be realized as an ordinary burner or as a shell and tube heat exchanger warmed by steam or hot oil. The regeneration gas flows through the adsorbent into a cooler (usually using cold air) and then further into the separator. Most of the desorbed humidity from the adsorbent is removed there. A downstream flow of wet NG through the adsorption column is usually applied. In this way, floating and channeling of an adsorbent is avoided. The regeneration is performed by countercurrent flow in order to provide complete regeneration from the bottom of the column, where the last contact of the dried NG with the adsorbent proceeds. The typical temperature course for 12 h regeneration of molecular sieves is shown in Fig. 3 [11].

The shape of the curve representing the course of the outlet regeneration gas temperature is typically composed of four regions. They are specified by time borders A, B, C and D with appropriate border temperatures T_A, T_B, T_C and T_D. Regeneration starts at point A. The inlet regeneration gas warms the column and the adsorbent. Around a temperature of 120°C (T_B) the sorbed humidity starts to evaporate from the pores. The adsorbent continues warming more slowly, because a considerable part of the heat is consumed by water evaporation. From point C, it can be assumed that all water has been desorbed. T_D is further heated to desorb C_{5+} and other contaminants. The regeneration is completed when the outlet temperature of the regeneration gas reaches 180–190°C (T_D). Finally, cooling proceeds from point D to E. The temperature of the cooling gas should not decrease below 50°C, in order to prevent any water condensation from the cooling gas [11]. Usually part of the dehydrated NG is used as the regeneration gas. After regenerating the adsorbent the gas is cooled, and the water condensed from it is separated. After H_2O separation, the regeneration gas is added back to inlet stream or alternatively to dehydrated stream.

The total energy used for regeneration is composed of heat to warm load 25%, heat for desorption 40% and from heat going to the construction 35%. By proper internal insulation of adsorption towers the heat going to the construction can be minimized and over 30% of energy invested can be saved.

So-called LBTSA (Layered Bed Temperature-Swing Adsorption) processes are an upgrade of the TSA method. Here, the adsorption column is composed of several layers of different adsorbents.

3.3. Condensation

The third conventional dehydration method employs gas cooling to turn H_2O molecules into the liquid phase and then removes them from the stream. Natural gas liquids and condensed higher hydrocarbons can also be recovered from NG by cooling. The condensation method is therefore usually applied for simultaneous dehydrating and natural gas liquids recovery. NG can be advantageously cooled using the Joule-Thompson effect (JT effect). The JT effect describes how the temperature of a gas changes with pressure adjustment. For NG, thanks to expansion, the average distance between its molecules increases, leading to an increase in their potential energy (Van der Waals forces). During expansion, there is no heat exchange with the environment or work creation. Therefore, due to the conservation law the increase in potential energy leads to a decrease in kinetic energy and thus a temperature decrease of NG. However, there is another phenomenon connected with the cooling of wet NG. Attention should be paid to methane hydrate formation. Hydrates formed by cooling may plug the flow. This is usually prevented by injecting methanol or monoethylenglycol hydrate inhibitors before each cooling. Fig. 4 depicts a dehydration method utilizing the JT effect and hydrate inhibition.

The wet NG is throttled in two steps inside the flash tanks. The lower temperature (due to the JT effect) of the gas stream in the flash tanks leads to partial condensation of the H_2O vapors. The droplets that are created are removed from the gas stream by a demister inside the flashes. In cases where cooling by the JT effect is insufficient (the usable pressure difference between the UGS and the distribution network is insufficient), the air pre-cooler and the external cooler are turned on. Since dehydration is normally applied to large volumes of NG,
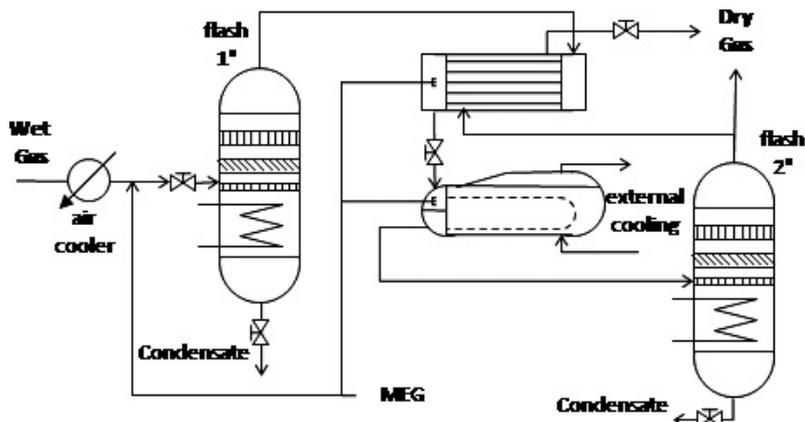
Fig. 4. Dehydration method utilizing the JT effect and hydrate inhibition

