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Case Study of Liquids Drop-Out in a Natural Gas Pipeline Network

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ABSTRACT

Liquid drop-out in natural gas pipelines is becoming increasingly common because of high changes in the composition and low quality of the natural gas supply. Predictions of possible locations where liquid drop-out occurs are, on occasion, very difficult to obtain. Moreover, estimating the amount of liquid condensation in the gas pipeline is even more challenging. From an operating gas company prospective, it is fundamental to identify those issues and take the appropriate actions to solve them before they significantly affect the operation of the entire pipeline system

Modeling of pipeline networks has increased in the past decade due to the use of powerful computational tools that provide good quality representation of the real pipeline conditions. Therefore, a commercially available single-phase pipeline network flow model was used to model a very complicated transmission network that covers an entire country. The system includes approximately 4400 miles of interconnecting pipelines, 11 main compressor stations, 21 different injection points and 110 extraction locations. The developed model takes into account heat transfer with the surroundings, changes in elevation, flow and pressure regulations points as well as diverse operating conditions. Simulation scenarios cover a wide variety of flow and pressure conditions. A baseline model is developed and tuned with real operating conditions. Parameters such as roughness, heat transfer coefficients and ground properties are obtained by using real operating data. It is essential to note that conventional assumed friction factors and heat transfer coefficients are affected significantly with the presence of

liquids that originate a two-phase transport mechanism. In order to obtain predictions of possible locations of liquids drop-out, simulation results are compared with the phase envelope of the different gas streams along the pipeline network. Pressure, temperature and velocity parameters define the conditions for hydrocarbons condensation. Model results are compared with snapshots of the operational conditions to complement the validation of the model and improve simulation results. Recommendations for managing the liquids in the pipeline are presented.

This paper provides a methodology on how to determine the possible hydrocarbon liquid drop-out in a pipeline network by combining a modeling tool with mathematical calculations. In addition, results for a case study are presented and discussed. It will also provide a solution for predicting liquids accumulation to improve the general operation of the pipeline by minimizing maintenance and operational costs.

Methodology

Simulations of the system operating under steady-state conditions can provide velocity, temperature and pressure profiles of every single pipe branch. There are several specific conditions that can be identified with velocity, temperature and pressure profile data, in which condensate formation is most likely. Utilizing an equation of state and an initial gas composition, the phase envelop of the gas transported is generated. Comparison of the pressure and temperature results obtained from the pipeline simulation with the phase envelop data is used to determine if the gas flow is under possible mixture conditions that could result in liquid drop condensation. In addition, low velocity points can indicate possible locations where the condensate liquids and solids may accumulate in the piping system, resulting in caked solid deposits and liquids hold-up. A schematic diagram that shows step wise the methodology process to be followed is shown in Figure 1.

