GAS QUALITY TRACKING IN DISTRIBUTION GRIDS WITH SMARTSIM – APPLICATION IN COMPLEX AND MESHED GRIDS.

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ABSTRACT

In this article we describe the application of SmartSim on complex, meshed grids. A new calculation kernel makes it possible to simulate these grids more efficiently und accurately. First the theoretical background for loop treatment is introduced and so the influencing parameters on the pressure losses in loops can be identified. On this basis the validation of simulation results and the possibility for grid calibration will be described. The application and advantages of the method will be illustrated by reference of the Malmö gas grid.

1 INTRODUCTION

Natural gas will make an important contribution to the energy turnaround towards more efficient and environmentally friendly energy supplies. Enormous potential will be tapped for reducing CO_2 emissions and enhancing supply security when integrating renewable energies such as biomethane or hydrogen produced from excess power into the natural gas supply system. But these developments will also pose a major challenge for gas infrastructures and gas applications. Gas qualities will vary more widely - a trend we have been observing in Europe for some years now as a result of increasingly diversified natural gas/LNG supplies. Aside from compliance with technical rules for gas appliances, gas quality is also relevant for accurate energy billing. German verification regulations require the CVs at end users to be determined with an uncertainty not exceeding 2% (the maximum permissible billing error). This requirement is the basis for the so-called 2% rule in DVGW Code of Practice G685 (Gas Billing) [1] which states that when different gases are

injected into a distribution grid, the CVs of the gases averaged over the billing period must not deviate from the volume-weighted CV determined for the relevant supply area by more than 2%. Biomethane is therefore conditioned prior to injection by admixing propane to obtain the CV prevailing in the grid. But this is costly and has a negative effect on the CO_2 balance. In the case of hydrogen, CV adjustment would hardly be possible for technical and economic reasons, and so SmartSim has been developed by E.ON. SmartSim will help to ensure accurate energy billing after injection of biomethane or hydrogen on the basis of gas quality tracking by simulation. Such systems have already been used in transmission grids for quite some years.[2] SmartSim is a new method developed over the past few years for use in distribution grids with only a limited measurement infrastructure. Non-measured exit volumes are calculated on the basis of standard load profiles derived from customer-specific consumption data. The method was validated in cooperation with E.ON Avacon for a distribution grid and approved in August 2012 by Mess- und Eichwesen Niedersachsen (MEN) following agreement with Physikalisch-Technische Bundesanstalt (PTB). A detailed description of the method is published in gas for energy issue 3/2012 [3].

2 GAS QUALITY TRACKING WITH SMARTSIM

SmartSim requires topological data and measured values as its input parameters. The topological data include the pipe's length, its diameter and its roughness. The hourly measurements are the CVs measured at the entry points and the entry and exit volumes. Because exit volumes are often not measured in distribution grids, they may be estimated from standard load profiles (SLPs) developed at TUM (Technical University Munich) [4] using customer-specific consumption data.
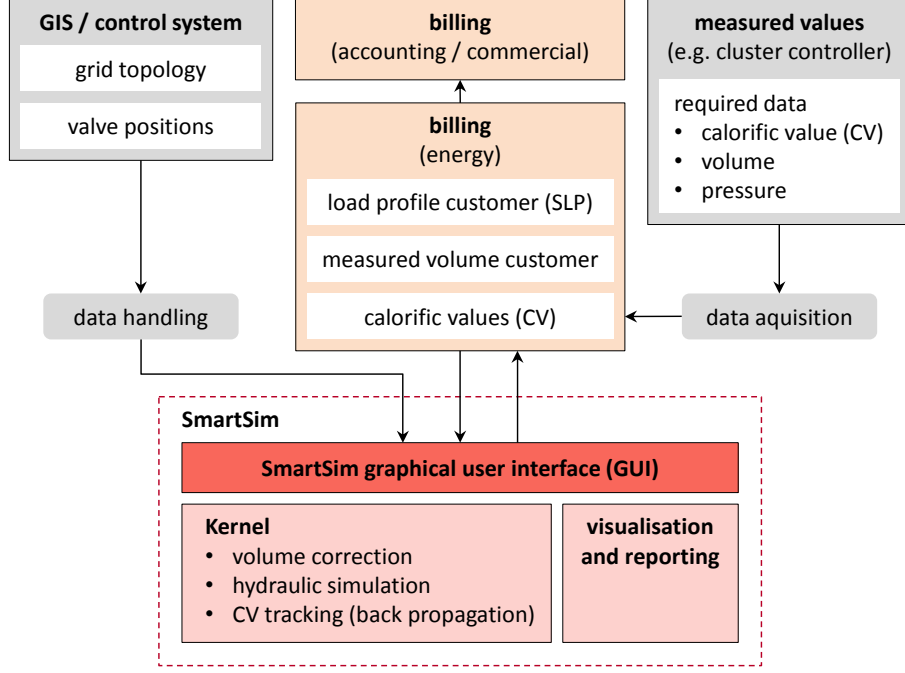
Figure 1 SmartSim input parameters.

