A new type of dehydration unit of natural gas and its design considerations*

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Abstract A new type of dehydration unit for natural gas is described and its basic structure and working principles are presented. The key factors affecting the performance and dehydration efficiency of the unit such as nucleation rate, droplet growth rate, the strength of the swirl, and the position at which the shock wave occurs are discussed. And accordingly the design considerations of each component of the unit are provided. Experimental investigations on the working performance of the unit justified the design considerations.

Keywords: supersonic, swirling flow, dehydration, natural gas.

Natural gas is contained at high pressure beneath the earth surface in large cavities or porous rock formations called gas deposits. The main component of the natural gas is methane. Besides methane, it often contains water vapor and many other heavier hydrocarbon vapors. Before the natural gas is delivered to the customers, most of water and heavy hydrocarbon vapors should be removed from natural gas. These water and heavy hydrocarbon vapors in natural gas not only reduce the heating value of natural gas as fuel but also result in various serious problems in gas process facilities. Changing pressure or temperature may cause water and heavy hydrocarbon to condense, resulting in corrosion, water hydrate or even ice blockage. Mercury in natural gas can also react with alloy components in downstream equipment to form amalgams. To prevent such problems gas dehydration facilities have been used to eliminate all liquid phases and all components that might condense during delivery or consumption processes[1].

The typical traditional natural gas dehydration techniques include absorption, adsorption, refrigeration and so on. These conventional technologies have many advantages such as good dehydration performance, high reliability but they also have many disadvantages such as the need of huge facilities, large investment, energy consuming, complex mechanical work and damage to the environment[2]. In Refs. [3, 4], a so-called Twister™ supersonic separator was introduced, which overcomes all the disadvantages stated above, and the experimental results suggested that the supersonic separator could obtain a maximum dew point depression of 22—28 ℃, but the detailed experimental conditions were not given.

In this paper, a new dehydration unit[5] that is based on the theory similar to that of the Twister supersonic separator but with a different structure is described. The purpose of this study is to find the factors that affect its dehydration efficiency, to give out the comprehensive design considerations for each component of the unit, and to justify the considerations through the experimental investigations.

1 Structure and fundamentals

1.1 Structure

From the view point of thermodynamics and aerodynamics, a supersonic swirling separator is similar to a system that is formed by a turbo-expander, a cyclone gas/liquid separator and a compressor[6]. Fig. 1 shows the schematic configuration of the supersonic swirling separator. The separator is composed of a Laval nozzle that is used to expand the wet feed gas to supersonic velocity, which results in a low temperature and pressure, a cyclone and separator which can generate a highly swirling flow and sepa-

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rate liquid from the gas and a diffuser that slows down the flow and recovers some of the initial pressure.

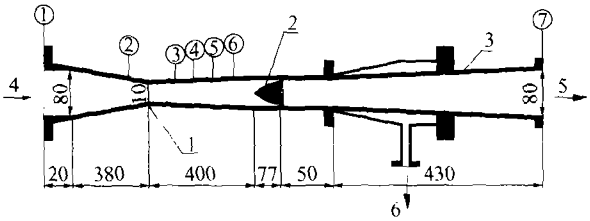

Fig. 1. Schematic configuration of supersonic swirling separator. 1, Laval nozzle; 2, cyclone; 3, diffuser; 4, wet gas inlet; 5, dry gas outlet; 6, liquid outlet ②—⑥, thermocouple; ① and ⑦, humidity/temperature transducer.

1.2 Fundamentals

First, the wet natural gas flows through a Laval nozzle, and is accelerated to the supersonic speed. Due to the isentropic acceleration the temperature and pressure of the natural gas will drop, making the natural gas mixture supersaturated. Nucleation will take place and droplets will start to grow. Subsequently, a swirl is induced in the gas flow by means of a cyclone, which is placed in the tube behind the Laval nozzle. The droplets in the flow will be swirled to the wall of the tube. As a result, the core of the flow through the tube becomes dry and the boundary layer part of the flow near the tube wall contains most of the vapor components. The boundary layer part of the flow is then drawn out of the flow and discharged to the liquid outlet, leaving only the dry gas in the main flow. Finally, the dry gas goes into a diffuser and some of the pressure is recovered.

2 Design considerations

Although the principles of the unit are quite simple, when it comes to design, it is not. The fundamentals show that the basic condition for dehydration is that the wet gas condenses into a two-phase flow in the Laval nozzle. So the nucleation rate, droplet growth rate and the sizes of the droplets in the outlet of the Laval nozzle must have a strong impact on the dehydration efficiency. Wet gas first condenses into a large amount of small droplets of various sizes, existing in the two-phase flow in the form of multiple disperse phases. The two-phase flow then flows through the cyclone and attains certain strength of swirling, resulting in a gas-liquid separation due to different centrifugal forces on the two phases. Therefore, the strength of swirling is another factor influencing the dehydration efficiency.

