ASSESSMENT OF POTENTIAL LIQUID PHASE FORMATION IN NATURAL GAS PIPELINES

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Abstract

The formation of liquid hydrocarbons in natural gas pipelines is an important issue affecting the stability and efficiency of gas transportation systems. Even small amounts of condensed liquid can significantly influence flow regimes, pressure behavior, and overall hydraulic performance of pipelines. Therefore, early detection of conditions that may lead to liquid formation is an important task in the analysis of gas pipeline operation.

This study investigates the potential formation of liquid hydrocarbons in a natural gas pipeline using hourly operational data, including pressure, temperature, and gas composition. Particular attention is given to the variation of propane concentration, which represents one of the heavier hydrocarbon components in the gas mixture and has a higher tendency to condense compared to methane and ethane. The analysis focuses on two consecutive days of measurements, considering the identical time interval from 12:00 to 00:00 in order to ensure comparability of the data. The temporal behavior of propane concentration was analyzed and visualized using concentration trend graphs. Additionally, a Hydrocarbon Dew Point Proximity Index was introduced to evaluate the relative closeness of the gas mixture to hydrocarbon condensation conditions. This index provides an indirect indication of the likelihood of liquid phase formation based on variations in the concentration of heavy hydrocarbons.

The results show that during the first analyzed day the propane concentration remained relatively high and stable, indicating a gas mixture richer in heavy hydrocarbons. In contrast, the second day exhibited noticeably lower propane concentrations and greater variability over time. The calculated dew point proximity index demonstrated higher values for the first day, suggesting that the gas mixture was thermodynamically closer to hydrocarbon condensation conditions during this period. The combined analysis of propane concentration trends and the dew point proximity index provides a practical and data-driven approach for identifying potential liquid formation conditions in gas pipelines. The proposed method can be applied for operational monitoring and preliminary diagnostics of multiphase flow risks in natural gas transportation systems.

Annotation

This study investigates the potential formation of liquid hydrocarbons in natural gas pipelines by analyzing hourly variations in gas composition. Temporal trends in heavy component concentrations were used to identify periods where the gas mixture approaches hydrocarbon condensation conditions. The results demonstrate that compositional fluctuations can serve as an effective indicator for assessing the risk of liquid phase formation in pipeline operation.

Keywords: gas pipeline, multiphase flow, propane concentration, liquid hydrocarbon formation

Introduction

Natural gas transmission pipelines are generally designed to transport dry gas under single-phase flow conditions. However, natural gas streams usually contain a certain amount of intermediate and heavy hydrocarbons such as propane, butanes, and pentanes. Under specific thermodynamic conditions, particularly when pressure and temperature approach the condensation region of the mixture, these heavier components may partially condense and form a liquid phase inside the pipeline. The appearance of liquid hydrocarbons in a gas pipeline may significantly influence the hydraulic behavior of the flow, leading to increased pressure losses, changes in flow regimes, and operational instabilities such as slugging, intermittent flow, or liquid accumulation in low sections of the pipeline. [3]

In gas-condensate systems, phase transitions are often associated with the phenomenon of retrograde condensation, where a liquid phase forms as the pressure of the gas mixture decreases at approximately constant temperature. This behavior occurs when the thermodynamic state of the gas approaches the hydrocarbon dew point, which defines the conditions under which the first droplets of liquid hydrocarbons begin to appear in the gas phase. Accurate prediction and detection of these phase transitions are essential for reliable pipeline operation, since even small quantities of liquid hydrocarbons may alter the flow structure and affect the performance of pipeline equipment such as compressors, separators, and measurement stations. [4]

Direct measurement of liquid hydrocarbon formation within operating pipelines is often difficult because multiphase flow monitoring requires specialized instrumentation and dedicated measurement systems. In many practical situations, pipeline operators rely primarily on standard operational data obtained from flow measurement stations. These data typically include pressure, temperature, gas flow rate, gas density, and detailed gas composition measured using chromatographic analysis. Although these parameters are routinely recorded for operational control and accounting purposes, they can also provide valuable information about the thermodynamic behavior of the transported gas. [2, p.253-260]

