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RAW GAS DEHYDRATION ON SUPERSONIC SWIRLING SEPARATOR

ODWADNIANIE GAZU NATURALNEGO W NADDŹWIĘKOWYM ODDZIELACZU MIESZAJĄCYM

Abstract

The supersonic separation is a promising new technology. The main advantage of the method is the small size of the supersonic nozzle. A program was designed to select the nozzle combination for an interval of inlet volumetric flow. Industrial application of supersonic separation was tested on a production facility offshore Malaysia.

Keywords: gas dehydratation, supersonic separator, raw gas

Streszczenie

Oddzielanie naddźwiękowe jest nową, obiecującą technologią. Główną zaletą tej metody jest niewielki rozmiar dyszy naddźwiękowej. Opracowano specjalny program w celu dobrania odpowiedniej dyszy do przedziału objętości przepływu w otworze wlotowym. Zastosowanie oddzielania naddźwiękowego na potrzeby przemysłu było testowane w zakładzie produkcyjnym znajdującym się w strefie przybrzeżnej Malezji.

Słowa kluczowe: odwadnianie gazu, oddzielacz naddźwiękowy, gaz naturalny

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1. Introduction

Natural Gas (NG) is a gas mixture that consists mainly of methane and small amounts of other compounds such as ethane, propane, butane, nitrogen, carbon dioxide and water. Typical compositions of NG occurring in Europe are shown in the next table.

Table 1

Typical compositions of NG occurring in Europe

Source of NG	Russia (Transition)	Norway (Ekofisk)	Algeria (Hassi Mel)	Netherlands (Groningen)	Czech (Moravia)
Components	Volume fraction of component [%]				
Methane CH_4	98.39	85.8	86.9	81.31	97.7
Etane C_2H_6	0.44	8.49	9	2.85	1.2
Propane C_3H_8	0.16	2.3	2.6	0.37	0.5
Butane C_4H_{10}	0.07	0.7	1.2	0.14	-
Pentane C_5H_{12}	0.03	0.25	-	0.09	-
Nitrogen N_2	0.84	0.96	0.3	14.35	0.6
Carbon Dioxide CO_2	0.07	1.5	-	0.89	-

NG is found mostly in reservoirs underneath the earth. Once brought from underground, and before NG can be used as source of energy, it should be refined to remove the impurities such as water, sand and the higher hydrocarbons, which are commonly sold separately. Higher hydrocarbons serve as raw materials for oil refineries or petrochemical plants or as sources of energy with higher calorific value.

During a year there are large fluctuations in gas demand. Demand changes between the non-heating and heating seasons. When there is a lower demand for NG then is stored, and conversely is withdrawn when is used for heating. In order to balance these seasonal fluctuations, large storage volumes are required. In the same way, the reserves operate to smooth short-term peaks of NG consumption. Underground Gas Storages (UGS) are the most advantageous option for storing NG.

UGSs reduce the dependency of NG supply and allow the maximum capacity of distribution lines to be exploited. However, during the storage the gas become saturated by water vapors, not meeting the requirements for its distribution and use. The water content of NG at saturation is dependent on temperature and pressure. With increasing pressure of the gas the water content decreases, and with increasing temperature the water content in the gas increases. The water content of the gas can be calculated using the following equation [3, 4]:

$$w_{\mathrm{water}} = 593{,}335 \cdot \exp(0.05486 \cdot t_G) \cdot P_G^{-0.81462} \tag{1}$$

where:

w_{water} – in kilograms of water per 10^6 m_s^3 of NG,
t_G – temperature of NG in °C,
P_G – pressure of NG in MPa.

Care must be taken with the formation of methane hydrates. 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 methane hydrate production from a unit amount of water is higher than the ice formation. Methane hydrates forms in high pressure gas if the temperature of gas decreases below the T_{dew} of the water vapors present in the gas. This fact carries with it many problems like fouling of heat exchangers and fittings, erosion of expanders and even blockage of a transmission line.

Gas dehydration is one of the most important unit operations in the NG plants; the removal of the water vapor that exists in solution in NG requires a complex treatment. These treatments are usually based on one of three traditional dehydration methods: absorption of water vapors into the triethyleneglycol, being the most widely used procedure; adsorption of water vapors on silica gels, alumina or molecular sieves and finally, the condensation of water is achieved by decreasing the temperature of NG. For high-pressure gas, a Joule-Thompson effect to cool down the gas can be used (A decrease in gas pressure leads to decrease of temperature).