These estimates involve a degree of uncertainty so are corrected in SmartSim using an appropriate volume balance of the grid. Beside the entry and exit volumes, the linepack ΔV_{grid} is also taken into consideration.

$$V_{corr} = V_{en} - V_{SLP} - V_{meas} - \Delta V_{grid} \qquad (1)$$

The correction volume V_{corr} obtained with Eq. (1) is then split among the individual SLP consumers using Eq. (2). Achieving the grid's volume balance can be guaranteed at any point in time with this approach.

$$\widehat{V}_{\text{SLP},i} = \left(1 - \frac{V_{\text{corr}}}{\sum_j V_{\text{SLP},j}}\right) \cdot V_{\text{SLP},i} \qquad (2)$$

For accurate flow simulation with high performance a new calculation kernel has been developed which is now an integral part of the SmartSim software. A detailed description of the calculation procedure is given in [5]. The essential steps are given in the following (see Figure 1):

1. volume correction
2. hydraulic simulation
3. CV tracking (back propagation)

Once the volumes for each hour have been corrected using Eq. (2), the grid's flow situation is determined by a hydraulic calculation. The flow velocities as well as the mass and volume flow rates in the individual pipes are now known. In the final step, for every exit point the exit volumes are tracked back through the grid as far as the entry points. This is done with the help of a special gas package model, the so-called 'back-propagation algorithm'. This algorithm enables SmartSim to show the proportions of the injected gases, including lead times, at each exit point. The advantage of this approach is that the CVs at the exit points can always be related to the calibrated measured entry CVs. A further benefit is that other relevant gas characteristics such as the K number or CO_2 emission factor can be derived from the entry points in a single calculation step. Ultimately therefore, SmartSim supplies the calorific values for all exit points in the grid which can then be used for billing. The billing CV is usually determined as the volume-weighted monthly average value.

3 TREATMENT OF LOOPS

In non-meshed grids, all volume flow rates are clearly determined by the volume balancing described in Section 2. Here there is only one possible solution which satisfies the grid's conservation of mass. Uncertainties in the topological input variables (pressure loss coefficients) have no significant impact on mass flow distribution in this case. The situation in meshed grids is different. If pressure losses in individual parts of a loop are not described with sufficient accuracy, the effect on the distribution of mass flows in the particular loop and hence on the determination of the billing CVs can be quite significant. Figure 2 shows a very basic loop with two entry points and two exit points.

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If we assume that the two mass flows m_1 and m_2 are the same and that there is no difference between the four pipes in the loop, then the mass flows are all evenly divided when they enter the loop. Consequently the two exit points are supplied half with Gas 1 and half with Gas 2. This ratio will shift as soon as the pressure loss coefficient of a pipe in the loop differs from the others in this example. This can have a significant influence on the billing CV even when the gas qualities of Gas 1 and 2 are different. Correct modelling of the pressure losses in meshed grids is therefore imperative.
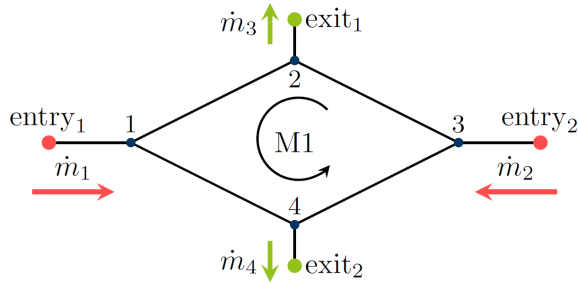

Figure 2 A simple loop with two entry and two exit nodes.