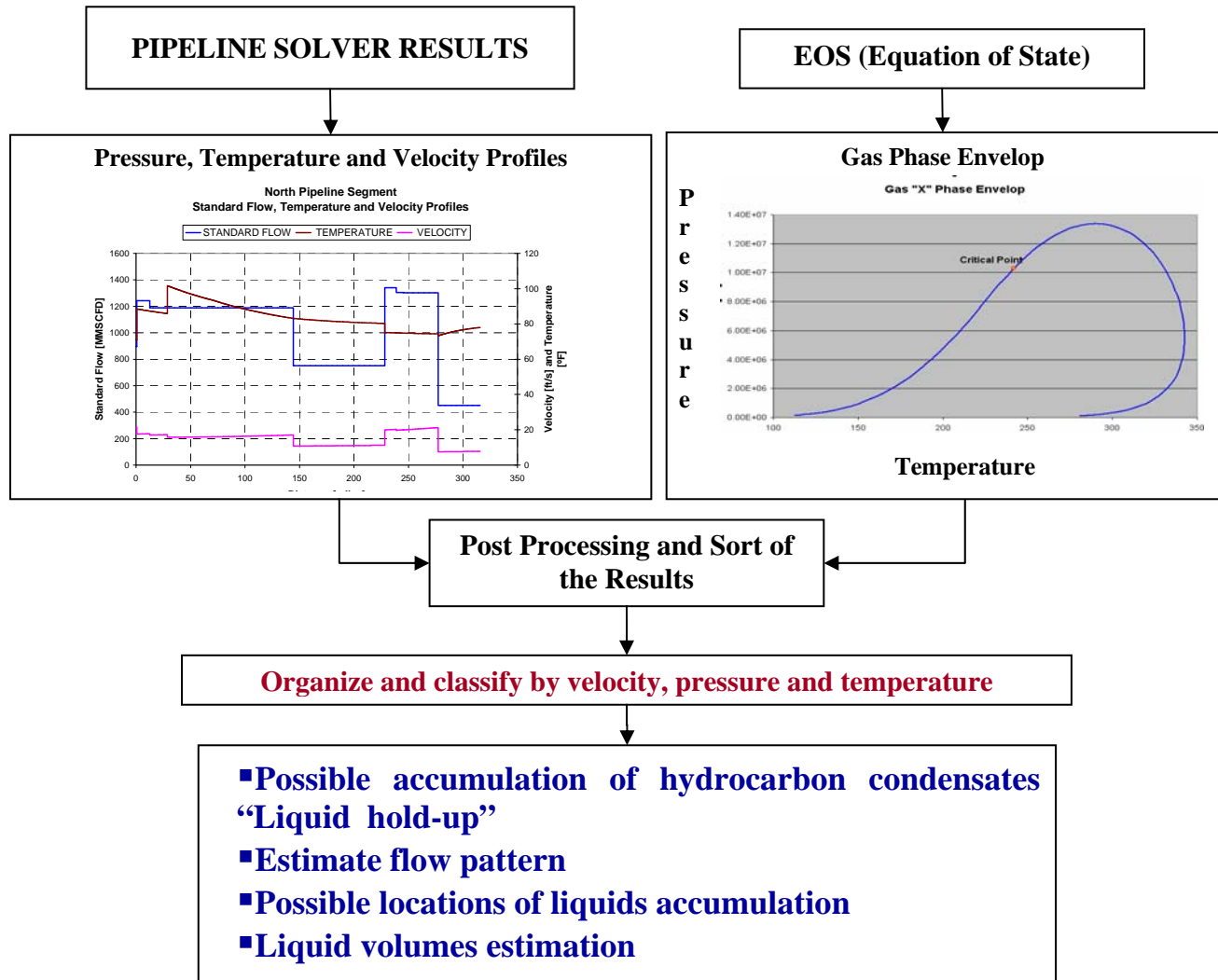


Figure 1. Methodology Process

An example case of the methodology is present for the pipeline location. A phase envelop of the average gas composition is generated and then combined with the temperature and pressure profiles obtained from the simulation to determine if the gas flow conditions fall into the mixture zone of the gas. The result from this comparison is illustrated in Figure 2. This result points out that the operation of the pipeline in this segment will have some gas condensation. In addition, the modeling results for the studied zone show low velocity values for the gas stream and that is beneficial for the liquid hold-up mechanism. Moreover, the initial gas composition indicates the possible presence of liquids in the stream due to a higher concentration of heavier components such as C10, C11, and C12. In this case, concentrations higher than C6, C7, C8, and C9 may indicate some entrainment of liquid in the gas stream.

