Chapter 1

Introduction

Natural gas is one of the most widely used sources of energy in Europe. The whole supply chain of natural gas, from the gas well through several kinds of elements to final customers, creates an integrated and closed network system. With the increasing gas demand in Europe, natural gas pipeline systems become more and more complex as years pass. To ensure safe and reliable gas transmission to customers, optimal design and efficient operation of natural gas network is one of the key factors. Gas network simulation is a good solution which allows predicting the behaviors of gas network under different conditions by defining the mathematical model of the gas transport and distribution systems. Such predictions can be effectively used to guide decisions regarding the design and operation of the real system. At the stage of designing a gas pipeline, simulation helps the experts to plan the structure of the network, as well as the technical parameters of the pipes in the case of given parameters of gas supply and demand. Simulation also facilitates the selection of sites where no-pipe elements (for example: compressor stations) should be installed. The operation and control of a gas system also require simulation in order to predict or obtain information about the working conditions (pressures or flow rates etc.) at given points within the network. Considering the complexity of today's gas network, computer simulation tools are state of the art as far as network develops and efficient operation is concerned.

1.1 Background

Both the market and the infrastructure sides of the European natural gas supply are currently undergoing substantial changes. First, because of the relatively low carbon dioxide emissions in the context of growing climate concerns and political climate measures, the natural gas demand in Europe is forecasted to increase in the future. Second, indigenous production can only partly satisfy the European gas demand which means the rising of import dependency and the investment in gas transport and storage infrastructures. Third, a progressive liberalization of the natural gas industry has been pushed by the European Union from years past. In this process, ownership unbundling, free third party access to gas transport and storage infrastructures and some other principles lead to more players involved into the natural gas business have been introduced / are introducing into the structure. [1]

At present Europe, especially in Germany, the national natural gas transmission systems, regional grids and connected facilities like underground storages, are owned and operated by independent companies. Nonetheless all the infrastructures have to build up an integrated logistics system, to connect producers in and outside Europe with the customers. This is of course only possible by the cooperation and interaction of all major individual infrastructure elements and their operators.

However, each individual system is currently simulated by its owner, assuming certain fixed boundary conditions at interconnection points with other operators. In many cases, physical conditions at such interconnection points are legally regulated especially as far as intrastate regulation is concerned. But such official regulations are currently still rather rudimentary, and bilateral coupling agreements between transmission operators on both border sides are voluntary and generally not published. There exists obvious inaccuracy of simulation between the fixed assumed conditions at interacting points and the real physical conditions there, which certainly creates error during simulation processes. Therefore the real transmission capacities for each transmission system operator (TSO) and also for entire German or European grid are anything but transparent.

1.2 Motivations

Under such background, the establishment of an overall hydraulic model for pan-Germany & Europe is significant, which would provide higher simulation accuracy and show the real gas flow patterns from a national or European level, because the current individual network models are integrated into one and the fixed boundary

[1] The liberalization is still in progress with different levels in different European countries. Cf. chapter 3, paragraph 2. [1]

conditions inside are eliminated. The legal framework of liberalization of the energy markets in Europe requires all network operators to publish the booked and free gas flow capacities at entry and exit points of their systems. This enables gas transport experts to gather required information about supply and demand data and combine with the knowledge about the transportation network infrastructures to simulate the overall gas flow.

This PhD research topic is an investigation on the methodology of simulation and capacity calculation in real German and European interconnected gas transport systems. The major motivations of this research can be summarized into four aspects:

- Methodology of modeling a complex gas grid
- Methodology of developing simulation scenarios for such complex system with consideration of various gas demand behaviors
- Methodology of capacity calculation
- Case studies and evaluations with the overall model

The model is simulated in steady state flow conditions because it will generate acceptable results in most cases to define the overall maximum or free network capacity of a complex gas transport system. The finished model is supposed to accomplish the following purposes:

- Presenting condition of national TSOs
- Consequences and requirements in the legal and regulation framework
- Support of pan-German and European transport optimization
- Indicate the infrastructure investments

It is obvious that the model is definitely significant for both TSOs and national regulators in optimizing and coordinating the transport capacity and operation activities.

