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Gas Quality Parameter Computation in Intermeshed Networks

Peter Hass

*IPSOS Industrial Consulting GmbH, Berlin,
Germany*

1. Introduction

The increasing number of biogas plants which is favored now as a part of the energy concept of the German Government and the European Union has major impact on traditional gas distribution and transmission systems. In addition, synthetic methane gas or hydrogen injections must be considered in the near future which will originate from wind power generation (conversion of excess capacities). The main aspect of this change is the resulting calorific value which may be subject to changes in a short time which must therefore be measured, calculated and permanently surveyed.

This chapter describes the basics of gas mixing and the various situations which may be encountered and must be handled in the transportation or distribution process. There are some limitations which must be considered for industrial consumers and power plants. Measurements and simulations are required to survey and control the process of gas distribution and finally generate figures for accounting and billing. Some typical examples are presented to give an insight into real situations and projects.

The problems and limitations of the gas distribution process in heterogeneous networks and biogas injections are discussed with respect to the IT-structure and organizational environment. The final benefit that can be achieved is an individual calorific value for each consumer in the grid enabling a fair billing despite the variations of many gas injections from many sources.

2. Current and future gas injections of biogas vs. gas demand

2.1 Biogas to the grid

When the biogas finally had been produced, treated und conditioned it will either be fed into a nearby gas pipeline system or grid or it will be burned and transformed into electric power which is fed into the electric grid. In the following chapters we review and discuss the aspects of the gas grid, only.

Normally, the gas grid used by biogas plants will be a low or medium pressure operated distribution network. Certain conditions may require that the biogas is compressed to a higher level and being fed into a high pressure transportation network.

Typical locations of biogas plants and the major cities the corresponding gas transportation and distribution network are shown in figure 1.



Fig. 1. Biogas plant locations in Germany 2011 (source: DENA)

2.2 The location paradox

Typical biogas plants have preferred locations in rural areas, where the renewable material grows and the transportation is short and easy. In opposition to the rural places the areas of higher gas demand or actual consumption are located in or near urban areas. So, in most cases the biogas must be transported in pipelines over a longer distance spreading also over a wider network area before the biogas is consumed totally. Depending on the network structure and the total consumption figures there exist mixing areas of biogas and natural gas or pure biogas.

2.3 Adverse production-load situations (summer-winter)

As gas is used – at least in middle Europe and Germany - for heating to a high percentage there will be a big difference in consumption figures between winter and summer (see figure 2).

