Technology Status Assessment Report:

Virtual Pipeline System Testbed to Optimize the U.S. Natural Gas Transmission Pipeline System

Prepared for
The Department of Energy
Strategic Center for Natural Gas

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1.0 Introduction

Arguably, the natural gas transmission pipeline infrastructure in the U.S. represents one of the largest and most complex mechanical systems in the world. This system delivers about 0.623 tcm (22 tcf) of natural gas per year, and is made up of over 4.828×10^5 km (300,000 miles) of pipe driven by 8,000 engines and 1,000 gas turbines with 2.983×10^5 MW (40 million horsepower) of compression capacity. The system produces over 1.86×10^9 MW-hrs (250 billion hp-hrs) of compression power every year. This system has been developed over the last 60 years, and is controlled at a very low level of sophistication.

Figure 1 illustrates a section of a pipeline system. The natural gas enters the pipeline from a supply source, and then is transported to one or more delivery points. The pressure in the pipeline is on the order of 800 psia and the pipeline pipe is on the order of two to four feet in diameter. Compressor stations are located about every 60 miles along the pipeline. The compressor stations are necessary to overcome the gas pressure drop in the pipe. The compressor stations house the engines, gas turbines, and compressors.

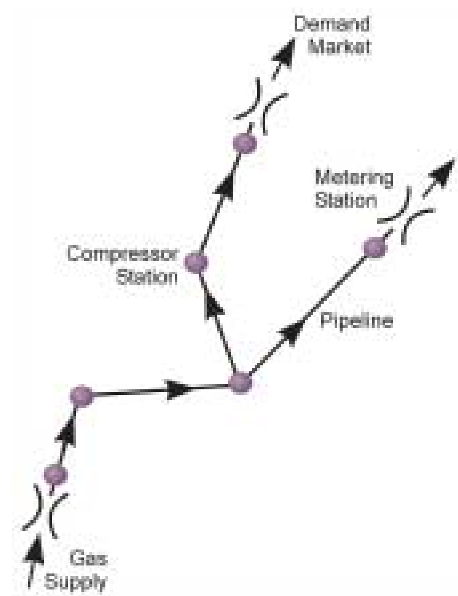

Figure 1. Illustration of a pipeline system.

2.0 Review of pipeline modeling techniques

This report reviews the existing technologies that are used to simulate the performance and operation of the various components that collectively make up the natural gas pipeline system.

Tian and Adewumi (1994) used a one-dimensional compressible fluid flow equation to determine the flow of natural gas through a pipeline system. This equation provides a functional relationship between the gas flow rates; and the inlet and outlet pressure of a given section of pipe that then describes steady state compressible flow of gas. Tain and Adewumi (1994) coupled the compressible flow equation with the conservation of energy equation to determine the fluid flow friction factor.

Costa *et al*. (1998) provided a steady–state gas pipeline simulation. In this simulation, the pipeline and compressors are selected as the building elements of a compressible flow network. The model of a pipeline again uses the one-dimensional compressible flow equation to describe the relationship between the pressure and temperature along the pipe, and the flow rate through the pipe. The flow equation and the conservation of energy equation solved in coupled fashion to investigate the differences between the isothermal, adiabatic and polytropic flow conditions. The compressors are modeled by simply employing a functional relationship between the pressure increase and the mass flow rate of gas through the compressor.

Sung *et al*. (1998) presented a hybrid network model (HY-PIPENET) that uses a minimum cost spanning tree. In this simulation, a parametric study was performed to understand the role of each individual parameter such as the source pressure, flow rate and pipeline diameter on the optimized network. The authors found that there is an optimal relationship between pipe diameter and the source pressure.

Rios-Mercado *et al.*(2001) presented a reduction technique for natural gas transmission network optimization problems. This results are presented for steady-state compressible flow through a network pipeline. The decision variables are the mass flow rate through each arc (pipeline segment), and the gas pressure level at each pipeline node.

Martinez-Romero *et al.*(2002) described steady-state compressible flow through a pipeline. They presented a sensibility analysis for the most important flow equations defining the key parameters in the optimization process. They used the software package "Gas Net," which is based in Stoner's method with improvements for solving the system of equations. The basic mathematical model assumed a gas network with two elements: nodes and nodes connectors. The connectors represent elements with a different pressure at the inlet and outlet, such as the pipeline, compressors, valves and regulators.

Doonan *et al.*(1998) used Simulink™ to simulate a pipeline system. The simulation was used to investigate the safety parameters of an alternative control a considerable distance down stream from the main pressure regulating station. The elements used in this model were very limited. Simulink™ is very limited in the knowledge provided about pipeline operation and reliability. The main limitation for Simulink™ is steady-state analysis.