Besides these three conventional methods a new innovative method for NG dehydration has appeared and its description follow below

2. Supersonic Swirling Separator

Supersonic gas separation is a technology to remove one or several gaseous components out of a mixed gas (typically raw NG). Consists in the use of the Laval Nozzle, which is a tube that is pinched in the middle and with the shape of an hourglass. It uses the Joule-Thompson effect as a principle. Pressurized gas expands to low pressure at constant enthalpy transforming the potential energy (pressure and temperature) into kinetic energy (velocity) and accelerates the gas to a supersonic speed. During expansion sufficient temperature drops occurs to reach the T_{dew} of the water vapor in the NG. Figure 1 depicts the profile of pressure, temperature and velocity of a gas passing through the supersonic nozzle.

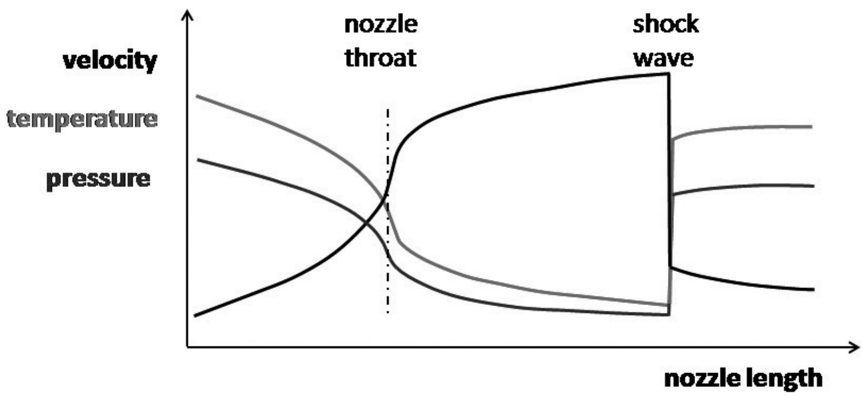

Fig. 1. Profile of pressure, temperature and velocity of a gas in a supersonic nozzle

Rys. 1. Wykres nacisku, temperatury i prędkości gazu w dyszy naddźwiękowej

Right after the formation of the droplets, a procedure called "Droplet enlargement method" studied by Qingfen [5] should proceeds. If a gas mixture contains no foreign particles, the appearance of the liquid phase is governed by the process of homogeneous nucleation. The natural process on which the water is condensate, allow the formation of very fine droplets, which are at high super saturation condition. This droplets size is around 1μm, making very difficult the separation from the dry stream (for satisfactory separation droplets should be larger than 2,5 μm) [5]. For this reason, to improve the separation performance for the treatment of NG the droplets should be enlarged. The authors developed a method, which add solid particles to a gas phase to act as "nucleation centers". Thanks to particles, vapor molecules deposit on their surface forming large drops.

While the gas is entering the nozzle, is traveling at subsonic velocities and the static blades located in the inlet section, lead to the swirling flow of NG. Then the diameter of nozzle contracts and the gas is forced to accelerate until it reaches the nozzle throat. In the throat the cross-sectional area is the smallest and the gas velocity becomes sonic. From the throat, the area then increases leading to the expansion of the gas and the velocity becomes progressively more supersonic. The water droplets that are formed are separated by the centrifugal force on the walls. Centrifugal force can reach values up to 500 000 g causing the cyclonic separation [6].

The mixture moves in the direction of flow into the separation channel. The dry gas continues forward while the liquid phase together with some slip gas (about 25 % of the total stream) is separated by a concentric divider and exits the device as a separate stream [7]. The concentric divider leads into the heated degas separator. From here, the slip gas is returned back to the main stream and the water condensate is removed. Finally in order to recover the initial pressure of the gas, a shock wave is generated. To obtain shock wave the velocity must change from supersonic to sonic speed. This effect is in nozzles achieved by a rapid enlargement of the nozzle diameter. The final section has the so called diffusers and the gas is slowed down and about 65–80% of the inlet pressure is recovered [8]. This section might also include another set of static devices to undo the swirling motion. Figure 2 shows location of each part of supersonic swirling separator [9].