Variations in gas composition, particularly in the concentration of intermediate hydrocarbons such as propane, may reflect changes in phase equilibrium within the pipeline system. When a portion of heavier hydrocarbons condenses into a liquid phase, their concentration in the gas phase may decrease, while the relative fraction of lighter components such as methane increases. Such compositional changes are often accompanied by variations in gas density and may occur simultaneously with changes in operating pressure, temperature, or flow rate. Therefore, analysis of temporal fluctuations in gas composition can potentially provide indirect evidence of phase behavior changes inside the pipeline. [1, p.156-161]

Recent research in pipeline flow monitoring has increasingly focused on the use of operational data for diagnosing abnormal flow conditions and detecting multiphase phenomena. Time-series analysis of pressure, temperature, and gas composition can reveal transient events that may be associated with phase transitions, liquid accumulation, or changes in the thermodynamic equilibrium of the gas mixture. In particular, fluctuations in the concentration of intermediate hydrocarbons may serve as useful indicators of transient thermodynamic processes occurring in the pipeline. [6]

Multiphase flow phenomena represent one of the most significant operational challenges in natural gas transportation systems. The presence of liquid hydrocarbons in gas pipelines can alter the hydrodynamic characteristics of the flow and lead to various operational problems, including pressure fluctuations, liquid accumulation, and changes in flow regime. Even small amounts of condensed hydrocarbons may significantly influence the stability of gas flow and the overall performance of pipeline systems. The formation of liquid phases in natural gas pipelines is therefore closely related to thermodynamic conditions and the concentration of heavier hydrocarbons, which may condense when the gas approaches hydrocarbon dew point conditions. [5]

The present study investigates the relationship between fluctuations in heavy hydrocarbon concentrations and operational parameters in a natural gas pipeline. Hourly monitoring data recorded at a gas measurement station are analyzed, including pressure, temperature, flow rate, gas density, and detailed gas composition. Special attention is given to variations in propane concentration and their correlation with changes in methane content and gas density during the analyzed period.

The objective of this work is to determine whether temporal variations in intermediate hydrocarbon concentrations can provide indications of possible liquid hydrocarbon formation or other phase behavior changes within the pipeline. By examining real operational data from a gas transportation system, this study aims to demonstrate the potential of routine monitoring data for identifying thermodynamic anomalies and improving the understanding of transient processes occurring during gas pipeline operation.

Methodology

The present study is based on the analysis of operational measurements obtained from a natural gas transmission pipeline. The primary objective of the methodological approach is to investigate whether variations in the concentration of heavier hydrocarbon components, particularly propane (C_3), may indicate thermodynamic processes related to the formation of a liquid phase or redistribution of heavier hydrocarbons within the pipeline system. In gas transmission systems, fluctuations in heavy hydrocarbon concentration can provide indirect information about phase behavior, especially when the gas mixture approaches hydrocarbon dew point conditions.

The dataset used in this study was obtained from a continuous monitoring system installed at a measurement station located along the gas pipeline. The monitoring system records hourly values of several operational parameters, including pressure, temperature, gas flow rate, gas density, and detailed compositional information. Gas composition is measured using an online gas chromatograph, which provides the molar fractions of the principal components of natural gas. These components include methane (C_1), ethane (C_2), propane (C_3), and other heavier hydrocarbons. Continuous compositional monitoring makes it possible to analyze temporal variations in heavy hydrocarbon content and evaluate their potential relationship with thermodynamic conditions in the pipeline. For the purposes of the present investigation, a specific observation window was selected from the available dataset. The analyzed time interval corresponds to the period between 12:00 and 24:00 for two consecutive days. The selection of identical time intervals for both days allows a direct comparison of gas composition behavior under similar operational conditions. Restricting the analysis to this period also reduces the influence of transient operational disturbances and focuses the investigation on gradual compositional variations.

Prior to the analytical stage, the dataset was subjected to a consistency verification procedure. This step included inspection of the recorded measurements for missing values, abrupt discontinuities, or anomalous spikes that could potentially indicate measurement errors. Because the data originate from an industrial pipeline monitoring system, the recorded parameters are assumed to be reliable within the typical accuracy limits of pipeline instrumentation.