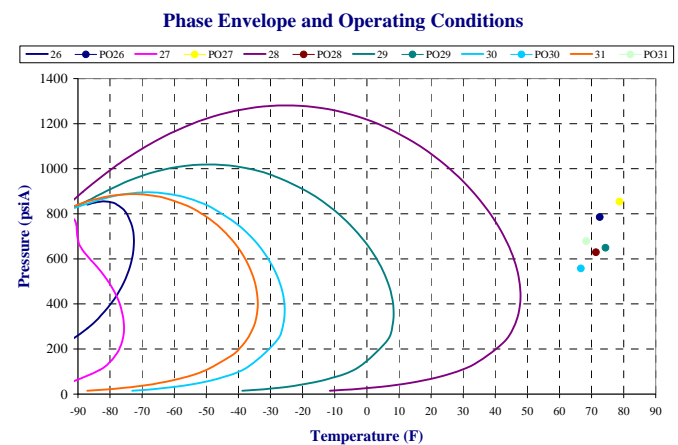


Figure 2. Phase Envelope and Operating Conditions Comparison

Results from the computational model are used to determine the different gas mixtures that are present in the pipeline system as well as operational conditions such as pressure and temperature. Phase envelopes of the different mixtures are calculated based on the gas composition obtained from the simulations results and their average operating conditions are used to calculate the physical properties at specific operating conditions for each pipe segment. Gas mixtures are organized and classified based on their content of the different components such as methane, ethane, propane, etc. Moreover, similar mixtures flow through common pipeline segments. So the analysis is simplified to pipeline segments level. Each pipeline segment is analyzed for the possible presence of liquids or conditions that may aid liquids drop-out from the gas stream.

A liquid prediction criterion is based on mechanistic two-phase models. These models have been generated based on fundamental mass balance, continuity, and pressure equations combined with closure relationships obtained through several experimental data bases. Flow pattern predictions were conducted by utilizing the Taitel & Dukler model combined with the Lockhart-Martinelli parameter. Using the predicted flow patterns, inclination angle, liquid hold-up, mixture main velocity, estimated liquid volumes and a general criteria for predicting possible accumulation of liquids in the pipeline system initial prediction of possible locations of liquids drop-out were obtained. These initial predictions should be compared with real operational data for its further validation.

Taitel and Dukler model is applicable for steady state, fully developed, Newtonian flow in horizontal and slightly inclined pipelines as is the studied pipeline system. This model has been successfully tested against real operational data and some experimental scaled data. The model starts assuming equilibrium stratified flow and then a stability analysis is performed to determine the stability of the flow configuration. Therefore, transition boundaries are defined to stable the limits between the different flow patterns. These boundaries are calculated based on the pipeline geometry such as diameter and inclination, and fluid properties while operational conditions such as superficial velocities of the two streams are used to determine the possible flow pattern regimen encountered.

Flow pattern predictions involve many physical parameters and analysis. Therefore, an existent flow pattern model calculator is used for processing all the information obtained from the pipeline simulator. Typical flow patterns encounter in a gas-liquid two-phase flow depends on variables such as operational parameters such as gas and liquid flow rates, geometrical parameters, including pipe diameter and inclination angle and physical properties of the two phases such as density, viscosity and superficial tension.

Since the flow pattern depends on the inclination of the pipeline, different categories have been created based on the configuration of the system. These categories include

horizontal and near horizontal flow, vertical and sharply inclined flow and downward inclined and vertical flow. Each of those categories contains various types of flow patterns that are based on the operational conditions and other parameters.

In the horizontal and near horizontal flow, possible patterns will be stratified, intermittent, annular, and dispersed bubble flows. Each of those patterns present specific characteristics which are unique to them. In addition, pressure drop calculations are based on the flow pattern present in the pipeline system. Moreover, closure relationships used for the pressure drop calculations depend on the actual flow patterns. Therefore, it is critical to have a good estimation of the expected flow pattern for design and modification purposes.

In this case, pressure drop calculations have been obtained through a pipeline simulator and validated with the real system values. Therefore, the process utilized is inverted to the regular process. Simulation results are used to determine the expected flow pattern and then based on those predictions, calculations of the liquid hold-up, low velocity point and the inclination angle a possible liquid drop-out and accumulation locations can be estimated.

In order to understand some of the parameters used in this analysis, it is critical to define some general concepts such as liquid hold-up, superficial velocities and average fluid properties. Liquid hold-up is the fraction of a volume element in a two-phase flow field occupied by the liquid phase (H_L). The instantaneous liquid hold-up refers to a differential volume element, and represents the hold-up at a given time and space point in the flow field. The average liquid hold-up refers to a cross-sectional area of the pipe and a finite volume of the pipe bounded by the pipe wall and two imaginary planes perpendicular to pipe axis, respectively.

