MODELING OF HYDRATE FORMATION MODE IN RAW NATURAL GAS AIR COOLERS

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Abstract. Air cooling units (ACU) are used at all the gas fields for cooling natural gas after compressing. When using ACUs on raw (wet) gas in a low temperature condition, there is a danger of hydrate plug formation in the heat exchanging tubes of the ACU. To predict possible hydrate formation, a mathematical model of the air cooler thermal behavior used in the control system shall adequately calculate not only gas temperature at the cooler's outlet, but also a dew point value, a temperature at which condensation, as well as the gas hydrate formation point, onsets. This paper proposes a mathematical model allowing one to determine the pressure in the air cooler which makes hydrate formation for a given gas composition possible.

1. Introduction

Gas cooling is one of the steps in the gas treatment process before it is delivered to a major gas pipeline. As in other industries, various types of air coolers are used for that purpose. The degree of cooling the process fluid in such apparatuses depends on their design, geometry of heat exchanging tubes, principle of cooling employed, physical and chemical properties of the cooled fluid, ambient conditions, etc. When cooling raw (wet) natural gas at low ambient temperatures, there is a danger that a hydrate plug will form in the heat exchanger tubes.

Hydrates of hydrocarbon gases are unstable compounds of hydrocarbons and water that appear as white ice-like crystals. They consist of one or more molecules of gas (methane, propane, carbon dioxide, etc.) and water. The main factors determining hydrate formation are pressure, temperature, gas composition and density, a degree of water vapor saturation in the gas. More often gas pipelines become plugged during the winter due to extreme cooling of the gas stream moving through the pipeline. If conditions for hydrate formation appear, the hydrate plug grows fast in such section of the pipeline as more water and hydrate-forming gas flow in. At that, there is a release of water vapor from the gas, reducing their pressure and accelerating the formation of the local hydrate plug [1]. As a result of hydrate formation, pipe blockage occurs and rupture of the heat exchanging tubes follows (Figure 1).

It should be noted that operating an air cooler is a rather energy consuming process, so the control systems are usually based on the task to optimize the behavior of an air cooler and a gas cooling system taken as a whole, as one of energy conservation resources in natural gas transportation [2, 3]. When operating on raw natural gas, the design of ACU shall employ a mathematical model, able not only to reflect adequately the temperature at the ACU outlet, but also to determine the current hydrate formation temperature to prevent formation of hydrate plugs.
This paper proposes an imitation model of the gas ACU thermal mode, allowing one to model not only the thermal field of gas inside the tube, but also condensation and hydrate formation areas. This thermal mode model may be employed in the ACU control system.

2. Overview of known solutions and formulation of research objective

By the principle of operation, ACUs are recuperative heat exchangers consisting of two main parts: a cooling surface and an air delivery system (motor-driven fans, usually with variable-frequency drive). The cooled heat-carrying agent is high pressure compressed natural gas moving through small-diameter tubes with external fins to intensify heat exchange. The coolant is atmospheric air, fed by the fans. The finned tubes are usually divided into several groups called sections. Each ACU, depending on its type may have from one to six fans. At low ambient temperature, ACUs may be switched to a fanless mode (switching off all or some of the fans). Heat extraction from the working substance (product, energy carrier, heat carrier) in this case occurs by airflow of gravity-type of cooling air.

Mathematical modeling of the ACU thermal behavior is a rather complex task, because it is closely related to the gas dynamic mode of the ACU operation, making the problem of modeling a non-linear one. There is a significant number of previous literature dedicated to ACU modeling, for example, see [4-7]. Each of those models have its own advantages and disadvantages, however they all have one common drawback: they model the thermal behavior without considerations for possible hydrate formation, making them of little use for ACUs cooling raw natural gas in low-temperature ambient conditions.

Detecting the danger of hydrate formation with instrument methods is impossible due to absence of standard instruments and relevant procedures. Besides, it is very difficult to implement. A single ACU would require at least 45 temperature sensors arranged in accordance with a rather complex scheme [8].

Thus, the task to develop a mathematical model of ACU operation, which is not able to just calculate adequately the gas temperature at the ACU's outlet, as well as to predict the hydrate formation onset, is timely. Such model may serve as a base for an ACU control system operation.

3. Main part

3.1 Equilibrium conditions of hydrate formation

By now, equilibrium conditions of hydrate formation of almost all natural gases have been experimentally reproduced and studied. The main factors determining possibility of natural gas hydrate formation in tubes are gas composition, pressure, temperature and a dew point. Among the natural gas components, there are methane, ethane, propane, iso- and n-butane, carbon dioxide, hydrogen sulfide, nitrogen and oxygen may form hydrates. Presence of even single-digit percentages of ethane, propane, iso- or n-butane leads to sudden changes in hydrate formation conditions. So, at a temperature of
283.15 K, adding 1% of propane leads to a significant drop in hydrate formation pressure: from 6.99 MPa for pure methane to 4.36 MPa for the mixture; addition of 1% of iso-butane reduces the hydrate formation pressure down to 3.04 MPa [9].