In addition, supersonic swirling separator is a Laval nozzle based unit, so shock wave might appear inside it[7]. According to the theory of aerodynamics and thermodynamics, the position at which the shock wave occurs influences the performance of the unit significantly, so the position where the shock wave may occur is also a key factor that affects the working efficiency.

In order to obtain good dehydration efficiency, all the factors stated above should be considered for design.

2.1 Laval nozzle

The flow in the Laval nozzle is multi-component, non-equilibrium and with phase changing. Macroscopically, this will result in the release of latent heat to the flow and the spontaneous generation of a liquid droplet cloud, whose properties strongly depend on the coupling between the flow and the condensation process itself. The non-equilibrium condensation can be separated into two distinct processes, namely, homogeneous nucleation process and droplet growth process. The homogeneous nucleation process refers to the spontaneous formation, within the vapor phase, of stable clusters by the kinetic process of evaporation and impingement of the molecules, the droplet growth process refers to the process in which stable droplets increase their size by gaining more and more molecules[8,9]. For the supersonic swirling separator, nucleation rate determines the total liquid amount separated, and the droplet growth rate determines the droplet size at the outlet of the Laval nozzle, which strongly influences the dehydration performance. If the droplets are too small they will just flow along the streamlines of the flow, and many of them will not be forced to the outside. If they are too large, their inertia will be too large for them to be swirled to the outside. Therefore, the successful design of the unit depends on a delicate balance between the flow speed, the strength of the swirl, the nucleation rate, the growth rate, and so on, which are all related to each other. In order to increase the efficiency of the unit, a good understanding of all the individual processes is needed.

2.2 Cyclone

Cyclone is a swirl generator which is placed in the tube behind the Laval nozzle. So its structure may strongly influence the position at which the shock wave occurs. If the equivalent friction of the cyclone is too large, the shock wave may occur inside the Laval nozzle, which may result in subsonic flow and may reduce the dehydration efficiency (the dehydration efficiency increases with gas velocity). Therefore, the best configuration of the unit is that the shock wave should be shifted to the inlet of the diffuser.

In order to shift the shock wave to the inlet of the diffuser, the cyclone should be designed with very small equivalent friction, and the pressure loss of the flow passing through it should be as small as possible.

2.3 Diffuser

A diffuser is used to slow down the flow and recover some of the initial pressure, so that the pressure loss of the flow will not be too large through the unit. The configuration of the diffuser does not have immediate influence on the dehydration process, so it can be designed by routine methods[10,11].

3 Experimental apparatus and method

3.1 Apparatus

A supersonic swirling separator was manufactured based on the above considerations. It was constructed of stainless steel, and was 1357 mm long. The specific dimension can be found in Fig. 1, and the details about the configuration of the cyclone can be found in Ref. [5]. To meet the requirement of the experiment, an indoor test rig was set up, and the overall apparatus is shown in Fig. 2. Wet air was chosen as the working fluid in this study. The working fluid was circulated in an open loop, which made provision for filtering, metering, and pre-cooling. The GA55 type compressor provided a maximum working pressure of 1.0 MPa, with air displacement of 600 m^3/h. The temperature of the fluid inside the supersonic swirling separator was measured with 5 copper-constantan thermocouples and their schematic locations are shown in Fig. 1. The accuracy of the thermocouples is ±0.1 ℃, and its estimated maximum possible error is 0.2 ℃. Humidity /temperature transducers were mounted at both the supersonic swirling separator inlet and the dry gas outlet. The transducer is accurate to ±1.5% in relative humidity and ±0.5 ℃ in temperature, and its estimated maximum error in relative humidity is 2.4% and that in temperature is 0.54 ℃. The pressure gauges were located in the inlet of the supersonic swirling separator, liquid outlet and dry gas outlet. The precision of these pressure gauges is all ±0.4%, and their estimated maximum error is 2%. The flow meters were located in the inlet and dry gas outlet. The precision of these flow meters is ±1.5%, and their estimated maximum error is 2.54%.

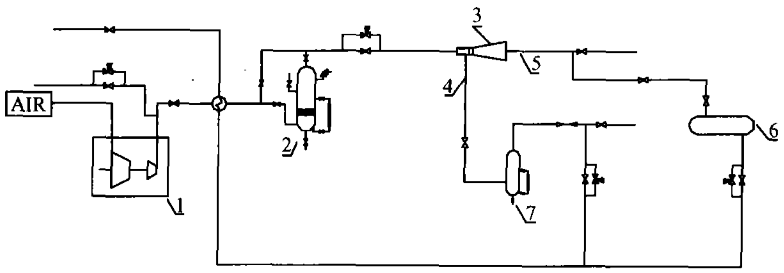

Fig. 2. Flow chart. 1, compressor; 2, humidifier; 3, supersonic swirling separator; 4, liquid outlet; 5, dry gas outlet; 6, surge tank; 7, liquid collector.