Kirchhoff's circuit laws apply to gas grids in the same way as they do to electrical engineering. Kirchhoff's second law is decisive when calculating the flow situation in a loop (see Equation 3). The sum of the pressure losses of all pipes R of a loop must be zero.

$$\sum_{r=1}^{R} \Delta p = 0 \qquad (3)$$

The pressure loss of a compressible fluid in a pipe r can be calculated according to Mischner [6] with the Darcy-Weisbach formula in Eq. (4). The correction factor k can be dispensed with here because the real gas behaviour was already taken into consideration when calculating the density $\rho_{1,r}$ and the flow velocity $u_{1,r}$ at the beginning of the pipe. Because the pressure loss is dependent on the volume flow, the latter must be determined iteratively until Eq. (3) is satisfied for all loops in the grid.

$$\Delta p_r = p_{1,r} \cdot$$

$$\left(1 - \sqrt{1 - \left(\lambda_m \cdot \frac{L_r}{D_r} + \sum \zeta \right) \cdot \frac{\rho_{1,r}}{p_{1,r}} \cdot u_{1,r}{}^2} \right) \qquad (4)$$

The mean pipe friction coefficient λ_m is determined using Zanke's formula [7,8]. This formula facilitates a complete calculation of pipe friction coefficients over the whole laminar and turbulent range and is therefore a function of the following variables:

$$\lambda_{m,r} = \mathrm{f}\left(Re, \frac{k}{D_r} \right) \qquad (5)$$

If the diameter and pipe friction coefficient are moved in front of the inner bracket and the resulting pressure loss related to the sure $p_{1,r}$ at the entry to the pipe, Eq. (6) is obtained.

$$\frac{\Delta p_r}{p_{1,r}} = 1 - \sqrt{1 - \frac{\lambda_{m,r}}{D_r} \cdot (L_r + L_e) \cdot \frac{\rho_{1,r}}{p_{1,r}} \cdot u_{r,1}^2} \qquad (6)$$

From this equation it is easy to see the variables which affect the pressure loss. They are the pipe friction coefficient λ_m, the pipe diameter D_r, the flow velocity u and the pipe lengths L_r and L_e. Any uncertainties in these variables have a direct effect on a pipe's pressure loss and hence on the mass flow distribution in a loop. The term density to pressure only depends on real gas behaviour, if we assume a constant gas temperature T.

The dimensioning of the grids has a decisive impact on the extent of the pressure losses and this is why the flow velocities (flow velocities as an hourly mean value in m/s) and diameters of 3 regional distribution networks have been analysed. In each case the flow velocities were investigated over a period of one year. This approach takes account of the different grid operating modes due to seasonal consumer behaviour. It was found that over 70 % of the flow velocities which occurred are equal or less than 0.5 m/s and that more than 80 % of pipelines have a diameter of over 150 mm. The pipe diameters and the relative frequencies of the flow velocities which occur are plotted in Figure 3. Despite the very low flow velocities, the flow is almost entirely turbulent. This is due to the fact that the dynamic viscosity η which is typical for natural gases is of the order of 10^{-5} and so makes for Reynolds numbers greater than 2300:

$$\mathrm{Re} = \frac{u \cdot \rho \cdot D}{\eta} \qquad (7)$$

As can be seen from the charts in Figure 4, the pressure losses at flow velocities of less than 1.0 m/s turn out to be very low, and it is only at flow velocities of 2.0 m/s and more that the influence of the other parameters acquires greater significance.

