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Research Article

About creation of the simulation model of the thermal mode in air cooling units for crude natural

AN Krasnov[1]

1 *Ufa State Petroleum Technological University (Ufa, Russian Federation)*

Corresponding author: *Andrei Krasnov* (ufa-znanie@mail.ru)

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Abstract

Many Russian gas fields in the Arctic are now in the final development stage, so there is a need for additional gas compression along the gas collection system between the wells and the gas processing plant. After the compression stage, the gas is cooled in air cooling units (ACU). Cooling crude (wet) gas in low-temperature environments using ACUs involves a risk of hydrate plugs forming in the ACU's heat transfer tubes. Variable frequency control of speed fans is typically used to control performance of the ACUs and the control criterion is the gas temperature at the ACU outlet. Even so, the chances of hydrate forming in the bottom of the tube bundle remain large owing to inhomogeneous distribution of the gas temperature in the tube bundles and the temperature jump between the inner surface of the tube wall and the gas flowing through that tube, despite the high gas temperature in the outlet header. To enable forecasting of possible hydrate formation, the mathematical model of the ACU's thermal behaviour that forms the basis of control system's operating procedure must ensure proper calculation not only of the gas temperature at ACU outlet but also the dew point at which condensate formation begins and the hydrate formation temperature. This article suggests a simulation model for crude gas ACU thermal behaviour that enables modelling of both the temperature pattern of the gas inside the tube and the areas of condensate and hydrate formation. The described thermal behaviour model may be used in ACU management systems.

Keywords

hydrate formation, air cooling unit, ACU, equilibrium conditions, variable frequency control, specific humidity, dew point, simulation model

Introduction

Almost every major gas field in Russia is located in the Arctic, so the harsh climate makes development of such deposits a real challenge from the very start. A large portion of explored reserves and almost all the gas produced in the region belong to Cenomanian deposits characterised by low formation pressure and temperature values (Ermilov and Laperdin 2011). Today, all the major deposits in this region have entered the stage of gas-lift operation, since natural formation energy is no longer sufficient to deliver the gas from the well to the gas processing plant (GPP). Produced gas is compressed by booster compressor stations (BCS). The gas temperature at the outlet of BCS gas compressor unit (GCU) may be as high as 150°C, depending on its initial value at GCU inlet and the compressor pressure ratio. This means the gas has to be cooled to prevent permafrost thaw and subsidence of pipelines buried in the permafrost, and to increase profitability of gas transport by reducing the gas volume by cooling. Furthermore, absorption dehydration techniques employed at the GPP are extremely sensitive to pressure and temperature conditions, since the quality and losses of absorbing agent depend primarily on the temperature of the gas delivered to the GPP (Galanin and Borodina 1978).

Different types of air cooling unit (ACU) are used to cool the gas. ACUs are environmentally friendly systems that help significantly reduce water intake by industrial facilities and do not require any pre-conditioning of the cooling agent, thereby dramatically cutting the gas cooling operating costs (Rubin 1980, Franklin and Munn 1974). Yet they are not suited to handling wet natural gas or operating in environments with low ambient temperatures. A prerequisite for hydrate deposition and plug formation is presence of cold surfaces (Netušil and Ditl. 2018), which are basically the inner walls of the heat transfer tubes. This is why the tubes that are cooled the most are the ones where hydrates are formed and deposited intensively, this eventually causing rupture of the tubes (Davletov et al. 1998) .

Consequently, ensuring hydrate-free operation is the key factor for proper performance of ACUs handling crude natural gas, so elaboration of measures to ensure such hydrate-free operation is a relevant applied research task.

Known solutions overview. Research task definition

Hydrate-free operation of pipelines can be assured in a number of ways, such as temperature increase or gas pressure reduction, injection of hydrate inhibitors or gas dehydration (Kalinin 2007). The first method cannot basically be applied in gas collection systems (GCS). Gas dehydration is a process carried out at GPP, meaning that this method serves to prevent hydrate formation during gas transportation along long-distance gas lines. The only hydrate control method that is suitable for GCS consists, therefore, in use of hydrate inhibitors, and this method is employed almost universally (Prakhova et al. 2018). When estimating the requisite quantity of inhibitor, which is typically methanol, account must be taken of its adverse effects on the dehydration process. A certain amount of methanol will inevitably enter the gas dehydration system and units of the glycol recovery system (glycol is used for dehydration purposes). The glycol recovery process parameters may be restored only after complete evaporation of methanol, which is impossible, since methanol is injected continuously (Davletov 2007). Other inhibitors have similar drawbacks, which is why injection of additional quantities of inhibitor into the gas flow upstream of the ACU is not feasible.

Another way to ensure hydrate-free operation of ACU handling wet gas is by altering the equipment design, i.e., building ACUs with longitudinally washed arrays of finned tubes, with cooling air circulated with the help of an air louver system (Davletov 2007), etc. These methods basically imply developing new types of ACU.