In order to study the dew point depression (ΔT_d) at different pressure loss ratios (γ), a surge tank was installed downstream the dry gas outlet, which could provide different back pressures for the supersonic swirling separator. Here the dew point depression (ΔT_d) is defined as the dew point of the inlet minus that of the dry gas outlet, that is,

$$\Delta T_d = T_{d1} - T_{de}. \quad (1)$$

And the pressure loss ratio γ is defined as the ratio of pressure loss through the supersonic swirling separator to its inlet pressure, that is,

$$\gamma = \frac{\Delta p}{p_1} = \frac{p_1 - p_e}{p_1}, \quad (2)$$

where T_{d1} is the dew point of gas at the inlet (℃), T_{de} is the dew point of the dry gas at outlet (℃), p_1 the pressure at inlet (MPa) and p_e the pressure at dry gas outlet (MPa).

3.2 Experimental procedure

In order to determine the performance of the supersonic swirling separator, the inlet parameters including pressure, temperature, humidity and flow rate were set to the prescribed values. The pressure, temperature, flow rate, relative humidity (RH) and dew points at the inlet and outlet of the supersonic swirling separator were recorded for a given back pressure at the outlet of dry gas.

To begin an experiment, the compressor was started, and the outlet pressure was adjusted to a given value. After the whole system achieved its steady state, the data needed for determining the performance of the separator were acquired by a data acquisition computer. By adjusting the dry gas outlet back pressure to another higher value, the above experimental procedure was repeated.

Supersonic swirling separator is a Laval nozzle based unit, so there is a critical flow rate. As we know, if the critical flow state is achieved inside the supersonic swirling separator, then the flow rate through the separator should be a constant and independent of the back pressure according to the theory of thermodynamics of compressible flow[12,13]. Therefore, if the regulation of the back pressure of the dry gas outlet results in change of the volumetric flow rate, then the flow inside the separator is fully subsonic and the experiment should be stopped.

4 Results and discussion

Dew point depression implying dehydration performance is shown in Fig. 3. It is seen from this figure that the dew point depression increases monotonically with the increasing of the pressure loss ratio, and it can also be seen that the maximum dew point depression of the supersonic swirling separator is about 20 ℃. So if the pressure of the natural gas to be processed is high enough, a satisfactory dehydration performance can be obtained.

Fig. 4 illustrates the temperature profile in the supersonic swirling separator. Though the temperatures measured by the thermocouples are not the real values due to the inevitable stagnation effect inside the supersonic swirling separator, their primary tendency along the axis is valuable, through which the position where the shock wave occurs can be determined.

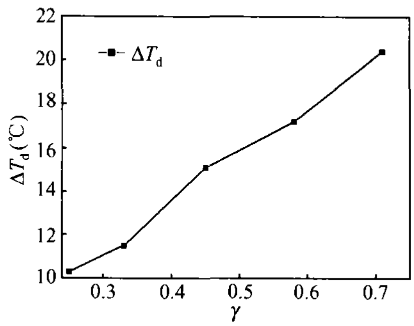

Fig. 3. Dew point depression versus pressure loss ratio (Inlet: $p_1 = 0.64$ MPa; $T_{d1} = 31.0$ ℃; $Q_1 \cong 345.0$ Nm^3/h; $RH \cong 95\%$).

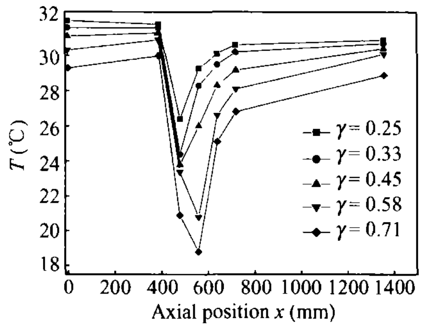

Fig. 4. Axial temperature distribution of the supersonic swirling separator (Inlet: $p_1 = 0.64$ MPa; $Q_1 \cong 345.0$ Nm^3/h; $RH \cong 95\%$).

The horizontal distance is measured from the inlet of the separator to the outlet of Laval nozzle. It can be seen that the general trend of all the curves at different pressure loss ratios is basically the same. And the temperature decreases suddenly inside the Laval nozzle. Later the temperature ascends gradually, implying that there must be a shock wave occurring in the vicinity of the position, and the position is shifted to the outlet side of the Laval nozzle as the pressure loss ratio increases.

Fig. 4 also illustrates the comparison of the dry gas outlet temperature with the inlet temperature. One can observe that these two temperatures have little difference, suggesting that the temperature of dry gas at outlet is almost recovered completely.

5 Conclusions

(i) The experimental results showed that the supersonic swirling separator has a satisfactory working performance, and the unit could attain a maximum dew point depression of about 20 ℃ without any need of external mechanical power and chemicals. All this shows that the design considerations presented in this paper are reliable.

(ii) The position at which the shock wave occurs is a key factor that affects the dehydration efficiency. In this test, the shock wave occurs in the divergent part of the Laval nozzle. This may cause subsonic flow and may reduce the dehydration efficiency, so according to the design considerations, further work should be done to design a cyclone with less equivalent friction.

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