The scheme of a supersonic dehydration line working on the principle introduced here is depicted in Fig. 3.

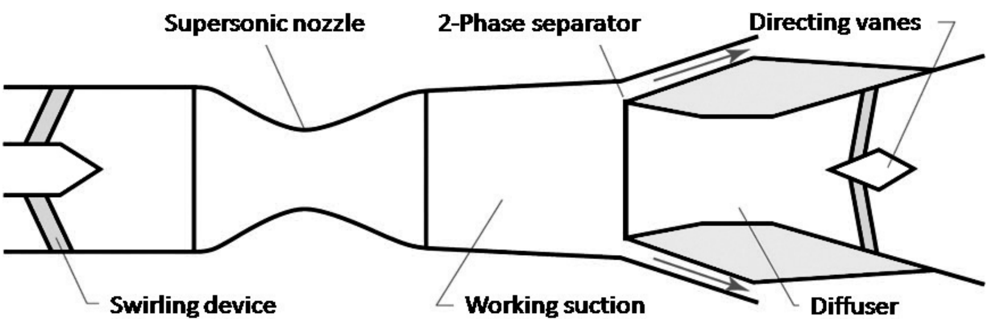

Fig. 2. Schematic diagram of each part of supersonic swirling separator

Rys. 2. Schemat każdej części naddźwiękowego oddzielacza mieszającego

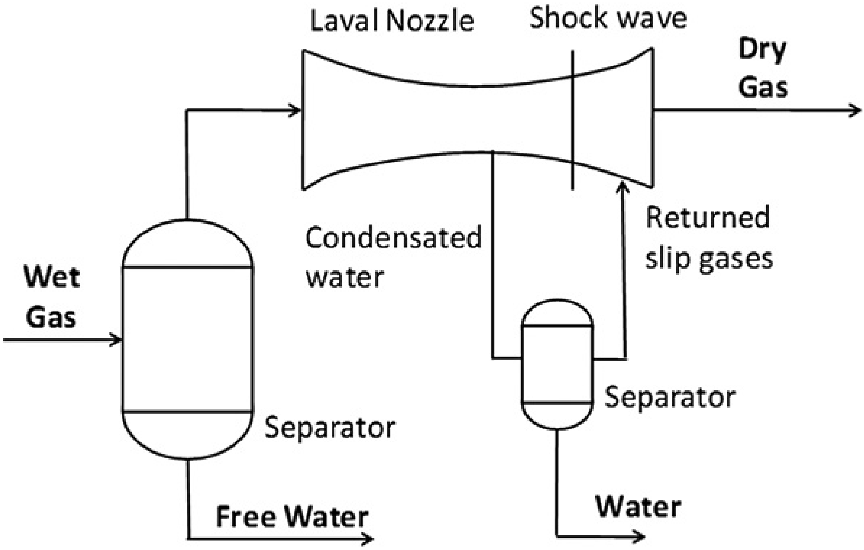

Fig. 3. Scheme of a supersonic dehydration line

Rys. 3. Schemat naddźwiękowej linii odwadniania

The gas residence time in the supersonic nozzle is below two milliseconds [10]. This time interval is too short for any methane hydrate formation, so no inhibitors are needed. Two operational plants successfully dehydrated wet gas in The Netherlands and Nigeria achieving a dew point of –30°C and –40°C respectively. A model of a supersonic dehydration unit was analyzed with the use of numerical simulation tools, and the separation efficiency in respect to lost pressure was evaluated. The simulations were performed on water saturated NG at 30 MPa and 20°C. The results are presented in Table 1 [11].

Table 2

Supersonic water separation efficiency in respect to pressure lost in the nozzle

Pressure lost in nozzle [%]	17.3	20.0	27.6	49.0	51.5
Water separation efficiency [%]	40	50	90	94	96

3. Effects of swirls

Long has been the discussion about the swirls effects on the supersonic efficiency. Malyshkina 2007 studied the vorticity inducing two different types of vortexes: quasi-solid or forced vortex and free or potential vortex [12]. It was obtained that because of the nozzle geometry, the main parameters of gas flow such as temperature, pressure and velocity, are non uniformly distributed allowing the swirling flow to create gradients of the radial velocity on the external layer. This gradients lead to mixing of the already condensate droplets with the dry gas.