The effects on the pressure loss of the uncertainties in the pipe lengths and diameters are quite minimal, especially at the low flow velocities.
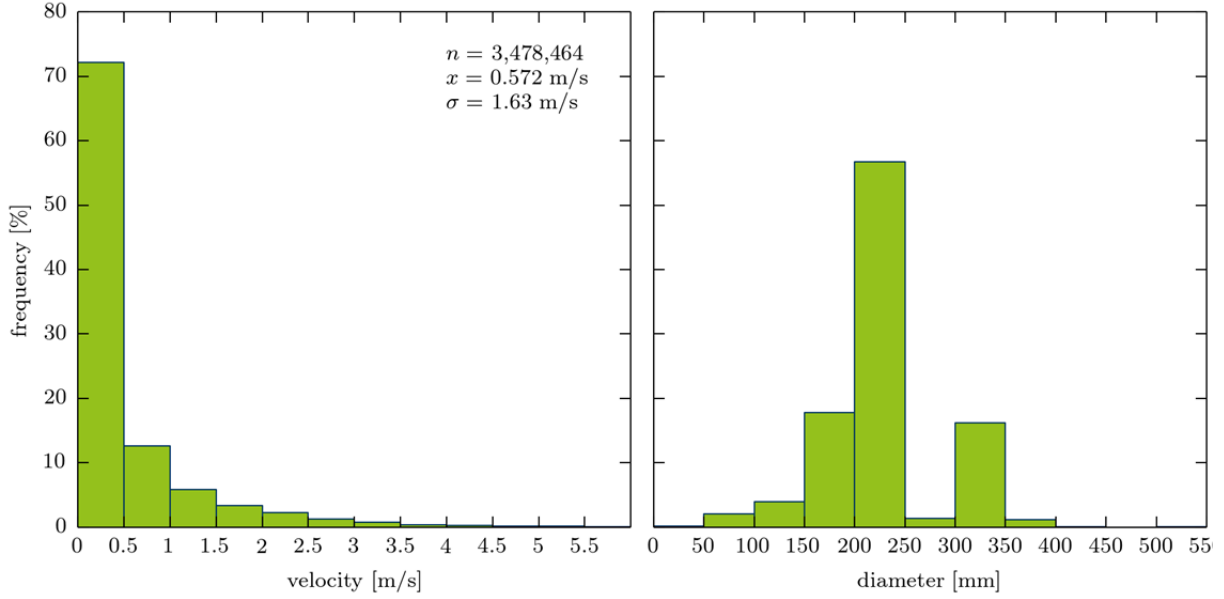
Figure 3 Frequencies of flow velocity in regional gas distribution grids and diameters per meter pipeline. Tree different gas distribution grids were evaluated.

The greatest uncertainties therefore arise from the pipe friction coefficients λ_m caused by the pipe roughness k.

The integral pipe roughness k' is usually used for k when calculating the pressure loss in gas grids. As well as the actual roughness of the pipe wall it takes account of additional internals and flow resistances. According to GW 303-1 [9] the following values can be assumed as guideline values for the integral pipe roughness k':

$k' = 0.1$
Steel and plastic pipes: elongated pipeline route, few internals, minimal meshing

$k' = 0.5$
Steel and plastic pipes: internals, usual meshing

$k' = 1$
Steel pipes: minimal deposits, internals, highly meshed

Steel and cast iron pipes: with heavy deposits, internals and highly meshed, have k' values >1

The values used for the integral pipe roughness are empirical variables which provide a good approximation of the pressure losses which occur in actual grids. In addition to the integral pipe roughness, the equivalent pipe length L_e from Eq. (6) can also be used to better model individual loops. This is a function of the pressure loss coefficients of individual resistances and is defined as follows:

$$L_e = \frac{\sum \zeta}{\lambda_m \cdot D_r} \tag{8}$$

The equivalent pipe length L_e can be used within the simulation as a freely variable parameter to adjust the pressure losses in the loops so that the flow pattern of the simulation closely matches the measured values. It should be adjusted once for 'calibration' for a grid. Depending on the observed behaviour of the pressure losses it may also be possible to use L_e in the form $L_e = f(T)$.
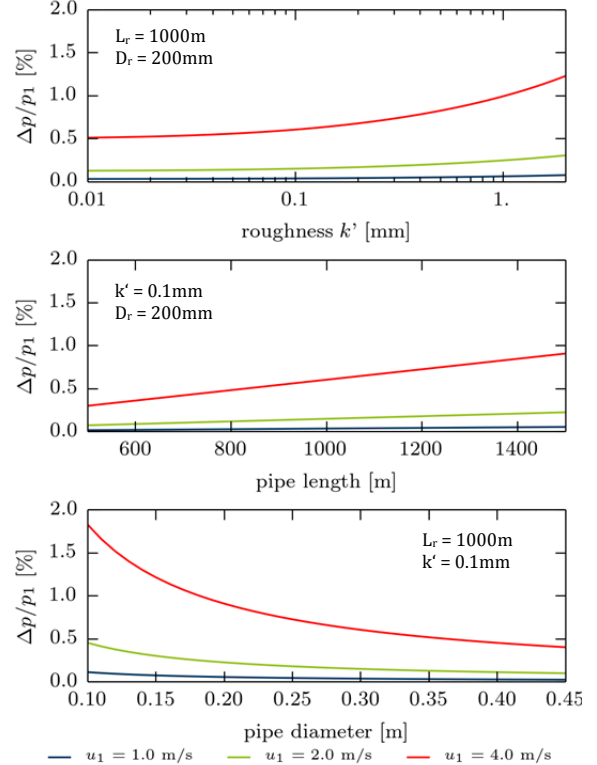