1.3 Workflow

The model (named as ITE-GS model) developed by this investigation is a simulation tool to model the hydraulic gas flow, calculate the physical transport capacity of the grid and furthermore analyze the future network development plans. The model currently focuses on the gas transmission grid in Germany and will be extended to a European scale in future. It is developed with different gas network simulation tools and for Germany's H-gas and L-gas (high or low calorific value natural gas) systems respectively. The model is able to simulate the major gas transmission network in Germany from a hydraulic aspect. Following Figure 1.1 gives an overview of the main inputs and outputs of the model.

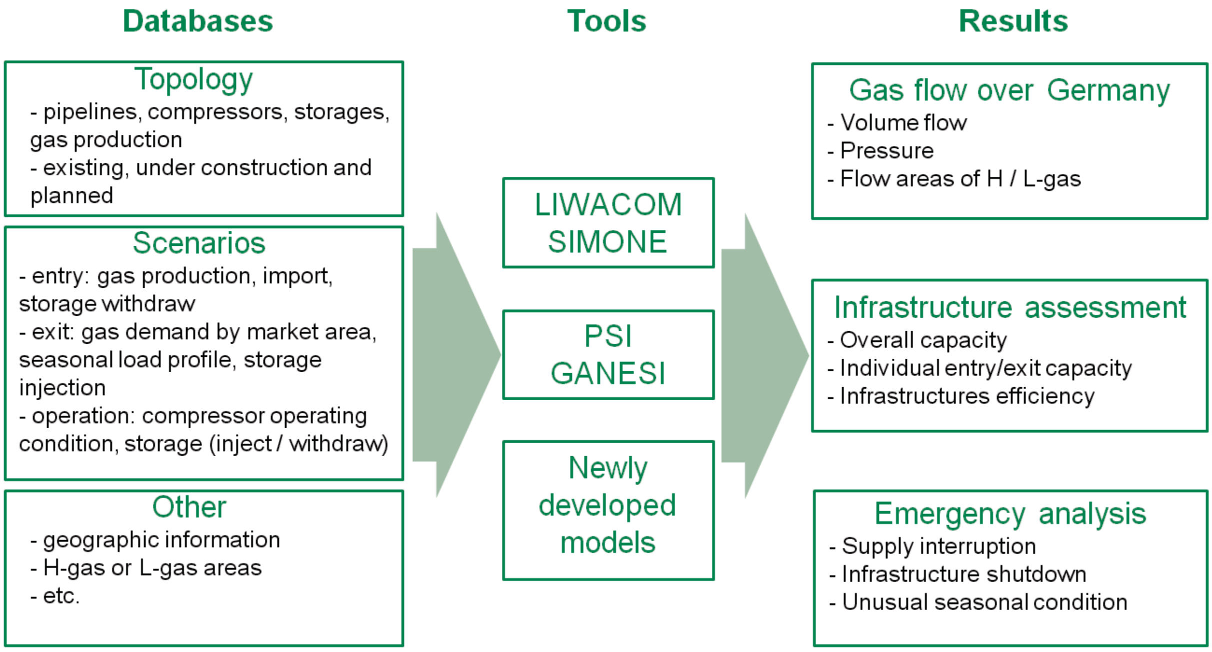

Figure 1.1: Overview over modeling workflow and results

The inputs for the model are depicted in above figure (left hand side) and can broadly be categorized into several databases from different aspects of objective topology and simulation boundary conditions. The collection of relative information and the establishment of different databases is one of the most challenging tasks during the modeling work. In subsequent chapters of this thesis, the author will illustrate the method to create such databases and introduce the relative data sources. Because of lack of the technical parameters of infrastructures, some technical, reasonable estimations or assumptions are unavoidably introduced into the investigation. The author will also expound the ideas behind them in future chapters.

Both most widely used simulation tools (LIWACOM SIMONE and PSI Ganesi [2]) in European gas pipeline transport & distribution industries are currently applied for the

[2] For the details of these two software, please see their websites. [2] [3]

investigation as the modeling platforms. The ITE-GS also considers developing other mathematical models in the future which provides the possibilities to integrate the hydraulic simulation with overall simulations from other aspects. Some examples include economics or policy.

The results of such overall simulations allow deriving an overall picture of gas flows over the whole country or countries which shows the situations of different TSOs. And with the developed methodology of capacity calculation, the delivery capability of the network and other infrastructures can be evaluated. In addition, different special cases can be also analyzed to assess the transport capacity and supply security of the national gas grid under emergency / newly developed situations.

