Uncertainty Evaluation for Quality Tracking in Natural Gas Grids

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Abstract. *Simulation tools are in used to manage the grids by allowing the reconstruction of the state of the grid (flows and pressures). This allows tracking of the gas properties while the gas is transported by the grid. In practice often only rough estimates of the momentary consumption by the end users are available creating uncertainty about the value calculated from the reconstruction of the state and therefore in the tracking of the transported gas properties. We present an approach based on the Guide to the Expression of Uncertainty in Measurement (GUM) Supplement 1 to evaluate the uncertainty involved with the state reconstruction and property tracking. In future, gas grids will transport gasses with a wider range of calorific values at the same time which complicates the correct billing of the delivered energy. We show how the uncertainty involved with the state reconstruction and the property tracking can be used to monitor the validity of a quality tracking system for natural gas grids.*

Keywords: Natural Gas Grids, Uncertainty Evaluation, Monte Carlo Simulation

1. Introduction

Natural gas grids are an important infrastructure in Germany since a significant fraction (about 30%, 2005) of the energy consummated today is generated using natural gas. Distributed natural gas grids can transport and store significant amounts of energy equivalents. Therefore gas grids will play an important role in solving problems with the energy supply in future by complementing the electrical grids.

In Germany, natural gas from 8 major origins is distributed through the transport grids. The composition of the gas is mainly dependent on its origin and for some sources it also has some time dependency. Table 1 lists the major natural gas sources for Germany together with some important properties. The calorific value is varying between 10.6 kWh/m^3 and 12.9 kWh/m^3. The maximal variability is about 20 %. The CO_2 fraction varies between 0 % for liquefied natural gas (LNG) and 2.9 % for bio-gas.

Table 1. Summary of natural gas sources for Germany with their main properties [1].

		Russia	**North Sea**	**Denmar k**	**Libya LNG**	**Nigeria LNG**	**Egypt LNG**	**Bio-gas**	**Bio-gas + LPG**
Calorific value	kWh/m^3	11.2	11.6	12.1	12.9	12.2	11.3	10.6	11.6
Difference to ref. 11.6		-3.4 %	0	+4.3 %	+11.2 %	+5.2 %	-2.6 %	-8.6 %	0
CO_2	Mol %	0.18	1.94	0.60				2.90	2.68

The most important property of natural gas is its calorific value. For industrial users the CO_2 content is important, too because it might affect their CO_2 balance.

The calorific value of natural gas can be measured with standard calorimeters or gas chromatography. But measuring equipment is expensive to install and to operate. Therefore in

Germany most transport grids are equipped with gas quality tracking systems since several decades.

Transport grids have a structure with a few input and output nodes all equipped with flow meters and long distance pipelines connecting them. Their nominal pressures are between 70 and 100 bar. Reliable quality tracking is relatively easy for transport grids.

Recent liberalisations in the market for natural gas and the introduction of bio-gas have lead to increased variability of the natural gas quality in the distribution grids. Distribution grids are operated with a nominal pressure between 10 bar and 25 bar. They are connecting the customers to the transport grids. Distribution grids have usually an intermeshed structure with several connections to different transport grids. The measurement infrastructure is often incomplete so that some output flows cannot be measured. Quality tracking for distribution grids is therefore challenging. But the concepts of uncertainty in measurement introduced by the Guide to the Expression of Uncertainty in Measurement (GUM) [2] and especially its Supplement 1 [3] can be used to manage the challenge.

2. Tracking Gas Qualities in Distribution Grid for Natural Gas

Quality tracking systems for transport grids and distribution grids can be decomposed in two parts (Fig. 1). The reconstruction of state calculates the internal (not measured) flow rates and pressures based on the grid topology and the measured input and output flows, the grid pressure and the temperature. A gas transport model evaluates the gas quality of the output flows based on the internal flows and the gas qualities of the input flows.