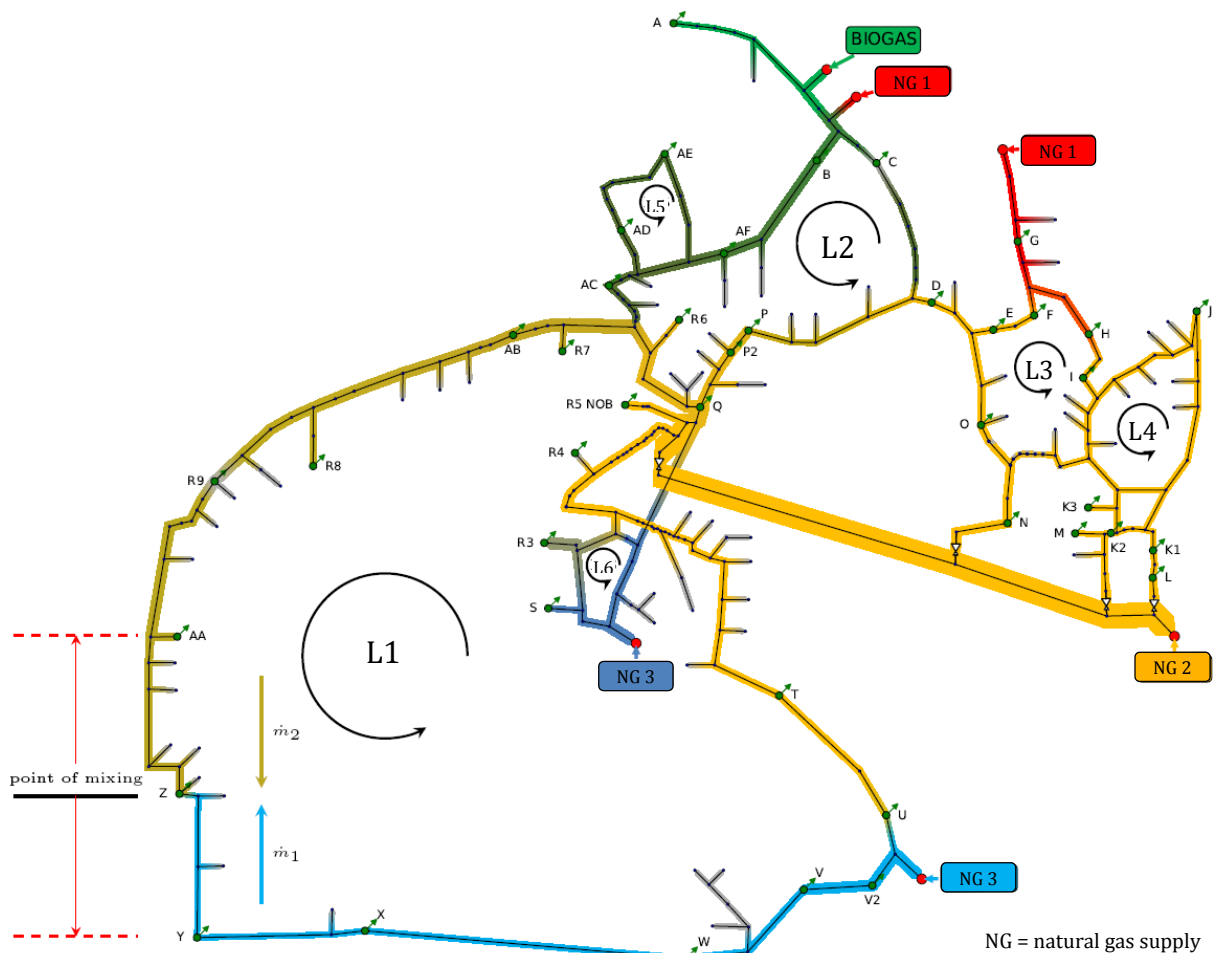Figure 4 Influence of roughness, pipe diameter and length on pressure loss.

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Figure 5 Distribution of injected gases in the Malmö grid sector.

