A Simulation Design Decision Support System for Natural Gas Pipeline Network Operations

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Abstract: This paper introduces a simulation design decision support system to support the development process of the pipeline network and provide decision support to the operations of the gas pipelines. The system has been implemented on Flash5*, which has a multimedia capabilities environment for designing and delivering low-bandwidth animations, presentations, and web sites. It also offers scripting capabilities and server-side connectivity for creating applications and web interfaces. Hence a user can interact with the system on the World Wide Web.

1. Introduction

Pipeline systems are very important for transporting gas, oil, petroleum products as well as water in North America, since they are the most cost effective ways for moving fluid products over long distances. Pipeline network simulation is the most common tool for control and operations of pipeline systems because it can be used to simulate and analyze network behaviors under different operating conditions. This is important for ensuring demands of customers can be met. However, the design and implementation of such simulation systems is difficult since there are many factors that must be considered. The most important considerations include properties of gas such as viscosity, compressibility, temperature, and other factors such as the diameter of pipe, pressure and flow rate of gas.

This project introduces the development of a decision support system (DSS) to aid the operator in desinging pipeline network system as well as optimizing natural gas pipeline operations. The DSS is a hybrid system that combines a simulation module with a knowledge base module to assist natural gas pipeline operators in their operational decision making. The simulation module generates pressure and flow information for each compressor stations and customer locations. The information involves a large amount of raw data which a novice operator finds difficult to understand. An expert system was developed to help the operator interpreting the information with visual illustrations about the processes.

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2. System Development

The objective of the project is to construct a simulation design decision support system that supports the development process of the pipeline network and provide decision support to the operations of the gas pipelines. The system consists of two modules; a simulation module and a knowledge base module which contains information on compressor operations. This system can support decision making by providing a comprehensive process simulation that spans from the early stage of pipeline network design to operation. The simulation module can generate data regarding operating conditions but a novice operator may not be able to comprehend the significance of the data. By incorporating the knowledge base component, the system can facilitate training by providing information to the operator that combines learned heuristics with real life operation. This is useful because the system consists of not only mathematical models but operational expertise. Figure 1 displays an overview of simulation design decision support system for the natural gas pipeline network operations

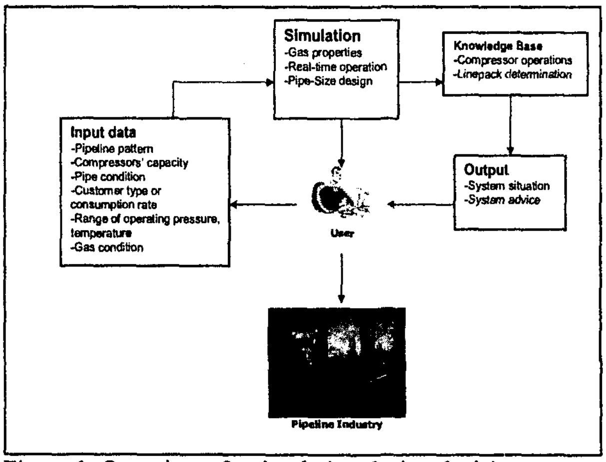

Figure 1. Overview of a simulation design decision support system

2.1 Simulation Module

The objective of simulation module is to help developers create a system that simulates the dynamic behavior of a pipeline network system with different system configurations and varying diameters, lengths of pipes and sizes of compressors, and total natural gas consumption. The module integrates mathematical equations of natural gas pipelines parameters such as gas properties, energy balance, and mass balance with a knowledge base.

The simulation module will provide information on hardware needed to build pipeline network simulation systems. The module can facilitate construction of a new pipeline network system or an extension of an existing system. This module helps configure a new pipeline network system or its subsections more efficiently.

The simulation module consists of three groups of equations on *(1)natural gas properties, (2)real-time operation, and (3)pipe-size design.* This simulation module includes functions to simulate all gas properties with the different proportions of natural gas specified by the operator. The following are the equations of natural gas properties.