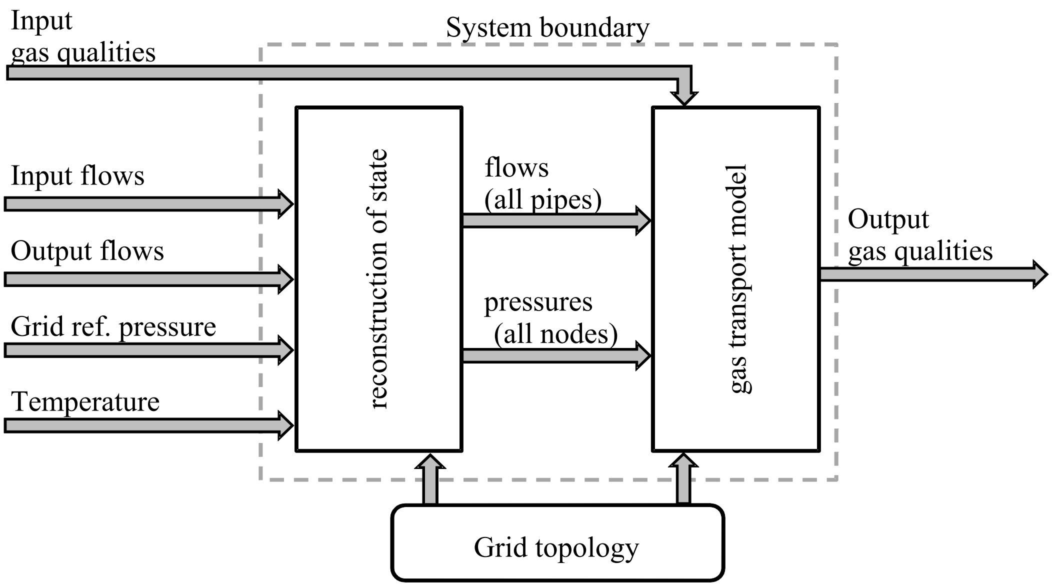

Fig. 1. Structure of the flow of information in a gas quality tracking system.

The reconstruction of state and the gas transport model are realized by complex software systems involving heavy numerical calculations and the solution of a system of differential equations. For the evaluation of uncertainty the calculations inside the reconstruction of state and the gas transport model can be treated as a black box.

3. Model of Evaluation

The reconstruction of state and the gas transport model are treated as the model function or model of evaluation. Input gas quality, input flows, output flows, grid pressure, temperature and output gas qualities are time series data. Every point in the time series is an individual input or output quantity. The time resolution should be one value per hour or better and the evaluation period is usually one month or more. This results in a system of a very large number of input and output quantities. For our studies we have used the small distribution grid simulation developed at the TU Clausthal [4]. The topology of the distribution grid is shown in Fig. 2. It is a small grid with 4 input nodes (K000, K002, K004 and K006), 25 output nodes and the time resolution is 12 min, but the model for the uncertainty evaluation has about 30000 input quantities and about 20000 result quantities.