4 A Practical Example: the Malmö Gas Distribution Grid

Background

The Malmö distribution grid operated by E.ON Gas Sverige supplies customers with a total annual demand of 500–750 GWh. The gas is sourced through Denmark, and in recent years some German natural gas has found its way to Malmö as well as the Danish gas. Around 10% of the annual total demand is supplied by a biomethane plant which is connected to the grid. A further biomethane plant is currently in the planning stage and is due to come on stream by 2015. Against the background of a low carbon energy supply, efforts are being made to further increase the biomethane content in Sweden in the coming years.

Since biomethane and natural gas have different calorific values, today the CV of the biomethane is adjusted by the admixture of propane so as to ensure accurate energy billing. Approx. 8% propane must be added to the biomethane to match the CV of the Danish gas. Admixing propane does not just involve considerable additional expenses, it also works against the aim of making the natural gas 'greener' since the CO_2 balance is made worse as a result.

This is the background against which a pre-study is currently looking at ways of determining the CVs at all exit points of the Malmö grid by means of flow simulation. This way, the use of propane may be avoided or reduced in future.

Grid Topology

The Malmö grid is divided into three pressure levels – 0.1 bar, 4 bar and 16 bar gauge pressure. The 4 bar grid which is the main object of consideration here is characterised by a number of natural gas/biomethane entry points and by meshed regions. The 4 bar grid is supplied through a total of 8 entry points from 3 pipelines with a nominal pressure of 16 bar. These 16 bar pipelines are in turn connected to an upstream transportation pipeline so that they all provide natural gas of the same quality
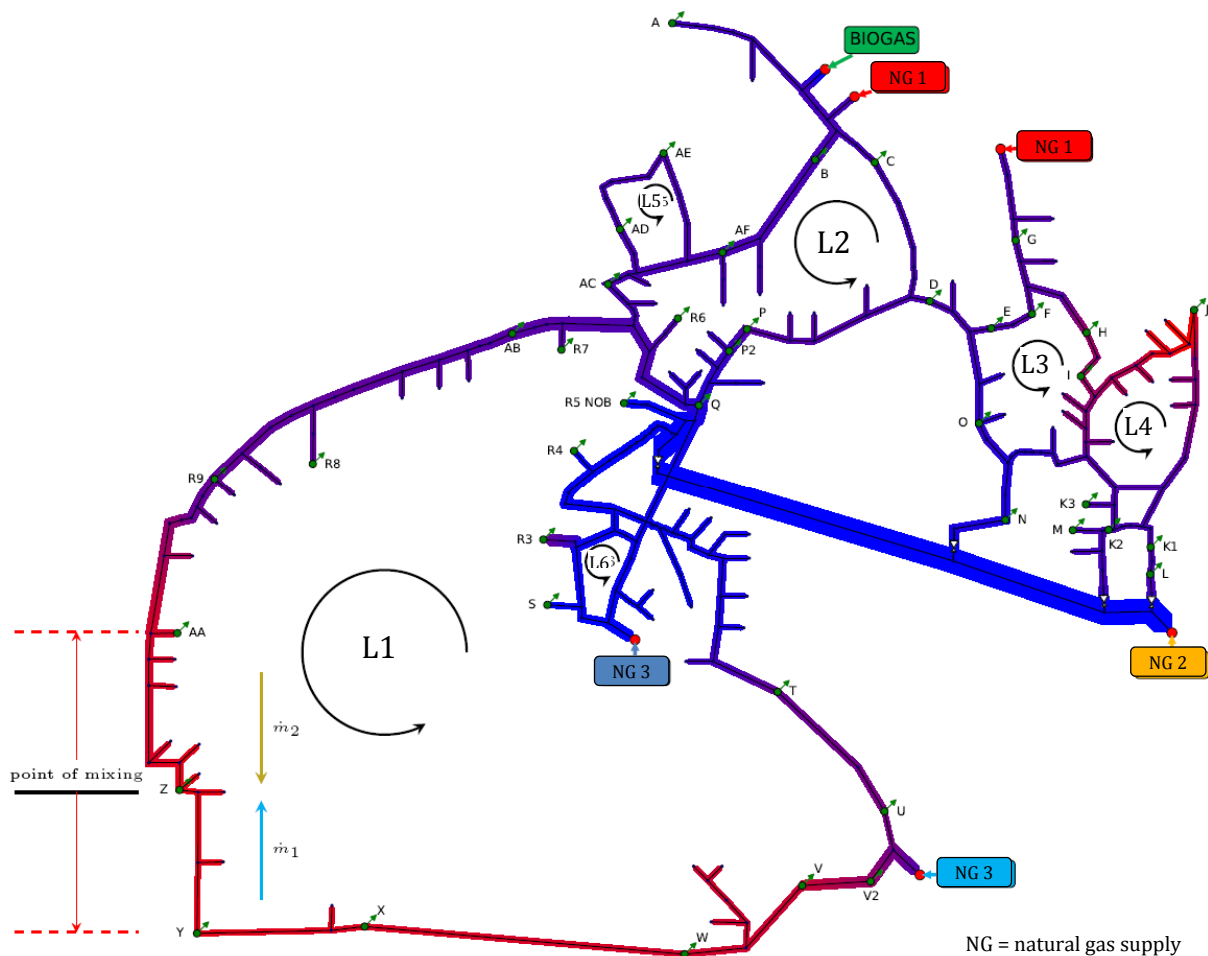
Figure 6 Pressure distribution in the Malmö grid. Blue represents the maximum and red the minimum pressure.