Considering the complexity during establishment of such models, it is necessary to approach the final model progressively. The study therefore starts with a simplified German transmission network and focuses on the H-gas system firstly and the developed methodology which will be utilized when extending the model to the entire European level. In this thesis, the author will chiefly introduce the simulations with the German H-gas model as an example.

The following gives a short presentation of the structure of following chapters in this thesis:

Chapter 2 reviews the current literatures on the fundamentals of gas simulation, introduces several existing overall models for the European gas market and infrastructure analysis. This chapter also explains how this PhD investigation utilizes these available studies as a reference and points out the extensions to current literature.

Chapter 3 gives an overview on the methodology of the modeling and simulation work. The author summarizes in this chapter the common challenges for such overall simulation and introduces the various approaches developed corresponding to different working packages.

Chapter 4 describes the methodology of creating the network topology in the SIMONE tool, explains the study scope and data sources of the current investigation, and elaborates the simplifications and assumptions principles for the network modeling.

Chapter 5 depicts the methodology of developing the simulation scenarios for the model. It focuses on the allocation of gas flow from the national level to the individual points and the calculation method to convert the yearly gas flow to hourly ones. This chapter also explains the definitions of the three basic seasonal cases and their applications for further case studies.

Chapter 6 illustrates the methodology of capacity calculation applied in this investigation and explains the calculations for individual point and overall network respectively.

Chapter 7 introduces several case studies by using the existing model which includes evaluations of newly developed infrastructures, supply emergency and the “energy transformation” subjects taking place in Germany and Europe.

Chapter 8 is the summary of complete work which consist main results, imperfections of current model and the possible further improvements.

Chapter 2

Literatures review

2.1 Fundamentals of gas simulation

As one of the key elements when studying the gas supply systems, the transport and distribution pipeline networks are investigated and discussed in order to better mirror the gas flow behaviors in such complex systems. Optimum development of such complex pipeline network system, as well as its economically rational exploitation, is only possible by applying simulation procedures. The simulation is generally based on a mathematical approach to the numerical simulation of complicated pipeline systems using well-known basic models of continuum mechanics, numerical methods of mechanics and hybrid methods of mathematical optimizations. Use of a computer during this analysis is necessary, in view of the complexity of the problem (formulation of the equations, dimension of the problem and complexity of the model).

The homepage of Pipeline Simulation Interest Group (PSIG) (2010) [4] gives a comprehensive overview on modeling, simulation and optimization of natural gas flows. And the PSI AG (2011) [5] summarized the general assumptions, basic conservation equations and the common procedures in gas simulations.

Furthermore, depending on the characters of gas flow in the system, the simulation can be distinguished into steady and unsteady states. The steady states in gas networks are described by systems of algebraic equations (in general non-linear) which are relatively simple to deal with and are far easier to understand. Steady state simulation software refers to software that does a single simulation for a single instant in time with all elements assumed to be at constant flow conditions at that instant. These simplifying assumptions of steady state analysis software do not allow for any time factors or variations to enter into the simulation.

In some cases, however, the dynamics of the flow cannot be neglected when a pipeline system is subject to significant changes in flow rate, pressure conditions, or prime mover availability over the course of time; it is then necessary to move beyond the simplifying assumptions of steady state flow simulation to use a dynamic model which leads to simulation which is computationally much more complicated. A transient model simulates real-world conditions found in the system that vary with time, such as: load profiling by varying the flow rate according to normal diurnal swings in usage patterns; tracking pressure changes caused by the opening and closing of valves, especially on liquid pipeline systems; or optimizing power costs by starting and stopping pumps or compressors at certain times of day to take advantage of lower energy rates.

A.J. Osiadacz (1987) [6] summarized the mathematical approaches in gas network modeling. In the book, he firstly introduced the fundamentals of fluid mechanics and thermodynamics for pipe and non-pipe elements in gas networks respectively, in addition with the detailed explanation of the fundamentals of arbitrary topology network. A.J. Osiadacz deals later in his book with mathematical models used for the simulation of networks in the steady and unsteady states respectively.

For steady gas flows, the fundamental equation was derived based on Bernoulli's equation and the loop and node modes were formulated with the help of Kirchhoff's laws. In the monograph, A.J. Osiadacz presented common uses of these equations in practice. In mathematical terms the steady-state simulation problem of gas networks consisted of solving a given system of non-linear equations. The Newton multi-dimensional method was therefore applied for this purpose. It required the solution of a system of linear algebraic equations in every iteration step, which, in the case of gas networks, had a sparse coefficient matrix. The analysis of the Newton method, characteristics of selected methods of solving systems of linear algebraic equations with sparse matrices were given in this book. A.J. Osiadacz also discussed the methods and algorithms for simulating steady-state gas networks, both simple ones (consisting of adequately connected pipes) and composite ones including non-pipe elements, in his book, including examples of computations illustrating the operation of the discussed algorithms.