Superficial velocity of a phase is the volumetric flux of the phase, which represents the volumetric flow rate per unit area. It means that the superficial velocity of a phase is the velocity which would occur if that phase alone flows in the pipe.

$$v_{SL} = \frac{q_L}{A_p} \quad v_{SG} = \frac{q_G}{A_p}$$

The average velocity of a two-phase flow mixture take into account the two existent phases and combines their properties through a volumetric ratio given by the liquid hold-up. Therefore, density, viscosity and superficial tension of the gas-liquid phases are average on the basic of the liquid hold-up ratio.

Mixture Density:

$$\rho_M = \rho_L H_L + \rho_G (1 - H_L)$$

Mixture Viscosity:

$$\mu_M = \mu_L H_L + \mu_G (1 - H_L)$$

PIPELINE MODEL

A model of an entire gas pipeline network using a pipeline simulator package was built. The model covers the three main zones of the entire gas pipeline system: north, central and south. The model includes primary components such as compressors, main pipelines and branches, regulators, valves, injection and extraction points, etc. In addition, a list of the delivery points, injection points, compressor operating conditions, and average ambient temperature per zone was provided.

The entire pipeline system includes approximately 4400 miles of interconnecting pipelines, 11 main compressor stations, 21 different injection points and 110 extraction locations. The developed model takes into account heat transfer with the surroundings, changes in elevation, flow and pressure regulations points as well as diverse operating conditions. Each zone covers four-five main sub-zones, including different pipeline diameters and lengths. Separate models for each zone were built with their respective boundary conditions. They were initially treated as independent models, then later combined since they must interact as a whole in order to reach a balanced condition. A simulation run of the entire system was performed to provide preliminary results of the system under the stipulated operating conditions. This initial run was taken as a baseline for further simulations. Moreover, the model was tuned and adjusted using as a reference this initial scenario.

Gas composition was specified at each injection point based on the data provided. Different gas compositions were incorporated into the model in order to represent the real properties of the gas stream in the pipeline. Mixing of the different gas streams was performed in the pipeline, based on the respective pressure, temperature, and compositional makeup of each stream and on the assumption of fully turbulent mixing of the gas.

Initial line packing was not assumed for the base line scenario, so a mass balance was assumed (steady-state conditions; mass in = mass out). This mass balance was accomplished through pressure injection points. Flow extraction points were maintained as initially input.

Ground temperature profiles and heat transfer coefficients were defined, so the simulation was run assuming heat transfer between the gas stream, the piping, and the surrounding ground. An average temperature for the ground was considered for each sub-zone of the model, based on the average ambient temperature and considering a margin of +2°F. At pipeline depths of about six meters or more, there is no significant change from summer to winter, and the mean ground temperature approaches the annual average air

temperature plus 2°F. The ground temperature changes very slowly, generally not more than two or three degrees Fahrenheit unless there has been a cold rain in the fall or a warm rain in the spring. Factors that determine the temperature of the ground can be grouped in three general categories: meteorological, terrain, and subsurface variables. Large-scale regional differences in ground temperature are determined primarily by meteorological variables such as solar radiation, air temperature, and precipitation. Micro or local variations are caused by differences in terrain, surface characteristics, and ground thermal properties. The properties of the ground that determine its response to temperature changes at the surface are volumetric heat capacity, C , thermal conductivity, K , latent heat (the heat required to freeze or thaw a unit volume of frozen soil) and water content. The ratio, K/Cv , known as thermal diffusivity, is important in calculating rate of heat flow in the ground.

In conclusion, for depths below 5 to 6 meters, ground temperatures are essentially constant throughout the year. The average annual ground temperature is practically constant with depth, increasing about 2°F per 50 meters due to geothermal heat flow from the center of the earth to the surface.