Rys. 4. Metoda odwadniania wykorzystująca efekt JT oraz inhibicję hydratu

the external coolers need to have high performance, so this type of cooling is very energy expensive. However, if the usable pressure difference is high, the JT effect inside the flashes is so strong that internal heating of the flashes is required to defreeze any ice that may form. A condensation method is applied when suitable conditions for the JT effect are available.

3.4. Supersonic separation

Principle of this method lays in the use of Laval Nozzle in which the potential energy (pressure and temperature) transforms into kinetic energy (velocity) of the gas. The velocity of gas reaches supersonic values. Thanks to that sufficient temperature drops are obtained, T_{dew} of water vapor in NG is reached and nucleation of droplets proceeds. On the next Figure a basic design of supersonic nozzle is depicted.
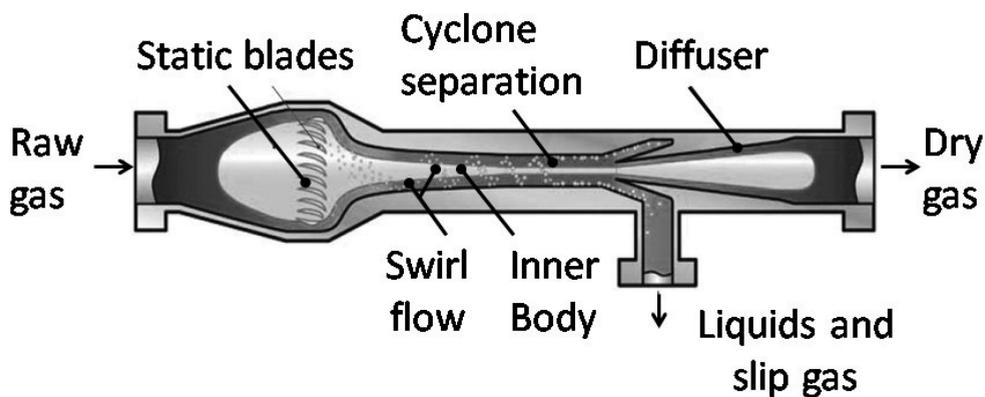

Fig. 5. Design of supersonic nozzle [13]

Rys. 5. Projekt dyszy naddźwiękowej [13]

At the inlet to the nozzle are static blades which induce swirling flow of the gas. The water droplets formed are separated by centrifugal force on the walls. Centrifugal force in supersonic part of the nozzle can reach values up to 500 000 g [14]. The thin water film on walls moves in direction of flow into a separation channel. Separation channel leads into heated degas separator. From here is slip gas returned back to main stream and water condensate is removed. After the separation of water it is important to recover pressure of the gas from its kinetic energy. To achieve this, shock wave is used. Generally shock waves form when the speed of a gas changes by more than the speed of sound. In supersonic nozzles the shock wave is created by fast enlargement of the nozzle diameter.

Each of the methods presented here has its advantages and disadvantages. Absorption by TEG is nowadays the most widely used method. Outlet T_{dew} around −10°C is usually reached. Indeed, with improved reboiler design (Vacuum stripping, Drizo, Coldfinger) the outlet T_{dew} is even 2–3 times lower. However TEG has a problem with sulfur or with gas contaminated with higher hydrocarbons. The TEG in the reboiler foams, and with time it degrades into a "black mud". BTEX emissions (the acronym for benzene, toluene, ethylbenzene and xylenes) in the reboiler vent are a further disadvantage.

Adsorption dehydration can achieve very low outlet water concentration T_{dew}< −50°C, and contaminated gases are not a problem. Even corrosion of the equipment proceeds at a slower rate. However, adsorption requires high capital investment and has high space requirements. The adsorption process runs with at least two columns (some lines use three, four, or as many as six). Adsorption columns are taller and heavier than an absorption contactor. The allowed flow velocity for TEG contactors is approximately three times higher than the velocity for adsorption. These results in an approximately 70% larger diameter of the adsorption column for the same amount of processed gas. Industrial experience indicates that the capital cost for an adsorption line is 2–3 times higher [5].