The molecular weight of a gas mixture can be determined by,

$$M_g = \Sigma y_i M_i \qquad (1)$$

where M_i is molecular weight of each hydrocarbon in natural gas, and y_i is the mole fraction of component i in the mixture.

Also the gas gravity is given by,

$$\gamma_g = M_g/M_a \qquad (2)$$

where M_g is natural gas molecular weight, and M_a is air molecular weight.

For mixture of hydrocarbon gas, Kay's mixture rule is used to find the effective critical properties:

$$p_{pc} = \Sigma y_i p_{ci} \ (3) \ \text{and} \qquad T_{pc} = \Sigma y_i T_{ci} \qquad (4)$$

where p_{pc} and T_{pc} are the pseudocritical pressure and temperature respectively for the mixture, y_i is the mole fraction of component i in the mixture, and p_{ci} and T_{ci} are the critical pressure and temperature respectively.

One of the most important characteristics of natural gas is the gas compressibility factor Z. Practically, value of Z depends upon pressure and temperature.

$$Z = f(p_r, T_r) \qquad (5)$$

where $p_r = p/p_c (6)$ and $T_r = T/T_c \qquad (7)$

For natural gas or gas mixtures, the reduced parameters (p_r and T_r) are denoted as pseudoreduced pressure and temperature. Standing and Katz [3] illustrated the relationship among the values of p_r, T_r, and Z for sweet natural gas with the chart. Gopal [2] found a straight line fits the Standing-Katz chart in the general form of

$$Z = p_r(A\,T_r + B) + C\,T_r + D \qquad (8)$$

where A, B, C, and D are correlation constants. Thirteen equations were applied to suitably represent the Standing-Katz chart.

The density of natural gas, ρ_g, can be calculated as:

$$\rho_g = pM_g/ZRT \qquad (9)$$

where p is the pressure, R is the gas constant, and T is the temperature of the system.

The dynamic viscosity, a measure of its resistance to flow, is defined as the ratio of the shear force per unit area to the local velocity gradient; this is represented in the following equation:

$$\mu = (F/A)/(dv/dL) \qquad (10)$$

Lee et al [5] expressed the equation for dynamic viscosity that can be used for programming:

$$\mu = K\exp(X\rho^{Y}_{g}) \qquad (11)$$

where

$$k = \left[\frac{10 - 4(9.4 + 0.02M)T1.5}{209 + 19M + T}\right] \qquad (12)$$

$$X = 3.5 + 986/T + 0.01M \qquad (13)$$

$$Y = 2.4 - 0.2X \qquad (14)$$

The ratio of the dynamic viscosity of a fluid to density is kinematics viscosity,

$$\nu = \mu/\rho \qquad (15)$$

With formulation of these fundamental natural gas properties, the simulation module is able to perform the two main tasks of real-time operation and pipe-size design.

The simulation module defines the transmission natural gas pipeline system to be a pipeline network with two basic elements: nodes and node connecting elements (NCE's). The energy and mass flow balance equations were applied to the simulation module to perform real-time operation and pipe-size design. Under an assumption for steady-state isothermal flow of gas through a horizontal pipe, the energy equation is being applied as:

$$q_{sc} = 5.6353821(T_{sc}/p_{sc})((p_1^2 - p_2^2)d^5/\gamma_g Z_{av} T f L)^{0.50} \qquad (16)$$

where q_{sc} is total consumption, T_{sc} and p_{sc} are temperature and pressure at standard condition, p_1 and p_2 are upstream and downstream pressure, T is flow temperature, f is the Moody friction factor, and L is length of the pipe.

The mass flow rate balance equation is also applied at each node and defined as:

$$\Sigma m_{i\,in} = \Sigma\, m_{i\,out} \qquad (17)$$

Based on equations described earlier, the system provides simulation results through the user-interface as shown in figure 2. The system simulates the pressure and flow rate at each compressor station and provides visualization of the customer stations.