SIMULATIONS

After completing all the necessary modifications of the model built, the transient simulation was run until the model reached steady-state, and then the tuning process started. Comparing the conditions obtained in the simulation with the real conditions, it was observed that there would be a need for some tuning of the computational model. Several parameters were used to tune the model; however, starting with the assumed parameter is the wisest choice, since it represents the critical source of the uncertainty in the model. Parameters such as pipe roughness, ground thermal conductivity, ground thickness, gas thermal properties, valve opening fraction, regulator set points, etc. were used to tune the model while it was running. Thus, system changes can be observed and then compared against the real values. It is important to highlight that, for changes in temperature, the model has to be run for a long period of simulation time (2-3 months) before reaching a new steady-state condition useful for comparison. Therefore, an iterative process was used to refine the model results until reasonable results were obtained.

A general schematic of the model and its zones was developed to facilitate the tuning process and used as a monitoring tool during a real time simulation. In addition, schematics of each sub-zone were developed. Sub-zone schematics cover details for each pipe branch and compressor station, so these are easier to use for tuning and controlling the system behavior.

After completing the baseline simulation, two more scenarios that represent the average operating conditions of the entire pipeline system were simulated to performance the liquid drop-out predictions and analysis. Therefore, it is expected

that these two simulations are a good representation of the normal operation of the system. The selected conditions cover minimum and maximum flow as well as packing rates. Therefore, both cases are analyzed to determine the possible location of liquid drop-outs and accumulation.

In addition, results from the three cases simulated are presented as a reference for the analysis. However, only the two extreme cases were considered for the main analysis. Average results are presented, analyzed and discussed. Results are presented for each main zone and scenario simulated.

Simulation Results

In order to analyze the results obtained from the simulations, pressure, temperature, velocity, and flow rate profiles were generated. In addition, the model was divided into three zones considering all the branches and junctions. These three zones are North, Central and South zone. In this case, the energy loss is due to pipe friction, elevation changes, and extraction points along the pipeline.

The changes in velocity and pressure in those zones are influenced by several factors such as compression, changes in elevation, and major extractions. In addition, complex pipeline networks are located in those areas, so intricate geometries and drastic diameter changes affect significantly the pressure and velocity. Figures 3 and 4 show pressure, elevation, temperature, and velocity profiles of one of the north pipeline segments.

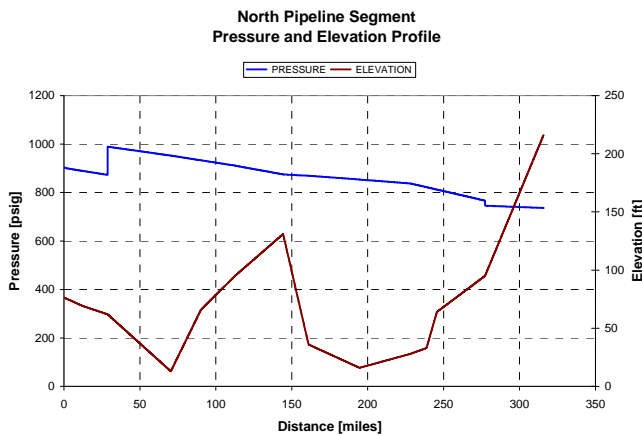


Figure 3. Pressure and Elevation Profiles

Reports of each transfer line were generated to be used during the analysis and to identify any unexpected behavior of the system under the simulated conditions. Parameters such as pressure downstream and upstream, velocity, density, packing rate, inventory, etc., can be monitored through these reports. Therefore, a steady-state condition of each pipeline was

recorded to facilitate the analysis. Tables that group all the transfer lines under steady-state conditions were generated. These tables are classified by zone (north, central and south). In addition, report tables were used to monitor the mass balance of the system and to find any problems with the injection and extraction locations.

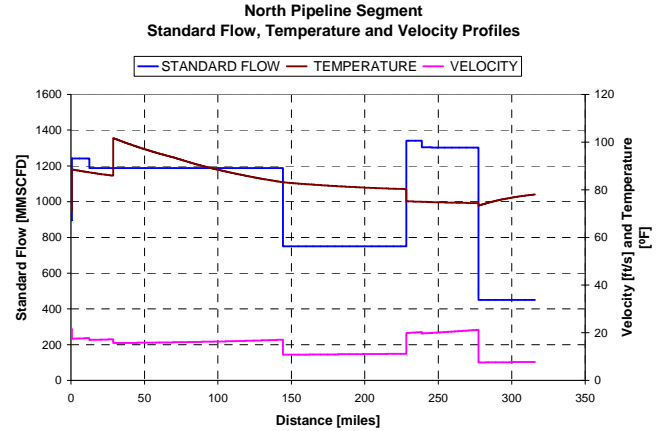


Figure 4. Standard Flow, Temperature and Velocity Profiles

The results approached the values obtained in the real system. Moreover, an average difference of approximately 4.51% was obtained between the initial simulation of the entire model and the real conditions provided.