The existing air cooling units for natural gas primarily employ automatic systems for variable frequency control of the ACU fan speed (Arshakian et al. 2010), allowing the desired gas temperature at ACU outlet to be maintained to a high degree of precision. In such systems, the gas cooling process is controlled proceeding from the gas temperature in the ACU outlet header. Variable frequency control helps optimise the ACU's energy efficiency, but the risk of hydrate formation remains. Hydrates form in a gas ACU when the inner surface of the tubes is chilled to a temperature below the phase equilibrium boundary for the "natural gas – water vapour" system. According to (Volkov et al. 1989), pure methane under pressure of 4 to 10 MPa has a hydrate formation temperature of 279–286 K. Even so, the minimum temperature of the tube surface in the ACU tube bundle can be much lower than the gas temperature at the ACU outlet (average of all the rows in the tube bundle). Non-uniformity of the gas temperature in different parts of the tube bundle and the difference between the temperatures of the inner tube surface and the gas flowing through that part of the tube can result in hydrate formation in the bottom tubes of the tube bundle even when the gas temperature in the outlet header is high (Belyankin et al. 2011).

The temperature of the inner wall of the cooled tubes is the key criterion restricting hydrate-free operation of ACUs for crude natural gas and one of the major parameters that drives hydrate formation is the specific humidity of the gas, characterised by the dew point temperature (DPT) (Prakhova et al. 2016). For this reason, when developing an ACU management system, a mathematical model must be used that is capable not only of real-time indication of temperature at the ACU outlet, but also real-time determination of the current hydrate formation temperature in order to avoid hydrate plugs developing. This article suggests a simulation model for crude gas ACU thermal behaviour that enables modelling of both the temperature pattern of the gas inside the tube and the areas of condensate and hydrate formation. The described thermal behaviour model may be used in ACU management systems.

Results and discussion

The risk of hydrate formation cannot be detected instrumentally owing to absence of standard measuring instruments and a corresponding methodology. Moreover, this would be extremely hard to do from a technical perspective. One ACU would need at least 45 temperature sensors distributed throughout the system in a sophisticated pattern (Shcherbinin and Ishinbaev 2004). This is why the ACU management system's operating procedure should rely on a mathematical model that must not only provide an adequate indication of the current temperature at the ACU outlet, but also forecast the initiation of a hydrate formation process.

Mathematical modelling of ACU thermal behaviour is a challenging task, since the thermal behaviour is closely linked to the ACU's gas dynamic behaviour, which means this will be a nonlinear model. The issues of ACU modelling are described in multiple publications, such as (Kuntysh et al. 2013, Kamaletdinov 2001, Kuntysh and Samorodov 2010, Biyuan et al. 2017, Brenci et al. 1992). Each of these models has certain strengths and certain weaknesses, but they all have one common drawback: they simulate thermal behaviour without possible hydrate formation, which makes them of little use for ACUs that cool crude gas in environments with a low ambient temperature.

Equilibrium conditions of hydrate formation for almost all known natural gases have already been empirically identified and explored. Formation of natural gas hydrates in tubes depends primarily on the gas composition, pressure, temperature and dew point. The hydrate-forming components of natural gas include methane, ethane, propane, i-butane and n-butane, carbon dioxide, hydrogen sulphide, nitrogen and oxygen. If the gas contains as much as several per cent of ethane, let alone propane and i- or n-butane, the conditions for hydrate formation change drastically. For example, adding 1% of propane to the gas at a temperature of 283.15 K results in a significant reduction in the hydrate formation pressure – from 6.99 MPa for pure methane to 4.36 MPa for the mixture, and adding 1% of isobutane – to 3.04 MPa for the mixture (Makogon 1978).

Current best practices offer numerous techniques for calculating equilibrium conditions for hydrate formation, since experimental methods are extremely laborious and require expensive equipment. In the absence of proper harmonisation, laboratory experiment results and findings of theoretical computations are poorly compatible. As a result, even given robust computational methods, engineering practices employ simple empirical equations to identify the conditions for hydrate formation in natural gases.

The most frequently used methods are approximate calculation ones, including the Curzon–Katz, Skhalyakho–Makogon and Ponomarev methods (Istomin and Kvon 2004), in which the equilibrium conditions are identified relying on the reduced density of gas. There are also other empirical methods, including the Baillie–Wichert method (Baillie and Wichert 1987), Trekell–Campbell method (Campbell 1992), Burmistrov method (Stepanova and Burmistrov 1986), McLeod and Campbell method (McLeod and Campbell 1961), etc. Yet the resulting equilibrium temperature values for a given pressure calculated using these methods sometimes differ by a factor or two or even three.

The conditions for hydrate formation in gases with different specific gravity are determined from the hydrate equilibrium curves. These curves divide the area of possible thermobaric states into two segments: the area where hydrates exist and that where they do not. The higher the specific density of the gas, the lower the hydrate formation pressure.

To identify the area of possible hydrate formation, the specific humidity and density of the transported gas, as well as its temperature and pressure, must be known (Shcherbinin 2004).