The primary parameter investigated in this study is the mole fraction of propane in the gas mixture. Propane represents one of the heavier hydrocarbon components commonly present in natural gas and plays a significant role in the thermodynamic behavior of hydrocarbon mixtures. Compared with lighter components such as methane, propane has a significantly higher tendency to condense under elevated pressure and moderate temperature conditions typical of gas transmission pipelines. The thermodynamic properties of the gas mixture depend strongly on its composition. One of the important characteristics of multicomponent gas mixtures is the average molecular weight. For a gas mixture consisting of several components, the average molecular weight can be determined using the mole-fraction-weighted sum of the molecular weights of individual components:

$$M = \sum_{i=1}^{n} y_i M_i$$

where M is the average molecular weight of the gas mixture, y_i is the mole fraction of component *i*, and

M_i is the molecular weight of component *i*. This relation reflects the fact that heavier hydrocarbons contribute more significantly to the overall molecular characteristics of the gas mixture.

Variations in molecular weight influence the density of natural gas under given thermodynamic conditions. The density of a real gas can be estimated using the real gas equation of state:

$$\rho = \frac{PM}{ZRT}$$

where ρ is the gas density, P is the absolute pressure, M is the molecular weight of the gas mixture, T is the absolute temperature, R is the universal gas constant, and Z is the compressibility factor. The compressibility factor accounts for the deviation of the gas from ideal behavior and depends on both the gas composition and the operating pressure and temperature. In particular, increases in heavy hydrocarbon concentration typically lead to higher molecular weight and higher gas density, which may indicate conditions approaching hydrocarbon saturation.

Although the present study does not involve a full thermodynamic phase equilibrium calculation, these relations provide a theoretical basis for interpreting compositional variations in the gas stream. In particular, increases in heavy hydrocarbon concentration typically lead to higher molecular weight and higher gas density, which may indicate conditions approaching hydrocarbon saturation. To analyze the temporal behavior of heavy hydrocarbons, the measured propane mole fraction values were examined as a time series. Graphical visualization of propane concentration allows the identification of trends and fluctuations over the selected observation period. Time-series analysis provides a practical method for comparing compositional behavior between the two analyzed days.

In addition to direct analysis of propane concentration, the study introduces a qualitative indicator referred to as the Hydrocarbon Dew Point Proximity Index. This index is designed to represent the relative closeness of the gas mixture to hydrocarbon condensation conditions. Because heavier hydrocarbons play a dominant role in determining the hydrocarbon dew point, variations in propane concentration can be used as a simplified indicator of changes in the thermodynamic state of the gas mixture. An increase in propane concentration may indicate enrichment of the gas with heavier hydrocarbons and therefore a shift toward conditions closer to hydrocarbon saturation. Conversely, a decrease in propane concentration may reflect either dilution of the gas mixture or partial condensation of heavier hydrocarbons in the pipeline.

The temporal behavior of propane concentration and the corresponding dew point proximity index were analyzed using graphical methods. The resulting plots allow a direct comparison of the compositional trends between the two investigated days and provide insight into potential thermodynamic processes occurring within the pipeline.

The final stage of the methodological framework involves the interpretation of observed compositional variations in the context of possible physical mechanisms occurring within the pipeline. Several mechanisms may explain fluctuations in heavy hydrocarbon concentration. One possible explanation is the partial condensation of heavier hydrocarbons when the gas mixture approaches hydrocarbon dew point conditions. In such cases, a fraction of the heavier components may transition into the liquid phase, temporarily reducing their concentration in the gas stream.

Another potential mechanism is the evaporation of previously accumulated liquid hydrocarbons present in the pipeline. If operating conditions change in a way that favors vaporization, part of the liquid phase may return to the gas phase, increasing the measured concentration of heavier hydrocarbons. Additionally, variations in gas composition may occur due to mixing processes within the gas transmission network when gas streams from different sources enter the pipeline system.