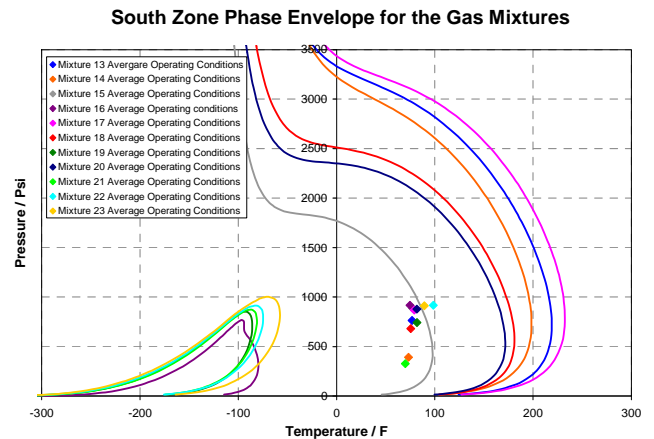


Figure 5. Phase Envelop for Gas Mixtures in the South Zone

The results obtained indicate that, in almost all locations, there may be liquid condensation. Pressure and temperature profiles indicate that the pipeline is being operated into the mixture zone of the gas streams. Only the North zone (gas mixture #3, 4, 5 and 6) seems to be operating out of the phase envelope, so it is not expected that any gas condensation will occur in these pipelines. In addition, it was observed that the initial composition of many of the injection points included more than a quarter of C6+ (heavier hydrocarbons). Therefore, it was expected to obtain phase envelopes with higher dew point curves, which is a clear indication of very rich gas streams.

Figure 6 shows some of the possible locations where liquid condensation might be occurring.

use homogeneous blending for their computations.

SUMMARY

In addition, those results were analyzed and processed utilizing the methodology proposed by SwRI and they seem to provide a reasonable good prediction of what could be occurring in the pipeline network. Moreover, the entire model was refined and modified by adjusting parameters such as pipe roughness, heat transfer coefficients, boundary conditions, etc. So this model is a good representation of the existent system and simulation results can be used with confidence as a decision making tool.

Schematics of the entire model and every zone and sub-zone were developed to be used during the tuning process and to facilitate the monitoring of the system while the simulation is running. A general schematic of the entire model was built, and more detailed representations of the other sectors were completed. Those schematics should aid in the refinement of the model, and monitoring of the flow, pressure, temperature, or other important variables at any point of the system, and to control the system while the simulation process is taking place.

In addition, an analysis of the results has been provided. All the pipeline branches were analyzed, and the results provided an initial idea of what kind of factors should be considered during the adjustment stage of the computational model. In addition, those results demonstrate the capabilities of the pipeline network software used, and it is expected that improvement in the results will be achieved by tuning the model. Predictions of liquid drop-out have become more accurate. Results indicate that almost all the pipeline branches will produce some amount of liquid condensation due to the change of phase predicted from the different phase envelopes. Moreover, almost all of the initial gas compositions at the different injection points contain a relatively high content of C6+ (heavy hydrocarbons >0.25%). It is expected that very rich gas mixtures with high heating values represent a favorable situation for liquid condensation. The only high quality gas was obtained from the R&PF where the pipeline conditions were out of the condensation region of the phase envelopes. In those zones, the gas compositions were for very dry gases with very low or no concentration of condensable hydrocarbons (C6+). Therefore, they were lean gas streams. Other key concerns are the natural gas sampling technique and compositional analysis used to determine the gas composition at each point. If the sample technique is inaccurate or inappropriate, the results obtained are not a good representation of what is flowing in the pipeline.