In order to describe the effects of the swirl intensity, Jassim et al. 2008 found out that the pressure increases (non-uniformly) when the swirl gets stronger to retain the mass flow rate and the effect of swirl was to decrease the mass flow compare to the non-swirling flow [13]. Later studies by Qingfen [5] showed that higher inlet pressure brings more energy, which is important to maintain the supersonic flow speed. By increasing swirling intensity, more energy losses are achieved and leave less energy to maintain the supersonic flow. On the other hand decreasing swirling intensity leads to reduction of centrifugal forces causing lower separation efficiency [5]. Similar results were obtained by Chuang et al. 2011 who claim that swirls play and important role in the NG separation. Firstly, a large tangential velocity is expected in the supersonic nozzle but in a second place, the swirling flow impairs the expansion characteristics of the nozzle because of the speed conversion from axial to tangential [14].

Therefore, it should be an optimal value of swirl for the separation best performance, not too strong to cause energy losses that affect the calculation of the parameters and the real separation efficiency, but also not weak enough to ensure that the centrifugal forces would not separate the condensate to the walls from the purified gas. Controlling the vanes at the entrance of the nozzle, moderated swirls can be achieved allowing low temperatures and strong centrifugal forces optimal to the separation process. In some designs a set of static devices is also present at the outlet of nozzle to undo the swirling motion.

4. Geometry of nozzle

The Laval Nozzle is formed of three principal parts. Firstly, at the inlet of gas it is the expander (subsonic zone). In the expander the swirling generator is located. It is composed of several blades tangent to the nozzle and when the gas flow passes through it, is accelerated and enters the nozzle with the tangential velocity of a certain value. In the ex-

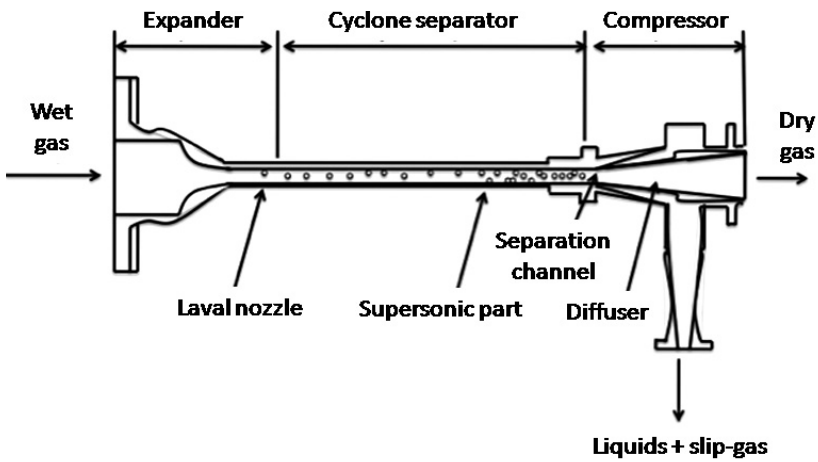

Fig. 4. Scheme of the Supersonic Swirling Separator

Rys. 4. Schemat naddźwiękowego oddzielacza mieszającego pander the wet gas is getting to a supersonic speed, bringing with it the decrease of pressure and temperature. The temperature decrease leads to the condensation of water vapors present in a gas.

A second part conformed by the cyclone separator (critical zone), where the already formed droplets after the expansion, are being separated to the walls because of the centrifugal force. Droplets separated on walls form thin film which is moving in the direction of the flow.

Finally nozzle ends with the third part, compressor (supersonic zone). In compressor a separation channel is located to separate the thin water film on walls from stream of dry gas. Compressor part leads to the diffuser to recover part of the initial pressure (65–80%). The following figure depicts the scheme of a Supersonic Swirling Separator [8].