Sun *et al.*(1999) discussed the a software support system, called the Gas Pipeline Operation Advisor (GPOA). The GPOA aids the dispatcher in optimizing natural gas pipeline operations in order to satisfy customer demand with minimal operating costs. The GPOA has been used both as an expert system and in operations research. The objective of the model is to minimize the overall operating costs, subject to a set of constraints such as the horsepower requirement, availability of individual compressors, types of compressor and the cycling of each compressor.

Santose (1997) discussed the importance of a transient simulation and the advantages of using transient simulation. He notes that transient simulation is not only an excellent tool for training operations personal, but it can also act as a helpful tool in on-line systems. He also emphasizes its use in the design phase of a gas pipeline. This paper focuses on a single line gas pipeline without storage facilities and with a flow demand that varies with respect to time in an hourly basis so as to show a behavior that could not be considered as a steady-state flow.

Mohitpour *et al.*(1996) presented the importance of a dynamic simulation on the design and optimization of pipeline transmission systems. In this paper, the authors explain that steady-state simulations are sufficient for optimizing a pipeline when supply/demand scenarios are relatively stable. And in general, steady-state simulations will provide the designer with a reasonable level of confidence when the system is not subject to radical changes in mass flow rates on operating conditions. In reality, the mass flow rate changes, hence the most useful and generic simulation must allow transient behavior.

Glenn *et al.*(1996) presented a method to determine the effective friction factor and overall heat transfer flow conditions in the pipeline. This transient flow model was based on a numerical solution of the one–dimensional; unsteady flow equations (continuity, momentum and energy), which were discredited using a highly accurate compact finite difference scheme. Glenn et al. (1996) simulated the pipeline in transient mode without considering the effects of turbulent flow.

Osiadacz (1994) described the dynamic optimization of high-pressure gas networks using hierarchical system theory. The authors explain that the transient optimization is more difficult mathematically than the steady state simulation, but the reward of using a dynamic simulation is that the operator can achieve higher savings. They further explain that it is of great importance to be able to optimize large-scale systems described by partial differential equations as fast as possible in order to achieve real time optimization.

Osiadacz (1996) compared a variety of transient pipeline models. Numerical solution of the partial differential equations, which characterize a dynamic model of the network, requires significant computational resources. The problem is to find, for a given mathematical model of a pipeline, a numerical method that meets the criteria of accuracy and relatively small computation time. The main goal of this paper is to characterize different transient models and existing numerical techniques to solve the transient equations.

Osiadacz (1998) compared isothermal and non-isothermal transient models for gas pipelines. Adiabatic flow relates to fast dynamic changes in the gas. In this case, heat conduction effects cannot be neglected. Isothermal flow relates to slow dynamic changes. Changes of temperature within the gas due to heat conduction between the pipe and the soil are sufficiently slow to be neglected.

Lewandowski (1994) presented an application of an object-oriented methodology for modeling a natural gas transmission network. This methodology has been implemented using a library of C^{++} classes for structured modeling and sensitivity analysis of dynamical systems. The model of a gas pipeline network can be formulated as a directed graph. Each arc of this graph represents a pipeline segment and has associated with it a partial differential equation describing the gas flow through this segment. Nodes of the graph corresponding to the nodes of the gas pipeline network can be classified as: source nodes, sink nodes, passive nodes and active nodes.

Zhou and Adewumi (1995) presented a "new" method for solving one dimensional transient natural gas flow in a horizontal pipeline without neglecting any terms in the conservation of momentum equation. In simulating transient flow of single-phase natural gas in pipelines, most of the previous investigators neglected the inertia term in the momentum equation. This renders the resulting set of partial differential equations linear. Numerical methods previously used to solve this system of partial differential equations include the method of characteristics and a variety of explicit and implicit finite difference schemes. Neglecting the inertia term in the momentum equation will definitely result in a loss of accuracy of the simulation results.

Cameron (1999) presented TFlow using an Excel-based model for steady state and transient simulation. TFlow comprises a user interface written in Microsoft Excel's Visual Basic for Applications (VBA) and a dynamic linked library (DLL) written in C^{++}. All information needed to model a pipeline system is contained in an Excel workbook, which also displays the simulation result. The robustness for general applications, however, is not readily apparent.

3.0 Conclusions

The primary conclusion from the literature review is that there has been and continue to be significant effort focused on the compressible flow of natural gas through the pipeline. Historically, this effort has been focused on steady-state flow conditions and only recently have researchers identified the need for transient flow simulations. At least two references were found that state the need for the development of robust dynamic simulations.

The second significant conclusion is that very little has been done to advance the state-of-the-art of the simulation of compressor station components. For example, most references model the compressor station as a black box where the input pressure is increased by some percentage to determine the compressor station output pressure. Even when engines and compressors are included within the simulation, the models require the user to input an engine load line or the compressor load line. Few if any simulations offer the ability to incorporate a complete engine or compressor load map, an no references were found that focus on the fuel consumption and pollutant emissions of the compressor station.

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