Furthermore for the unsteady state networks, A.J. Osiadacz discussed mathematical models [3] describing unsteady gas flow in the network and moreover the necessary

[3] Accurate model and simplified model respectively.

information on means of partial differential equations which were commonly used to describe the unsteady states in a pipe. The numerical methods of solving partial differential equations were further explained and the algorithms were illustrated through solving concrete equations and examples of computation describing unsteady gas flow in networks.

R.I.Il'kaev & V.E.Seleznev et al. (2005) [7] also deal with the description of the numerical simulation of pipeline systems in their monograph from the theory, computational implementation, and industrial applications aspects. The book firstly presented the principles of construction or selection of the corresponding mathematical models and methods for gas simulation. It introduced the methods and technologies for the development and application of high-accuracy computational fluid dynamics simulators for numerical analysis of gas transportation modes through long branched pipeline systems during their normal operation and in emergency situations. Furthermore, the book investigated the technology of numerical simulation of damage factors acting during the failure of high pressure pipelines and the theoretical footing and background of the industrial application of high-accuracy computational fluid dynamics simulators for cutting costs associated with the transportation of gases and fluids through extensive pipeline networks.

In addition, there were a large number of published articles with a technical approach to gas transportation from a steady state point of view. P. O'Neill et al. (1979) [8] presented a steady state model of gas flow which was presented for allocating natural gas. Also in D. De Wolf & Y. Smeers (2000) [9], a steady state model for optimizing gas flow through a network, with cost minimization was illustrated. In addition, the models could be detailed and accurate in their description of the physics of gas transportation, such as transient flow and interaction with transport facilities like compressors. A discussion of transient flows to optimize fuel consumption and contract utilization for any types of gas network and operating conditions was given in C. Kelling et al. (2000) [10]. M. Nowak & M. Westphalen (2003) [11] presented a linear model for transient flow modeling. K. Ehrhardt & M. Steinbach (2005) [12] presented a model for operational planning in natural gas networks. The transient flow model was used in the article to control the network load distribution for the next 24 to 48 hours. A. Martin et al. (2006) [13] introduced a model to optimize flow in a network, and minimize the costs of the compressors in the network. The model gave a detailed representation of the physical properties of natural gas transportation, and offered linearization techniques for the nonlinearities in the model.

2.2 Existing overall models

Numerical modeling is one way to quantitatively analyze gas market, next to theoretical modeling and econometric studies. At present, there are several different overall models simulating natural gas industry in Europe for different purposes. In this section the author gives an introduction to the literatures on different aspects of the five well-known simulation models for European gas systems, and in addition indicates in the next section where this thesis extends the existing literatures. In the following table, the author summarizes the investigated models and the relative literatures. [4]

Table 2.1: Investigated literatures about European gas models

Models	Investigated literatures
NATGAS	- G. Zwart and M. Mulder; NATGAS, A model of the European natural gas market; CPB Memorendum; 24 February 2006. [14]
GASMOD	- F. Holz, C. von Hirschhausen and C. Kemfert; A strategic model of European gas supply (GASMOD); Energy Economics, 2007. [1] - F. Holz, C. von Hirschhausen and C. Kemfert; A strategic model of European gas supply (GASMOD); Discussion Papers 551, DIW TU-Berlin, Jan 2006. [15]
GASTALE	- M.G. Boots, F.A.M. Rijkers and B.F. Hobbs; Trading in the downstream European gas market: A successive oligopoly approach; Energy Journal, 25(3), 74-102, 2004. [16] - W. Lise, B. F. Hobbs, and F. v. Oostvoorn; Security of supply in the liberalized European gas market, simulation results with the dynamic GASTALE model. In European Energy in Transition; 7th IAEE Europe Energy Conference Proceedings, 2005. [17] - W. Lise and G. Kruseman; Long-term price and environmental effects in a liberalized electricity market; Energy Economics, 30(2):230-248, 2008. [18]

[4] The review and summary in later sections of this chapter are all based on these literatures.