Expansion dehydration is the most suitable method in cases where a high pressure difference is available between UGS and the distribution connection. However the difference decreases during the withdrawal period and becomes insufficient, so that an external cooling cycle is needed. A cycle for hydrate inhibitor regeneration from the condensate separated inside the flashes is also required.

4. Comparison of dehydration methods

The energy demand of the methods presented here is compared on the basis of a model case, where a volume of 10^5 Nm³/hr of NG from UGS is processed. The NG is H_2O saturated at a temperature of 30°C. The pressure of the gas is varied from 7 to 20 MPa, but in the case of the condensation method the pressure range starts at 10 MPa. The required outlet concentration of H_2O in natural gas is equivalent to dew point temperature −10°C at gas pressure 4 MPa.

The total energy demand is composed of heat for TEG regeneration in the reboiler, energy for the pumps, filtration and after-cooling the lean TEG before entering the contactor. Enhanced regeneration is not considered. The basic parameters for the calculation are: regeneration temperature 200°C, concentration of lean TEG 98.5% and circulation ratio 35 l_{TEG} / kg_{H2O}.

For calculating adsorption dehydration, molecular sieve 5A is considered to be the most suitable adsorbent. The total energy demand is directly connected to the regeneration gas heater, and no other consumption is assumed. The basic parameters for all procedures are: temperature of the regeneration gas 300°C, time of adsorption/regeneration 12 hrs, and two column designs.

The condensation method was calculated on the basis of industrial data provided byTEBODIN s.r.o. and supplementary calculations of the JT effect. The key parameter influencing energy demand is the pressure of NG from UGS. Because it is not feasible to apply this method for low pressures, and because the provided data starts at 10 MPa, the pressure range was adjusted. The total energy demand consists of the air pre-cooling unit, the external cooling, the pumps for MEG injection and condensate off take, the heat for MEG regeneration, and flash heating.

The results obtained for the TEG absorption method are the same for each of the calculation procedures, and good agreement with industrial data was also obtained. However, the calculation procedures for the adsorption method lead to different results. Hence the average energy demand value was taken as the reference. The maximum deviation from it is below 20% for all calculation procedures. In the case of the condensation method, the calculated values for the JT effect were in good agreement with the industrial data.

The final energy consumption results for each dehydration method are summarized by the graph in Fig. 6.
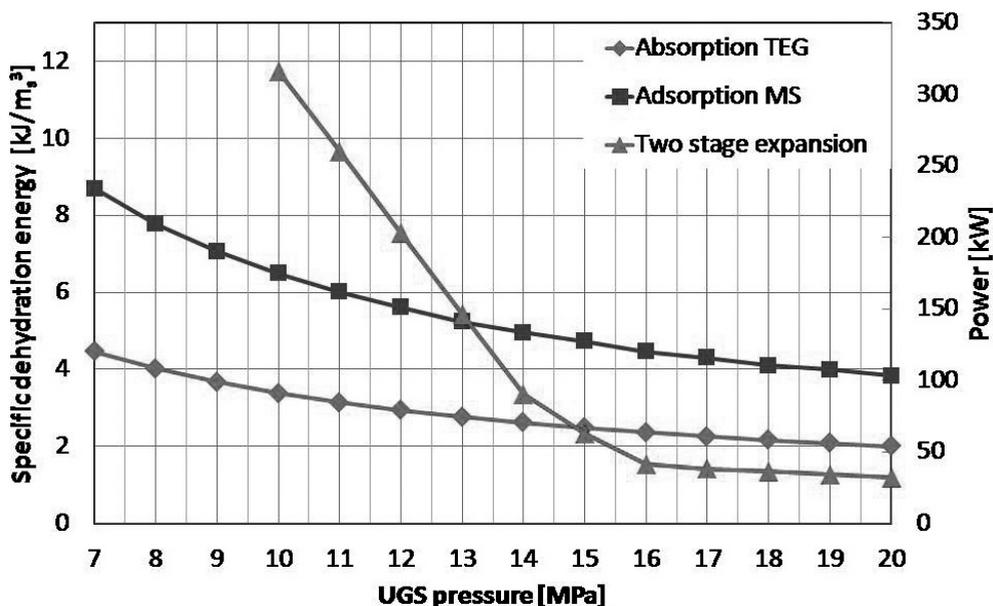