In the northern section of the grid there is also a biogas plant which injects biogas that has been upgraded to biomethane into the 4 bar grid. The biomethane is currently conditioned to the CV of the injected natural gas by the addition of propane. The 4 bar grid has been modelled with 42 exit points to which customers are connected directly or which have 0.1 bar low-pressure grids downstream. Customers connected to these downstream grids can usually be attributed with the CV of the respective exit point with sufficient accuracy. Because four of the entry points have no facility for measuring the volume flow and only the total volume flow of the upstream 16 bar pipeline is known, this 16 bar pipeline was included in the simulation (shown in yellow in Figure 5).

The complex topology means that it is no easy matter to estimate the flow situations in the grid or to assess the effects of future changes such as an additional biomethane plant. Simulation with SmartSim makes this possible however. With SmartSim we can match up all exit nodes and therefore each customer with their exact mix of injected gases and hence say which resulting CV they receive.

The visualisation of the biomethane and natural gas flows in the grid also allows us to assess in advance the effect of gas flow control operations, e.g. closing valves, or the impact of structural measures.

Flows of Biomethane and Natural Gas in the Grid

Simulation for Grid Malmö have been performed for the time period from January to December 2013

Figure 5 shows the topology of the distribution grid in Malmö and the distribution of gas flows at a time of high gas consumption in January 2013 as an example. The envelope shown following the course of the pipeline represents the current flow, with the colour indicating the source, i.e. the entry point of the gas. The entry points are indicated in red, blue and yellow depending on which of the three 16 bar pipelines supplies them. The biomethane which enters in the north of the grid is shown in green. Gas mixtures are indicated by the mix of corresponding

colours. The biomethane for example mixes with the gas injected at entry point NG 2 (shown in yellow) and is transported along the left-hand arm of loop L1 towards the south. At exit point Z there is a mixing point where gas coming from the north and the south stream jointly supply a downstream low pressure grid. Because the amount of biomethane that is injected is more or less constant, its level in the grid rises as overall gas consumption falls, e.g. at weekends when there is less demand from industry or during the summer months. As a consequence the propagation of biomethane in the grid also increases and the mixing points such as U and Z in Figure 5 also move towards other exit nodes.

Pressure Distribution in the Grid

Figure 6 shows the grid topology with an envelope whose thickness corresponds to the current flow. In this case the colours indicate the pressure distribution in the grid. Blue colouring indicates the maximum and red the minimum pressure. The maximum grid pressure is given by the colouring with the higher operating pressure of 16 bar. If we disregard this pipeline, the pressure losses in the entire grid are minimal, and amount to less than 100 mbar. This can be explained by the predominantly low flow velocities typical of distribution grids.

As expected, the maximum pressures in the 4 bar grid are found at the entry points, from where biomethane and natural gas flow to regions with lower pressures. In loop L1 we can see that the pressure decreases steadily in the direction of flow towards the mixing point at exit point Z. This is where we find the minimum pressure of loop L1 and of the whole simulated grid. Uncertainties in pressure loss calculation can lead to a shift of the mixing point from Z to Y or AA. Another region in which the pressure drops can be seen in the north-west at exit node J and is an indication that here the offtake quantities are comparatively large relative to the pipeline diameters.