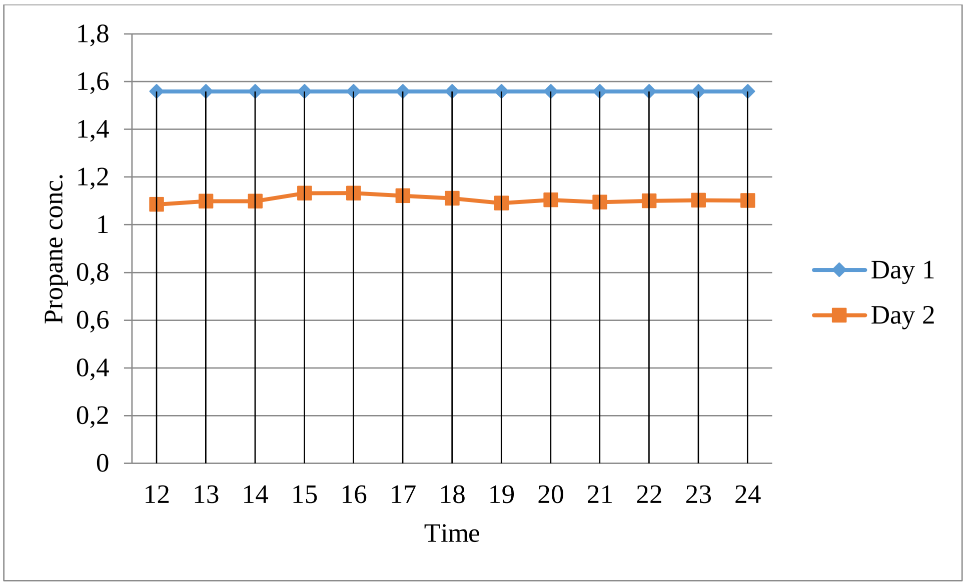
Because the present study is based on measurements obtained at a single monitoring location, it is not possible to uniquely identify the exact mechanism responsible for the observed variations. However, the combined analysis of propane concentration trends and the dew point proximity index provides a practical framework for evaluating the potential risk of liquid hydrocarbon formation in natural gas pipelines.

Results

Hourly measurements of propane mole fraction (C_3) were analyzed for the selected period between 12:00 and 24:00 over two consecutive days. The temporal behavior of propane shows significant fluctuations during the observation interval.

Diagram 1 illustrates the variations of C_3 over time for the two days. Peaks and dips in the propane concentration indicate transient changes in gas composition that may be associated with operational or thermodynamic effects.

Diagram 1



The analysis of heavy hydrocarbon behavior in natural gas pipelines is an important aspect of understanding phase stability during gas transportation. Even small variations in the concentration of heavier components may indicate thermodynamic conditions approaching hydrocarbon condensation. Among the heavier hydrocarbons present in natural gas, propane plays a particularly significant role due to its relatively high molecular weight and stronger tendency to condense compared with methane and ethane. Therefore, monitoring the temporal variation of propane concentration in the gas stream can provide valuable information about the potential formation of liquid hydrocarbons within a pipeline.

In the present study, hourly operational data from a gas pipeline were analyzed in order to investigate possible indications of liquid phase formation. The dataset included measurements of propane concentration, pressure, and temperature. For consistency of analysis, two consecutive days were considered and the same time interval from 12:00 to 00:00 was selected for each day. This allowed a direct comparison of the thermodynamic behavior of the gas mixture under similar operational conditions.

The first stage of the analysis focused on the temporal variation of propane concentration. The graphical representation of propane concentration over time allows identification of possible changes in gas composition and potential thermodynamic transitions in the system. During the first day of observation, the propane concentration remained essentially constant at approximately 1.5588%. The absence of noticeable fluctuations suggests that the composition of the transported gas was stable during that period. Such stability typically indicates a steady operating regime of the pipeline and a consistent composition of the incoming gas stream.

However, the absolute value of propane concentration during the first day was relatively high compared with the values observed during the second day. Since propane is one of the heavier hydrocarbons present in natural gas, a higher concentration of this component increases the overall heaviness of the gas mixture. In thermodynamic terms, this means that the gas composition moves closer to hydrocarbon dew point conditions. When a gas mixture contains a larger fraction of heavy hydrocarbons, the probability of partial condensation increases, especially if pressure remains relatively high and temperature decreases even slightly.

The second day of observation demonstrates a different behavior of propane concentration. Unlike the nearly constant values observed during the first day, the propane concentration during the second day exhibits moderate variations over time. At the beginning of the analyzed period, the propane concentration was approximately 1.0847%. During the following hours, a gradual increase was observed, reaching a maximum value of approximately 1.1328%. After this peak, the concentration began to decrease again and fluctuated within a range of approximately 1.09–1.10%.