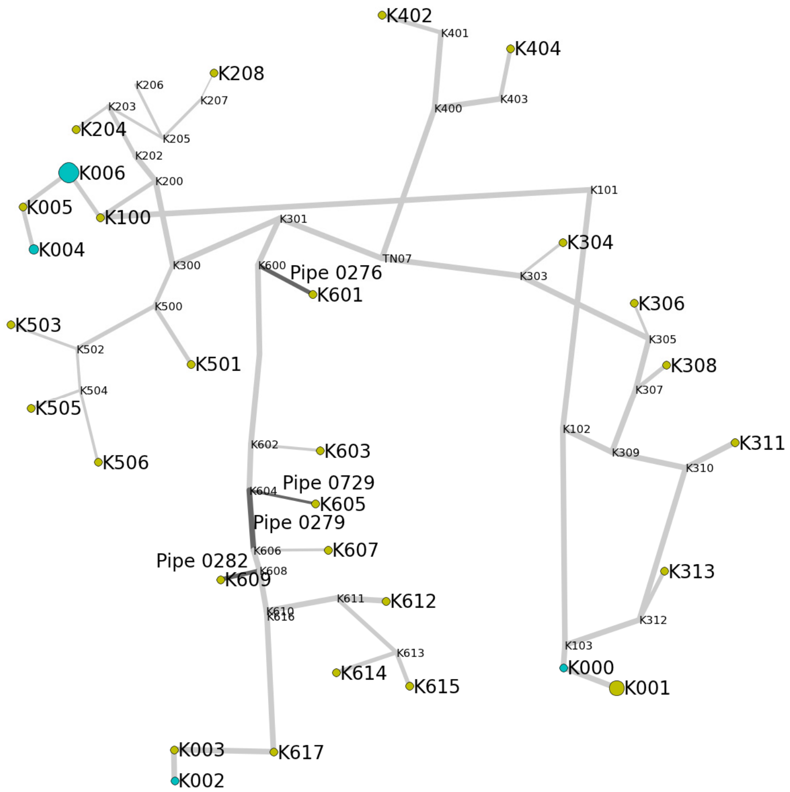

Fig. 2. Topology of the grid under investigation with 4 input node (K000, K002, K004 and K006) and 25 output nodes.

Table 2. Secification of the knowledge about the input quantities for the uncertainty evaluation.

Input quantity		Knowledge	Distribution
Calorific value of the gas sources		≤ 1 %	normal
Source (input) flow rate		≤ 2 %	rectangular
Drain (output) flow rate	online	≤ 2 %	rectangular
	load profile	30 %	normal
Grid reference pressure		≤ 5 %	rectangular
Temperature		0 °C – 15 °C	rectangular
Grid topology	length of pipes	≤ 10 %	rectangular
	diameter	≤ 5 %	rectangular
	roughness	≤ 50 %	rectangular

The available knowledge about the input quantities is summarized in Table 2. It should be noted that the output flow rates for 15 nodes out of the 25 nodes are actually not measured but estimated based on load profiles representing the typical customer consumption. This leads to the relative large uncertainties for these flow rates of 30 %. The specified knowledge in Table 2 represents the typical accuracy with which data can be made available for distribution grids.

4. Uncertainty Calculation

For the uncertainty calculation we have chosen the Monte Carlo (MC) simulation as described in GUM Supplement 1. Even if an evaluation model of this size would be semi-linear it is a huge effort to propagate all variances. The numerical calculation of the sensitivity coefficients would require at least 30000 complete calculations of the evaluation model which in this case is very demanding in respect to computational effort. If the number of Monte Carlo trails can be limited then MC is more economic.

With the assumption that the variances of the MC results are converging, the number of MC trails needed to achieve the required relative accuracy r can be calculated [5] using

$$n = \frac{1}{r^2} \times \text{norm}\left(1 - \frac{1-p}{2}\right)^2 \tag{1}$$

where n is the number of MC trails, p is a chosen probability for the accuracy interval and norm() is the quantile of the normal distribution. We choose a relative accuracy for the uncertainty of 5% (r=0.05) with a probability of 95 % (p=0.95) which leads to 1600 MC trails.

For our studies we have developed a Python script which generates for each run a set of random factors with expectation value of 1.0 and distribution based on the specification in Table 2 for all input quantities. For each MC run the original input data is multiplied with a set of factors and the reconstruction of state and the gas transport model are calculated. The uncertainties were calculated from the standard deviation of the results from all runs. Since we could only perform a limited number of MC trails a coverage interval based on spread of results would not be reliable. Therefore we chose a fixed coverage factor of k=2 to arrive at an expanded uncertainty statement which covers a large fraction of possible result values.

5. Monte Carlo Simulation Results

Since we are mainly interested in studying the uncertainties introduced by the limited knowledge about the transport process through the grid, we have treated the calorific values as perfectly known with no uncertainties during our simulations. The uncertainties introduced by the grid transport and the uncertainties associated with the calorific values of the gas sources are uncorrelated and the variances can simply be added to get the combined uncertainty of the calorific values of the output flows.

For the discussion we use simulation results from a period of 160 h while the calorific values of the sources were varying between 10.7 kWh/m^3 and 11.2 kWh/m^3.