5 VALIDATION AND OPTIMISATION

Validating simulation results is an important aspect of CV tracking. So far, this has been done using a mobile gas chromatograph [3,10,11] which is set up at representative points in the grid over a period of several months. These representative points are identified in advance by means of an uncertainty/sensitivity analysis of the grid. This is where SmartSim uses a Monte

Carlo Simulation. As well as the reference scenario, 1600 other simulation runs are carried out in which random errors are applied to all of the input variables.

Each one of these simulation runs is then compared with the reference scenario. A mean deviation of the calorific value is then formed for each exit node from all of the simulation runs. Consequently nodes in the grid where the greatest deviations in the CV occur, i.e. which react most sensitively to uncertainties in the input data, are deemed to be critical points.

As well as validating the billing CVs and CV profiles, the calculated run-times of the gases in the grid can also be verified in this way. If deviations which are outside the uncertainties determined by the MCS are observed between the measured values and the simulation, or if systematic deviations occur, then further action must be taken.

Regarding meshed grid sections it should be noted that the pressure loss calculation described in Section 3 can have a significant effect on the breakdown of the flows and hence on the CVs in the particular loop. In this case the pressure losses in the affected loops can be adjusted with the equivalent pipe length L_e to improve the quality of the simulation results. Precise pressure measurements and measurements of the gas quality – e.g. obtained with a mobile PGC – can also be used to determine the optimum equivalent pipe length for a particular section of pipeline. The use of sensors which pick up a signal that is characteristic of the gas composition is also being considered as a possible future option. In this case, results would be optimised by a multiple regression in which ultimately the deviations between simulation and measurement are minimised.

6 CONCLUSION AND OUTLOOK

This article presents how the SmartSim tool for gas quality tracking can be applied in complex and meshed gas grids. Since pressure losses caused by friction can have a significant influence on the gas flow when meshes are involved, the model includes an adjustable parameter that can be optimized by regression to measured data. In addition to measured pressure data, also characteristic signals for the gas composition, e. g. from infrared sensors, may be used in the optimization process.

The practical application of SmartSim is demonstrated in the Malmö grid of E.ON Gas Sverige, which is characterized by several natural gas

and biomethane injection points. Simulation runs for the year 2013 yield consistent results and indicate that Calorific Values can be determined with sufficient accuracy for all exit points so that in future CV adjustment of biomethane by admixing of propane can be avoided. Validation of simulation results by measurements will be a task for the next project phase.

To sum up, gas quality tracking can make an important contribution with regard to integrate renewable energies like biomethane or hydrogen from "Power-to-gas"-plants to the natural gas grid.

7 REFERENCES

[1] Deutsche Vereinigung des Gas- und Wasserfaches. G 685 Gasabrechnung. Bonn: DVGW; 2008.

[2] Altfeld K, Bödeker J, Frieling H, Schley P, Uhrig M. Modelling of gas flow in pipelines tracking gas quality. IGRC Paris 2008.

[3] Schenk J, Schley P, Hielscher A. A new method for gas quality tracking in distribution grids. gas for energy 2012(3).

[4] Hellwig M. Entwicklung und Anwendung parametrisierter Standard-Lastprofile. Dissertation. München.

[5] A. Hielscher, C. Fiebig, R. Span, J. Schenk, P. Schley. Gas Quality Tracking in distribution grids with SmartSim – a new kernel for flow calculation. IGRC Copenhagen 2014.

[6] Mischner, J., Fasold, H.-G., & Kadner, K. gas2energy.net mit DVD: Systemplanerische Grundlagen der Gasversorgung. München: Oldenbourg Industrieverlag; 2011.

[7] Zanke U. Zur Berechnung von Strömungswiderstandsbeiwerten. Wasser & Boden 1993.

[8] Zanke U. Zum Übergang hydraulisch glatt-hydraulisch rauh. Wasser & Boden 1996.

[9] Deutsche Vereinigung des Gas- und Wasserfaches. GW 303-1 Berechnung von Druckverlusten bei der Gasverteilung. Bonn: DVGW; 2006.

[10] Schenk J, Schley P, Hielscher A. Brennwertverfolgung in Verteilnetzen: Teil 2 - Auswertung Feldversuch und Implementierung. GWF / Gas, Erdgas 2011(10):676–83.

[11] Schley P, Schenk J, Hielscher A. Brennwertverfolung in Verteilnetzen: Teil 1 - Entwicklung und Validierung des Verfahrens. GWF / Gas, Erdgas 2011;152(9):552–6.