The temperature at which gas hydrates remain in thermodynamic equilibrium (equilibrium hydrate formation temperature) is calculated as follows (Istomin and Kvon 2004):

$$T_{hydr} = 2.322 - F_0 + 8.028 \cdot \ln(P), \text{ at } P \geq P_{term} \quad (1)$$

$$T_{hydr} = 2.322 - F_1 + 25.397 \cdot \ln(P), \text{ at } P \geq P_{term} \quad (2)$$

where P – pressure of gas in the ACU tube, MPa; P_{term} – terminal pressure value corresponding to a critical hydrate existence temperature of 273.15 K; F_0 and F_1 – functions of reduced density of gas.

The terminal pressure value is calculated as follows:

$$P_{term} = 19.317 + 12.171 \cdot (\Delta - 0.548)^{-0.616}. \quad (3)$$

The functions of reduced density of gas can be calculated as follows:

$$F_0 = 9.207 \cdot (\bar{\rho} - 0.546)^{-0.225}, \quad (4)$$

$$F_1 = 0.258 + 27.795 \cdot (\bar{\rho} - 0.544)^{-0.246} \quad (5)$$

Reduced density of gas $\bar{\rho}$ is calculated as follows:

$$\bar{\rho} = \frac{\sum_{i=1}^{k}(a_i \cdot \Delta_i)}{\sum_{i=1}^{k} a_i}, \quad (6)$$

where k – the number of hydrate-forming components of the gas mixture; a_i – volume fraction of the i hydrate-forming component in the source gas; Δ_i – relative density of the i hydrate-forming component.

Knowing that $P < P_{term}$ in the ACU, we can combine formulae (2) and (5) to obtain the following equation:

$$T_{hydr} = 2.58 + 27.795 \cdot (\bar{\rho} - 0.544)^{-0.246} - 25.397 \cdot \ln(P). \quad (7)$$

The gas temperature corresponding to the dew point temperature (DPT) can be determined using the formula below (Istomin and Kvon 2004):

$$T_{DP} = 282.84 \cdot P^{0.05032} \cdot W^{0.0564}, \quad (8)$$

where W – specific humidity of the saturated gas, g/m³.

The mathematical model of the hydrate formation process was integrated into the general mathematical model of ACU thermal behaviour. A simulation was developed for a specific type of ACU – the 2AVG-75, which is most frequently used in gas field operations. The existing model was enhanced with additional blocks for real-time calculation of the DPT at which condensate formation begins and the hydrate formation temperature.

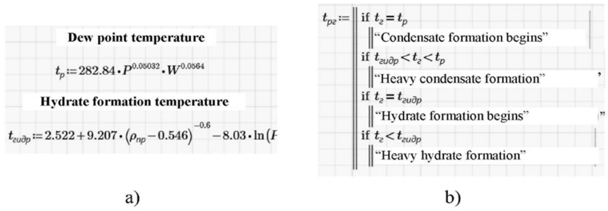

Fig. 1. Screenshots of modelling in *MathcadPrime* software

Fig. 1 below shows screenshots of analytical equations in *Mathcad Prime* software used for calculating equilibrium conditions for hydrate formation in ACU and the temperature criteria that correspond to certain stages of hydrate formation.

Fig. 2 below shows the modelling results: dependence of the dew point temperature on possible gas pressure and specific humidity in the ACU calculated using formula (8). The pressure varies in a range of 3 to 7 MPa, and specific humidity varies from 0.1 to 0.7 g/m³.

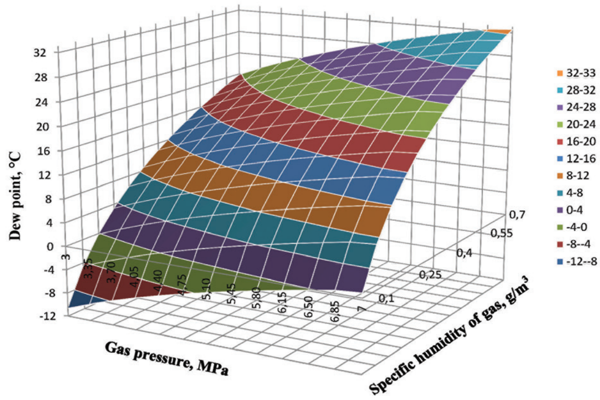

Fig. 2. Dependence of the dew point (°C) on gas pressure and specific humidity

A manual DPT analyser Chandler was installed at the ACU outlet to verify the model's suitability and the DPT value calculated using the model was compared with the analyser readings. The root-mean-square deviation of the calculated values from the real-life values did not exceed 1.5% (the representativeness of the sample consisted of 237 measurements).

Conclusion

Credible information about the current gas temperature values at the ACU outlet, the equilibrium temperature of hydrate formation and dew point temperature is crucial for ensuring effective service of ACUs and preventing local hydrate formation in such equipment. Furnishing an ACU with physical sensors takes a lot of effort and is uneconomical. For this reason, the ACU management system operating procedure involves a mathematical model that enables real-time calculation of said temperature values. An experimental test demonstrated suitability of the model.

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