In our simulations we found that the uncertainties associated with the reconstruction of the internal flow rates are time dependent and are varying a lot between different pipelines. Some internal flow rates can be reconstructed accurately with an uncertainty better than 2.5 % (see Fig. 3. For many internal flow rates the uncertainty of the reconstruction is about 30 %, but for some flow rates the uncertainty is 300 % and more (e.g. pipeline 0279, Fig. 4). It can be observed that the uncertainties are larger if the flow rates are small in respect to diameter of the pipelines.

Although it is useful to analyse the uncertainties associated with the reconstruction of the internal flow rates, the final quantities of interest are the calorific values and their associated uncertainties. Since the calorific values are only varying by about 5 % during our simulation period, the effect of the limited knowledge of the transport process on the gas transport model calculation can be expected to be significantly smaller than the uncertainty associated with the reconstruction of state.

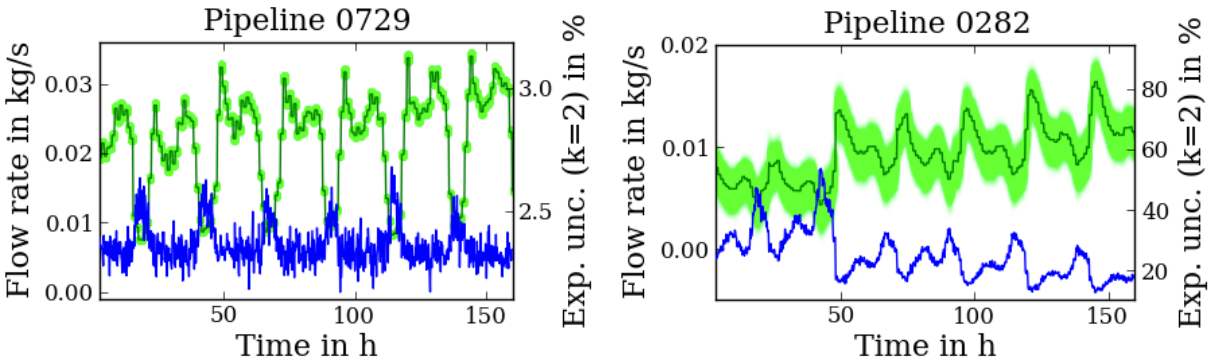

Fig. 3. Simulation results for the flow rate in pipeline 0729 and pipeline 0282. The top graph shows the flow rate and the bottom graph shows the relative expanded uncertainty (k=2).

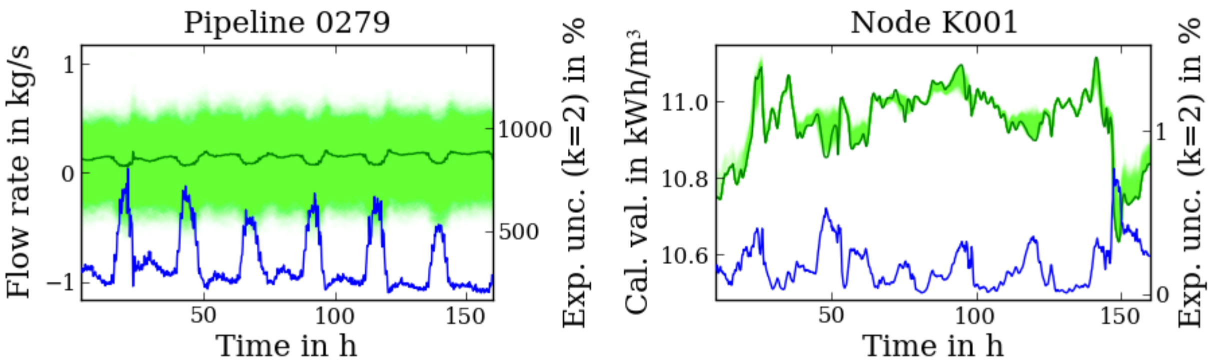

Fig. 4. Simulation results for the flow rate in pipeline 0279 and the calorific value for node K001. The top graph shows the flow rate or the calorific value and the bottom graph shows the relative expanded uncertainty (k=2).