To obtain supersonic velocity of the gas, the inlet diameter should be minimally √5 times higher than the nozzle throat and the converging length equal or bigger than the throat diameter. The geometry of the tapered section of the Laval nozzle is calculated by the following equations [6]

$$\frac{D - D_{cr}}{D_1 - D_{cr}} = 1 - \frac{1}{x_m^2}\left(\frac{x}{L}\right)^3 \quad \left(\frac{x}{L} \le X_m\right) \tag{2}$$

$$\frac{D - D_{cr}}{D_1 - D_{cr}} = \frac{1}{(1 - x_m)^2}\left(1 - \frac{x}{L}\right)^3 \quad \left(\frac{x}{L} > X_m\right) \tag{3}$$

where:

D_1, D_{cr}, L, X_m – the inlet diameter, the throat diameter, the length of the tapered section, and the relative coordinate of tapered curve, respectively,

x – the distance between an arbitrary cross section and the inlet,

D – the convergent diameter at an arbitrary cross section of x.

As mentioned previously, the resident time of the flow is very short due to the supersonic speed, so the settlement distance of the droplets is and important factor to considerate the designing the nozzle geometry and is the cross-sectional shape of the nozzle, which has the effect on the settlement distance.

According to the length of the nozzle, by increasing it, the separation efficiency should be improved because of the increasing wall surface area for particles collision and extend of the resident time for gas/liquid separation. However, the temperature increases because of the friction loss, casing a possible evaporation of the condensate droplets. Thus, the optimal length should be 10 times the diameter of the wall at the throat [16]. Also, the incorporation of a central body is necessary to allow the principle of conservation of angular momentum and ensure a concentric vortex.

A second throat diffuser could be used to reduce the effects of the backpressure changes. When the gas finally moves across the diffuser, where the shockwave occurs, the divergence angle should be in the right range because the shock can interact with the boundary layer and this might delay the transition from supersonic flow to subsonic. Therefore, a good separation performance can be obtained with an optimal value of the divergent angle, which should be kept between 2º and 6º. When is smaller, the boundary layers are very susceptible to disturbances, when is bigger, the inner friction loss leading to reduces the efficiency [6].

5. Benefits and applicability

The supersonic separation is a promising new technology. The main advantage of the method is the small size of the supersonic nozzle. For example, a nozzle 1,8 m in length placed in a housing 0,22 m in diameter was used for dehydrating 42 000 m_s^3 per hour of water-saturated NG at 25°C compressed to 10 MPa to output water T_{dew} < –7°C [11]. The corresponding absorption contactor would be 5 m in height and 1,4 m in diameter, and the corresponding adsorption line would be composed of two adsorbers 3 m in height and 1 m in diameter. A further advantage is the simplicity of the supersonic dehydration unit. The supersonic nozzle contains no moving parts and requires no maintenance and no man operation. The operating costs are much lower than for other methods. The only energy-consuming devices are the pumps for removing the condensate and the heater for the degas separator. However, during supersonic dehydration a pressure loss occurs. Nevertheless, if the same pressure loss were used for the JT effect, the temperature drop would be 1,5–2,5 times lower [18]. Supersonic separation enables simultaneous removal of water and higher hydrocarbons from the treated gas, and can be used as pretreatment method before NG liquefaction. This method could also be usable for other applications of gas separation, for example, Sforza et al. 2011 developed a method based on a swirling expansion process in a specially designed supersonic flow nozzle for coal-derived syngas purification and hydrogen separation [19].

The application of supersonic separation has some disadvantages. Probably, the most important is its novelty. The appropriate nozzle design is complicated, and "to know how" is expensive. The geometry of the nozzle ranges is in the order of micrometers. In addition, the construction material has to withstand abrasion and the impacts of a shock wave. But the most limiting condition of use is the need for stationary process parameters. Fluctuations in temperature, pressure or flow rate influence the separation efficiency. In fact, it is in many cases impossible to achieve constant process parameters. For example, this is the case when withdrawing NG from UGS. However, the supersonic swirling separator can be used even in this case.

6. Proposed solution to balance fluctuations on the inlet of nozzle

The problem with fluctuation of inlet parameters can be solved by arranging several nozzles into a battery configuration with a single common degas separator. The battery configuration enables an optimal number of nozzles to be switched on, depending on the inlet parameters of the gas.

A program was designed to select the nozzle combination for an interval of inlet volumetric flow. Four nozzles are combined to maintain gas dehydration. For a given flow is chosen the combination of nozzles with the closest designed flow. Scheme for the nozzle arrangement is depicted in Fig. 5 below.