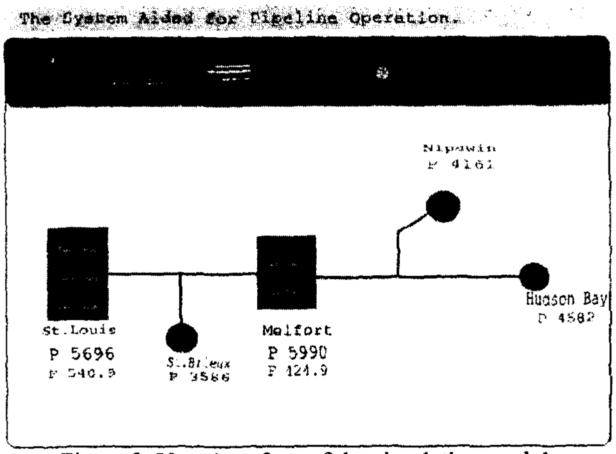

Figure 2. User-interface of the simulation module

2.2 Knowledge Base Module

In natural gas pipeline operations, a dispatcher is responsible for making two vital decisions: (1) increase or decrease compression, and (2) select individual compressor units to turn on/off. These decisions have significant impact on the effectiveness of the natural gas pipeline operation. When natural gas customer demand increases, the dispatcher adds compression to the pipeline system by turning on one or more compressors. If the customer demand for natural gas decreases, the dispatcher turns off one or more compressors to reduce compression in the pipeline system. Incorrect decisions made by the dispatcher will cause substantial economic loss. However, natural gas pipeline operations involve complicated decision making processes and often the dispatcher is required to make the most appropriate decision quickly. The gas dispatcher makes operating decisions to balance supply and demand in the gas pipelines. The operating data is supported by the simulation results provided by the graphical user-interface of the simulation module. The decision making process of pipeline operations is difficult when conditions of the pipeline system, particularly consumption rate from different types of customers, change without forewarning. The types of customers were classified into three groups, industrial, dehydrator, and heat sensitive customers. Each type of customer exhibits a different pattern of natural gas consumption as depicted in figure 3.

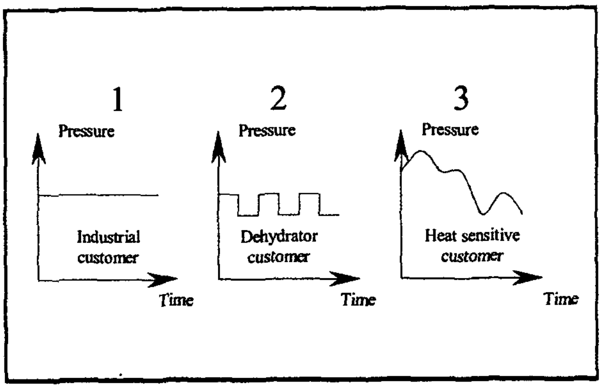

Figure 3. Types of customers

As a result of a change in consumption rate, other system properties such as inline pressure and volume of gas also dynamically vary depending on the seasons. Decision on how to operate the pipeline system under different system states and how to maintain operation efficiency of the pipeline are based solely on the dispatcher's experience. Some mistakes caused by operations can damage the entire pipeline system. Hence expertise from senior dispatchers who have operated the system for several years is important.

A knowledge base module was constructed as a decision support tool to aid the dispatcher in determining whether the current line pack level, volume of natural gas in the pipeline, could meet future customer demand for natural gas. The purpose of the knowledge base module is to inform the dispatcher whether compression should be added or reduced in a pipeline system and the horsepower requirement needed to produce the natural gas to satisfy customer demand. The demand of natural gas of the three types of customers is combined to become the demand curve. The graphs of demand versus supply are presented in figure 4.