General result uncertainties must be considered to incorporate any inaccuracy given by the use of the equation-of-state, software computations, and inconsistent assumptions. The impact of simplifying assumptions on the estimated temperature, pressure, velocity, and density of the gas stream

Operating Conditions and Phase Envelope Comparison of the Entire Model

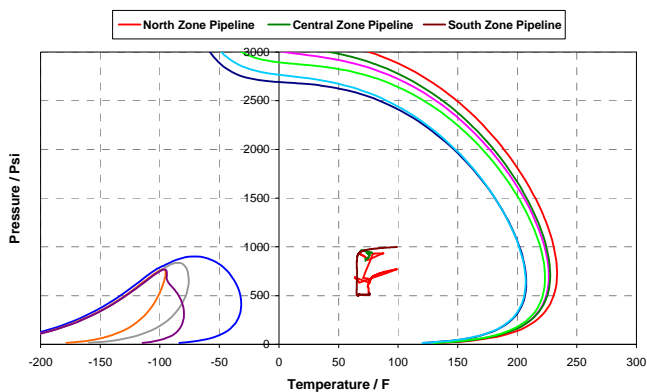


Figure 6. Phase Envelop for Gas Mixtures in the South Zone

Gas streams that originated at the refinery and petrochemical facilities (R&PF) are high quality since they are originated during a high quality refining process. Therefore, no condensation is expected in the pipelines originating at the R&PF.

In addition, it is important to mention that the pipeline conditions obtained through the simulation process match the real operating conditions of the pipeline network in all the segments within an acceptable uncertainty margin. However, the achieved conditions were more beneficial for avoiding gas condensation, since pressure and temperature overpredictions were observed in many of the transfer lines. Those conditions could locate the system out of the phase envelope. Contrastingly, the northwest part of the pipeline network showed pressure underpredictions that may put the system in a favorable condition for liquid condensation to occur.

Gas compositions may be changing in the real system, and the provided data might not be a precise representation of what is inside the pipeline, compared with what was initially injected. In addition, any equation-of-state calculation provides an uncertainty estimate of its calculations, so it is essential to consider some range of uncertainty in the results. The assumed homogeneous gas mixing may be a good representation in some cases, where favorable conditions exist. Large differences in heating values and Wobbe indices may affect the mixing rule and could affect the general mixing of the gas in the pipeline network. However, in the case studied, there was an acceptable difference in the Wobbe index for the gases injected. Only three dry gas streams presented a significant difference in the heating value and Wobbe index. Therefore, it is important to consider that, in the real system, not all the streams mix or blend homogeneously. They sometimes move as a batch of fluid with some diffusion at the interfaces. However, there is a limitation in the existing computational tools to simulate the real blending of various gas streams. So far, many of the existing pipeline simulators

may be significant, particularly if the model results will be used for predicting phase behavior. Heat transfer mechanisms closely represent the true heat transfer conditions in order to provide the most accurate estimates of the conditions in the pipe.

The model was validated against available operating data showing good agreement and acceptable results. An initial average difference of 4.51% was obtained. While a model was built for the normal operational conditions, snapshots of different scenarios were used to tune and validate the model. Many simulated elements may behave differently than the real conditions, so parameters such as pipe roughness, flow coefficients, header lengths, thermal coefficients, etc., were adjusted to make the model a useful tool that accurately represents the real conditions. Then, predictions and simulations of three particular operating conditions were performed with confidence.

In addition, results from the liquid characterization were obtained and used to estimate if pipeline segments operate under a two-phase configuration. Expected flow patterns were estimated using a two-phase modeling approach (Tailer & Dukler model). In addition, parameters such as pipeline inclination, liquid hold-up, superficial velocity and liquid volumes were calculated by combining simulation results and physical properties of the different gas mixtures.

A list of the possible liquids drop-out locations is provided as an initial estimation of possible liquid accumulation. In addition, possible expected condensate volumes were calculated considering minimum, average and maximum operating conditions.

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