Experimental determination of hydrate formation conditions is accompanied with significant difficulties due to non-stoichiometric and unstable nature of hydrates. Due to that, experimental data from different researchers may differ quite significantly. Presently, a number of analytic methods for equilibrium conditions of hydrate formation are employed in global practice, due to the fact that experimental methods are labor-intensive and require expensive equipment. Due to lack of unification, data of laboratory experiments and results of theoretical calculations do not show sufficient compatibility with each other. All this has led to a situation when, while there are quite strict analytical methods, in practice simple empirical dependences are used in engineering practice to determine natural gas hydrate formation conditions.

Among the most used ones, there are approximative methods of Carson-Katz, Skhalyakho-Makogon, Ponomaryov [10], where these conditions are determined from reduced gas density. There are other empirical methods as well, such as Baillie-Wichert [11], Trekel-Campbell [12], Burmistrov [13], McLeod-Campbell [14] and others. However, results of equilibrium temperature calculations for a given pressure between these methods may sometimes differ by a factor of two or three.

3.2 Mathematical model of a possible hydrate formation area

Conditions of hydrate formation of various natural gases with different relative density may be determined from the hydrate equilibrium state diagram (Figure 2) [9]. To the left of the curves there is an area when hydrates exist and to the right – when they are absent. The higher the specific gravity of gas, the lower the hydrate formation pressure.

To reveal a possible hydrate formation area, moisture content and density of the transported gas, as well as its temperature and pressure, shall be known, [15].

The temperature, when gas hydrates are in a thermodynamic equilibrium (equilibrium hydrate formation temperature), is calculated from the following conditions:

\[
T_{h,\text{hydr}} = \begin{cases} 
2.322 - F_0 + 8.028 \cdot \ln (P), & \text{when } P \geq P_{\text{ter}} \\
2.322 + F_1 - 25.397 \cdot \ln (P), & \text{when } P < P_{\text{ter}} 
\end{cases}
\]

(1)

(2)

where \( P \) is the gas pressure in the ACU tube, MPa; \( P_{\text{ter}} \) is the value of the terminal pressure corresponding to the critical hydrate temperature equal to 273.15 K; \( F_0 \) and \( F_1 \) are reduced gas pressure functions.

The value of the terminal pressure is determined from the formula:

\[
P_{\text{gr}} = 19.317 + 12.171 \cdot (\Delta - 0.548)^{-0.616}.
\]

(3)

The function of specific gravity of gas may be calculated from the expressions:

\[
F_0 = 9.207 \cdot (\bar{\rho} - 0.546)^{-0.225},
\]

(4)

\[
F_1 = 0.258 + 27.795 \cdot (\bar{\rho} - 0.544)^{-0.246}.
\]

(5)

The reduced density of gas \( \bar{\rho} \) is calculated with the formula:

\[
\bar{\rho} = \frac{\sum_{k=1}^{i} b_k (a_k \cdot \Delta_k)}{\sum_{k=1}^{i} a_k},
\]

(6)

where \( k \) is the number of hydrate-forming components in the gas mix; \( a_k \) is the volume ratio of the \( i \)-th hydrate-forming component in the source gas; \( \Delta_k \) is the specific gravity of the \( i \)-th hydrate-forming component.
Knowing that in the ACU $P < P_{cr}$, and combining formulas (2) and (5), let us obtain:

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

(7)

The temperature of gas corresponding to the dew point may be obtained using the formula:

$$T_p = 282.84 \cdot P^{0.05032} \cdot W^{0.0564},$$

(8)

where $W$ is moisture content of saturated gas, $g/m^3$.

### 3.3 Modeling in Mathcad Prime environment

The mathematical model of the hydrate formation was embedded into the general mathematical model of ACU thermal behavior. The modeling was conducted with a concrete type of ACU, namely 2AVG-75, one of the most commonly used in gas fields. The existing model was supplemented with blocks performing real-time calculations of the dew point corresponding to the onset of condensation and hydrate formation onset temperature.

Figure 3 shows screen shots of Mathcad Prime, reflecting assignment of analytical dependences for equilibrium hydrate formation conditions in the ACU and thermal criteria corresponding to certain stages of hydrate formation.

Figure 4 shows the modeling results: determination of dependence between the dew point, possible gas pressure and moisture content in the ACU, obtained using formula (8). The pressure varies in the
range from 3 to 7 MPa, moisture content varies between 0.1 and 0.7 g/m³.

![Figure 4](image)

**Figure 4.** Dependence of the dew point (°C) on pressure and moisture content

To check validity of the model, a Chandler portable dew point analyzer was installed at the outlet of the ACU, its readings were compared with the values calculated in the model. Mean-squared deviation of the calculated values from the actual values has never exceeded 1.5 %.

4. Conclusions
Valid information on current gas temperature at the ACU outlet, formation temperature of equilibrium hydrate and a dew point are necessary for efficient operation of an ACU and prevention of local hydrate formation inside. Provision of ACUs with hardware sensors is labor-intensive and uneconomic, thus the control system algorithm includes a mathematical model, calculating the values of the stated temperatures in real time. Experimental verification supports validity of the model.

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