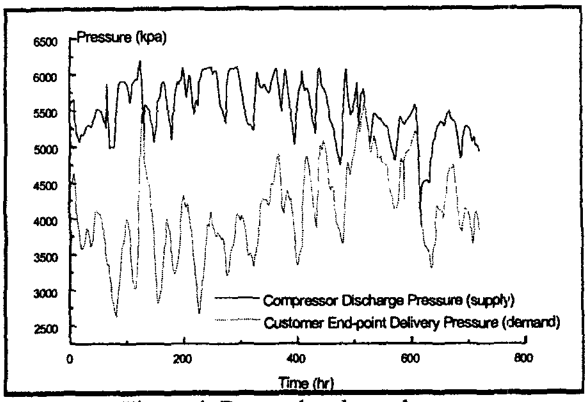

Figure 4. Demand and supply curves

These two curves indicate the relationship between demand and supply and the gap between the curves is called the comfort zone (CZ). An ideal operation means a small comfort zone (CZ) and minimal fluctuation of the pressure curves. CZ is the safety factor that a dispatcher uses. Each dispatcher has his/her preferred CZ, which varies with time. I the CZ is large, then customer satisfaction is guaranteed but fuel cost is high. On the other hand, if the gap is narrow, the operation is cost effective but future customer demand may not be satisfied. The optimal operation is reflected by a graph that has a narrow gap in which the curves do not overlap. In practice, each operator performs his/her task in a different manner, and a more experienced dispatcher is better able to close the gap while satisfying customer demand.

The operator issues the appropriate action for different types of changes. For instance, if the pressure is falling or customer demand is increasing, the operator needs to quickly turn the compressor on, otherwise the demand cannot be satisfied. On the other hand, if the pressure is rising or customer demand is decreasing, the operator needs to shutdown the compressor. A novice operator typically tends to turn on/off a compressor too early or too late. An experienced operator has good understanding of the relationship of the customer demand curves and the other process systems. In addition, each dispatcher should ideally operate the system with minimal fluctuation. A lower level of fluctuation in the pressure curves reflects a smoother operation. Excessive fluctuation causes unnecessary operating costs and maintenance costs. The more experienced dispatcher is better able to satisfy customer demand with smaller CZ and lower fluctuation than the inexperienced dispatchers. It usually takes four months to train a dispatcher to operate a natural gas pipeline system, but it take s a number of years for the dispatcher to become an expert operator who can operate the system smoothly and cost effectively.

Knowledge base module helps to document the operating knowledge of key senior dispatchers and engineers. The natural gas pipeline experts identified key variables in the control of pipeline operations including the conditional variables of change of pressure at the end-points, rate of change of pressure at the end-point, in-line flow, current line pack level, and the decision variable of state of the line pack. The key consideration in pipeline operations is line pack as a measure of the value of the comfort zone. Linepack is defined as the volume of natural gas between the compressor discharge pressure and the customer end-point delivery pressure. Line pack can be calculated for each pipeline subsection using the equation 18.

$$LP = \left[(Pave + 101.325) \times 27.72 - \frac{(0.000013265 \times Pave + 0.9973)^2}{1000} \right] \quad (18)$$

where *LP* stands for line pack, P_{ave} for average pressure

Since the operations personnel agreed that values of line pack and the change of end point pressure were critical for controlling natural gas pipeline network system, the system regards these values based on the relationships among them and notifies user if the natural gas in the system is not sufficient for the demand. Also, the information on compressor operations can be obtained using the equation 19.

BHP requirement = 2.77411 × (Upstream flow + Downstream flow) + 1132 *(19)*

3. Conclusions

This simulation design decision support system can generate sample operations of the pipeline system with different patterns and configurations, and can be used as a training tool for the dispatcher. Using simulation module coupled with knowledge base module provides more accurate operating information to the operator. This system is under development and can serve as a decision support tool for configuration or design of natural gas pipeline systems. The mathematic equations of fluid dynamic and the historical data were used to calculate natural gas properties and analyze consumption rate of the natural gas, respectively. Also, the user could access and run this model on the World Wide Web.

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