The nozzles work in the following proportion: The largest nozzle is designed to process 80% of the nominal gas flow. The three remaining nozzles are in the proportion 4:2:1 with respect to designed gas flow. Together the remaining nozzles process 40% of the nominal gas flow. This arrangement therefore enables ± 20% deviation of the nominal flow to be covered.

Specifying the inlet nominal gas flow, it is possible to calculate the nozzles design. Then the flows in the interval <0,8; 1,2> are calculated and a combination of nozzles is selected.

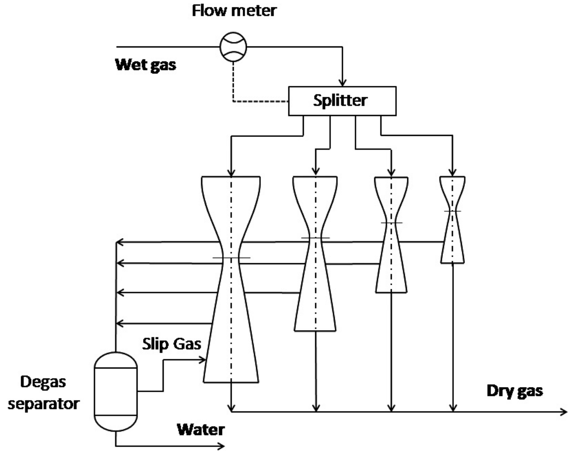

Fig. 5. Arrangement of supersonic nozzles for unsteady inlet parameters of NG

Rys. 5. Układ dysz naddźwiękowych dla zmiennych parametrów wlotowych NG

Therefore, two "types" of flow are distinguished, real gas flow and gas flow, corresponding to the one given by the calculation of the nozzle capacity which is the real value that can be processed by each nozzle and the one calculated by the intervals set by the deviation of nominal flow respectively. In the same manner, these two types of gas flow were compared and its deviation was calculated to verify and validate the accurate of the results and the efficiency of the arrangement of the supersonic nozzles.

The nominal gas flow and the deviation were plotted and it can be seen that the function obtained is periodical. With the appropriate switching of the nozzles, the maximal deviation between the real gas flow and the designed flow for the combination of nozzles is below 4%. Reflecting this was the effectiveness of the design. The graphic is shown in the Fig. 6.

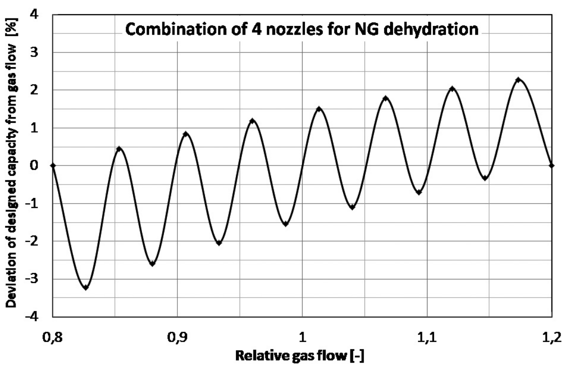

Fig. 6. Graphic of the relative nominal gas flow vs the deviation between the real gas flow and ideal gas flow for combination of nozzles

Rys. 6. Wykres względnego nominalnego przepływu gazu a odchylenie między realnym i idealnym przepływem gazu dla kombinacji dysz

7. Conclusions

Supersonic swirling separation is very promising method. In the field of NG dehydration has many advantages over the conventional dehydration methods. The main benefit lays in low capital cost of dehydration line. Moreover the operation costs are in comparison with conventional methods negligible. Finally an important advantage is the size of the line. Area requirements are lower which makes the supersonic dehydration very suitable for offshore applications. The limiting factor, which is the necessity of stable inlet parameters, can be solved by appropriate battery configuration of nozzles. As it is seen from the calculations shown, if varying inlet volumetric flow in interval <0,8; 1,2> the combination of 4 nozzles will customize with deviation below 4%.

Industrial application of supersonic separation was tested on a production facility offshore Malaysia. The first commercial application was in 2006 for Shell Nigeria (conditioning of wellhead gas for feed to a gas-fired power station). Next projects are operating in Colombia and Brazil [11].

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