Fig. 6. Power required for dehydration in our model case
and corresponding specific energy required
for dehydration vs. UGS pressure

Rys. 6. Wymagana moc i energia odwadniania w modelu a ciśnienie UGS

For low pressures (pressure of NG from UGS < 13 MPa), the condensation method is the most demanding. Its demand decreases linearly with pressure to a value of 145 kW for 13 MPa. At this point, the energy demand for the condensation method is roughly the same as for the adsorption method. When the NG pressure is further increased from 13 MPa to 16 MPa, the energy demand for the condensation method still decreases, but with a lowering tendency. For a high pressure of NG (> 16 MPa), the energy demand of the condensation method is at its lowest, and it remains nearly constant with an average value around 36 kW.

The course of the energy demand for the adsorption and absorption methods is quite similar: with increasing pressure of dehydrated NG the energy demand slowly decreases. The absorption method is less demanding on the whole pressure scale, and begins with consumption of 120 kW at 7MPa. The adsorption method starts with 234 kW at 7 MPa, but the energy demand decreases slightly more as the pressure of NG in UGS rises. This leads to a gradual decrease in the difference between these methods, and the energy demand at the final pressure value of 20 MPa is equal to 54 kW for absorption and 103 kW for adsorption.

5. Discussion

By far the highest energy demand of the condensation method at low pressures of NG from UGS is due to the pressure being close to the distribution pressure, so that pressure cannot be used for the JT effect in flashes. Cooling is then compensated by the air pre-cooler and the external cooling device, which are unsuitable for large volumes of processed NG. However, as the pressure difference between UGS and the distribution site increases, the space for expansion rises and the JT effect proceeds with increasing impact. This is projected into a linear decrease in the energy demand of the air pre-cooler and the external cooling device. From the point where there is a pressure of NG > 14 MPa, flash heating is gradually turned on to prevent any freezing caused by the strong JT effect. The energy demand of flash heating is reflected in the total energy consumption. Finally, for pressures of NG > 16 MPa, total cooling and subsequent condensation is achieved by the JT effect. The total energy demand remains constant, and consists of flash heating and inhibitor injection and regeneration.

In case of adsorption and absorption dehydration method, the similar falling course of the energy demand with increasing pressure of NG can be explained by the fact that with increasing pressure within a UDG the amount of H_2O present in the NG decreases. The absorption method generally consumes less energy, because the regeneration of TEG is less demanding than adsorbent regeneration. The composition of the total energy demand of the adsorption method can be divided into three parts. The heat for H_2O desorption is approximately 55%, for warming the adsorbent it is 31%, and for warming the column it is 14%. It also has to be assumed that just part of the heat in the regeneration gas transfers to the adsorbent, the column and heat loss leaves to the atmosphere, and the balance leaves with the hot gas.

In brief, in cases of high pressure the most appropriate dehydration method from the energy demand point of view is the stored NG condensation method. This holds for NG from UGS with pressure > 15 MPa and distribution pressure requirements 7 MPa. For lower pressures, the condensation method is used if the objective is to recover NGL and remove water simultaneously. However, this is usually not the case when storing NG in a UGS. In cases

where insufficient pressure difference is available, the absorption method is therefore favored over the adsorption method in terms of energy demand. TEG absorption is nearly twice less demanding. However, if a gas contaminated with sulfur or higher hydrocarbons is being processed, the TEG in the reboiler foams and degrades with time. This can occur when a depleted oil field is used as a UGS. Adsorption is preferred in cases where very low T_{dew} (H_2O concentration lower than 1 ppm can be achieved) of NG is required, for example when NG is liquefied.

It is worth to note that the power comparison can be used as a measure of the technical excellence. From power data the specific energy consumption was calculated and its values indicate that the energy cost is much lower than the investment cost (depreciations). On the other hand the energy cost represents more than 60% of the total operating cost.

Abbreviations

NG   – natural gas
SG   – shale gas
UGS   – underground gas storage
TEG   – triethyleneglycol
TSA   – temperature swing adsorption
LBTSA – layered bed temperature swing adsorption
JT effect – Joule-Thompson effect
BTEX – benzene, toluene, ethylbenzene and xylenes
m_S^3 – standard cubic meters of gas (293,15 K; 101,325 kPa)

Symbols

T – temperature, K, °C
T_{dew} – dew point temperature, K, °C
p – pressure of NG, MPa
P – power, energy consumption to dehydrated NG, kW, W

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