In our study we found that the uncertainties of the calorific values are also time dependent and they are varying between output nodes. Fig. 4 shows the calorific value at node K001 which has the largest consumption during the investigated period. The uncertainty is most of the time well below 0.5% with one peak up to 0.8 %.

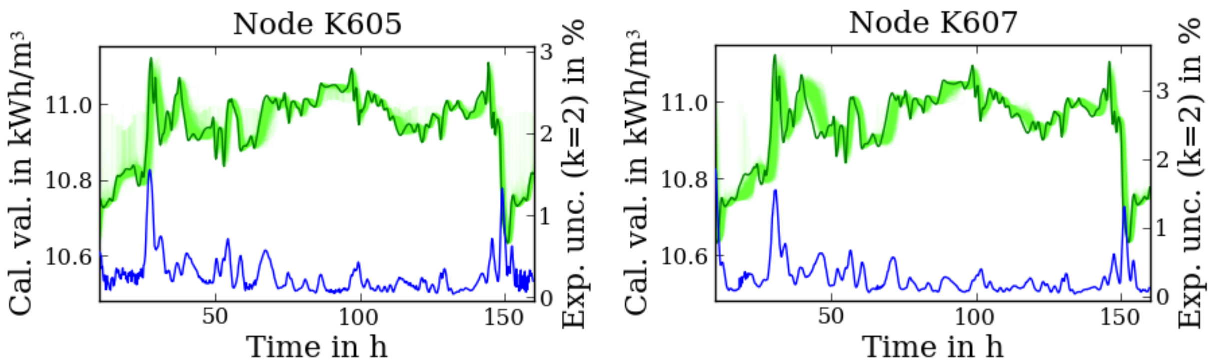

Fig. 5. Simulation results for the calorific value for node K605 and node K607. The top graph shows the calorific value and the bottom graph show the relative expanded uncertainty (k=2).

It can be observed that rapid changes over time of the calorific value are correlated with an increase in the uncertainty of the calorific value. This can be explained by the fact that the reconstruction of the internal grid state is used by the gas transport model to calculate the throughput time of the gas. Uncertainties in the reconstruction of the internal flow rates lead to uncertainties in the calculated throughput time. The effect on the calorific value is therefore dependant on how rapidly the calorific value is changing in time.

Output node K605 and K607 are connected via pipeline 0279 (see Fig. 2). The associated uncertainty with the reconstructed flow for this pipeline is as large as 700 %. As shown in Fig. 5, the calorific value of the nodes can still be reconstructed relatively well with a peak uncertainty of 1.4 %. The uncertainty is 0.5 % or less most of the time. This demonstrates that good quality tracking is possible even if the knowledge about the internal state of the grid is rather limited. As expected the calorific values and the uncertainties for node K605 and K607 are very similar. The signal at K607 is a bit shifted in time since the distance to the major source at K006 is larger.

For billing purposes often an average calorific value for a longer period (1 month or 1 year) is of interest. It is possible to calculate the uncertainty of average value by including the averaging in the model used by the MC calculations.

6. Conclusions

Uncertainty evaluation according to GUM Supplement 1 is a useful addition to quality tracking systems for natural gas grids. Especially for distribution grids where some of the output flow rates cannot be measured and are only estimated by load profiles, it is difficult to ensure that the calculated calorific values are reliable under all possible operating conditions without evaluating uncertainties.

Providing a complete result including measurement uncertainty for all calorific values characterising the reliability of the gas transport model and the reconstruction of state supports the decision that the results are ‘fit for its intended use’.

The uncertainty evaluation is not replacing a validation of the simulation model by real measurements. The uncertainty statement is not covering for differences between the model and the real system. It is a statement about the reliable of the results under the assumption that the model is correct. An evaluation of uncertainty is complementing the ongoing operation of quality tracking system, ensuring that all the results are meaningful over time.

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