Although these intra-day variations are noticeable, the most important observation is the significant difference between the two analyzed days. The propane concentration during the first day was consistently higher than during the second day. The difference between the average values of propane concentration for the two days is approximately 0.4–0.45 percentage points. From a thermodynamic perspective, this difference is substantial, as heavy hydrocarbon components strongly influence the phase behavior of gas mixtures.

To further evaluate the proximity of the gas mixture to hydrocarbon condensation conditions, a simplified indicator known as the Hydrocarbon Dew Point Proximity Index (HDPI) was introduced. This index provides a practical method for estimating the likelihood of condensation using available operational data. In many practical situations, detailed thermodynamic calculations require complete compositional analysis and advanced equations of state. However, operational monitoring systems often provide only partial compositional data together with pressure and temperature measurements. Under such conditions, simplified indices can be useful for preliminary diagnostics.

The Hydrocarbon Dew Point Proximity Index was defined as the ratio between the product of propane concentration and pipeline pressure and the absolute gas temperature:

$$HDPI = \frac{C_3 P}{T}$$

where C_3 is the propane concentration in the gas mixture, P is the pipeline pressure, and T is the absolute gas temperature. The physical interpretation of this index is straightforward. Higher concentrations of heavy hydrocarbons increase the probability of condensation. Similarly, higher pressure tends to promote condensation by increasing the density of the gas mixture and moving the thermodynamic state closer to the dew point line. In contrast, higher temperature reduces the probability of condensation by shifting the system further away from phase equilibrium conditions.

Using the measured operational data, the Hydrocarbon Dew Point Proximity Index was calculated for both analyzed days. The results show a clear difference between the thermodynamic conditions of the two periods. During the first day, the index reached significantly higher values due to the elevated propane concentration in the gas mixture. In contrast, the second day was characterized by lower HDPI values because of the reduced concentration of propane, despite the slightly higher pipeline pressure.

The comparison of the calculated index values indicates that the gas mixture during the first day was closer to hydrocarbon dew point conditions than during the second day. This result is consistent with the observed behavior of propane concentration. Since propane represents a heavy hydrocarbon component with a relatively high condensation tendency, its higher concentration increases the probability of liquid hydrocarbon formation in the pipeline flow. Another important aspect supporting this interpretation is the overall density of the gas mixture. The density of natural gas strongly depends on its composition, particularly on the fraction of heavier hydrocarbons. An increase in the concentration of components such as propane, butane, and pentane generally leads to an increase in gas density. Conversely, a reduction in the concentration of heavy hydrocarbons results in a lighter gas mixture with lower density. Therefore, the higher density observed during the first day is consistent with the higher propane concentration and the higher HDPI values calculated for that period.

From a thermodynamic standpoint, these observations suggest that the gas transported during the first day may have been closer to conditions where partial condensation of heavy hydrocarbons becomes possible. Although the available data do not allow a full phase equilibrium calculation, the combination of higher propane concentration and higher dew point proximity index indicates that the probability of liquid hydrocarbon formation was greater during the first day of observation.The graphical analysis of propane concentration combined with the calculated dew point proximity index therefore provides a useful diagnostic approach for identifying potential condensation risks in gas pipelines. Such methods are particularly valuable in operational environments where complete thermodynamic characterization of the gas mixture is not available in real time. By continuously monitoring heavy hydrocarbon concentrations and evaluating simplified thermodynamic indicators, pipeline operators can identify periods when the gas mixture approaches hydrocarbon dew point conditions and take preventive measures if necessary.

In summary, the analysis of hourly operational data revealed a clear difference in the thermodynamic behavior of the gas mixture between the two analyzed days. The first day was characterized by a higher and stable propane concentration, which resulted in higher values of the Hydrocarbon Dew Point Proximity Index. These conditions indicate a gas mixture richer in heavy hydrocarbons and therefore closer to hydrocarbon condensation conditions. In contrast, the second day exhibited lower propane concentrations and lower index values, suggesting that the gas mixture was thermodynamically further from the dew point. The combined use of propane concentration trends and the dew point proximity index therefore provides a practical method for assessing the potential risk of liquid hydrocarbon formation in natural gas pipelines.

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