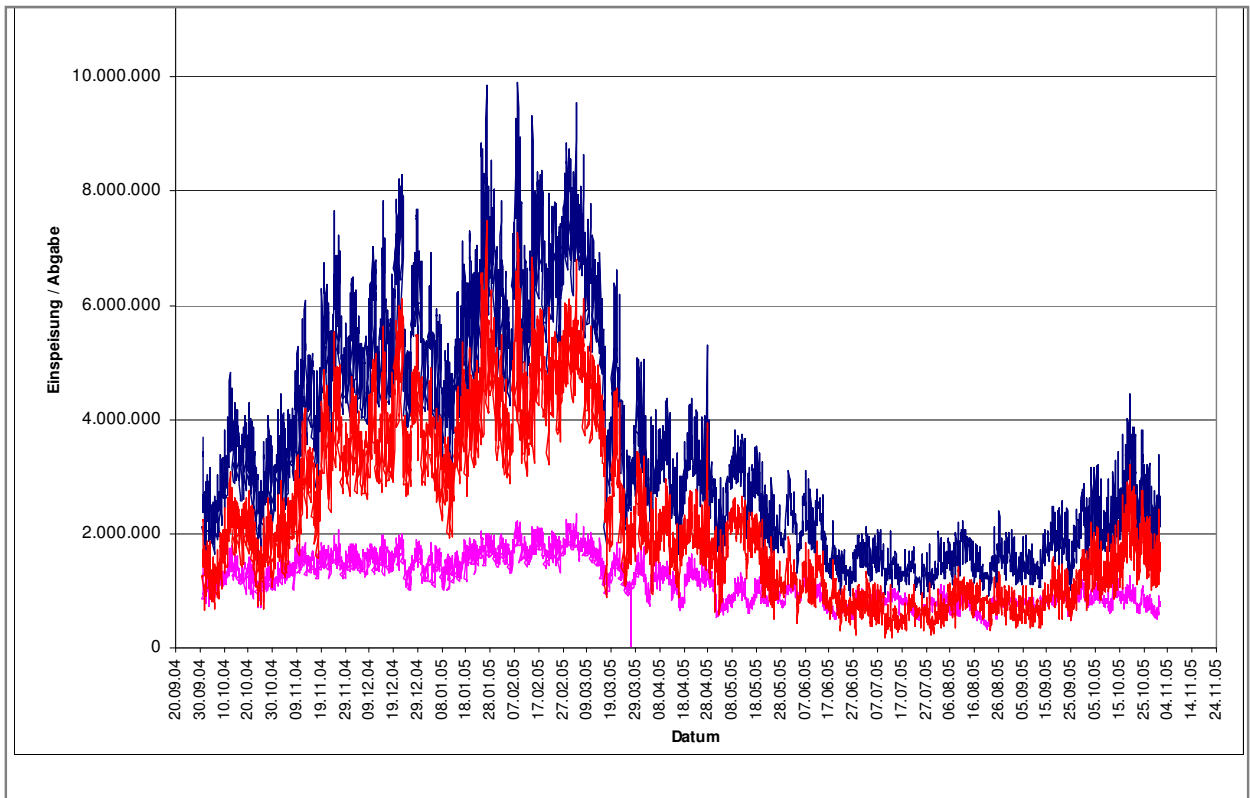


Fig. 2. Total load/feed-in (blue), industrial (RLM) and small consumer load (red) vs. time (hours) of a big city

In certain areas the biogas feed-in in the network is in wintertime only a small percentage and the area of influence is therefore small, too; but it is large in summertime. This fact principally leads to problems in pipeline connection, operation, constant gas quality delivery and fair billing (see below, Operational Aspects). In the future – when the number of plants and/or biogas production will increase - we will expect a considerable higher impact on network operation and surveillance tasks.

3. Basic methods of the gas mixing process

3.1 Gas parameters, gas quality figures (G 260, G 685)

The gas used in the networks for the final customer has to fulfill quality and composition requirements. According to the standard defined by DVGW G 260 working sheet two main types of natural gas (gas families) are distinguished which stem from different sources and production locations:

- H-Gas, high calorific value (Russian source, typically)
- L-Gas, low calorific value (North Sea source, mainly)

Aside from the composition of the gas, for technical reasons the values of calorific value and Wobbe-Index are important characteristics. A typical range of these values is used in practice and will be permanently measured and surveyed:

Value	Shorthand	Unit	Group L	Group H
Wobbe-Index Nominal Value	$W_{S,n}$	kWh/m ³	10.5 ... 13.0 12.4	12.8 ... 15.7 15.0
Calorific Value	$H_{S,n}$	kWh/m ³	8.4 ... 11.0	10.7 ... 13.1
Relative Density	d_n	-	0.55 ... 0.75	0.55 ... 0.75

Table 1. Essential gas parameters

The calorific value is generally used for the billing, as the final consumer/customer must receive his bill with the energy value included, meaning in the unit of kWh in a period (i.e. a year, a month). The energy value yields from multiplication of accumulated flow and calorific value, e.g. 3000 m³/a * 10.1 kWh/m³ equal to 30300 kWh/a.

3.2 Basic equations for mixing

Gas mixing occurs when streams of different gas qualities are united to a single stream. In pipeline systems this means that different gas sources meet in a T-type or Y-type of pipeline. A simple example of two streams of volume (V) with two calorific values (H) is given below (see figure 3). The resultant value depends on the product of volumes or flow (Q) and the amount of each calorific value according to:

$$H_{1,2} = \frac{V_1 * H_1 + V_2 * H_2}{V_1 + V_2}$$
$$H_s = \frac{\sum_i(V_i * H_i)}{\sum_i V_i} = \frac{\sum_i(Q_i * H_i)}{\sum_i Q_i}$$

$H_{1,2}$, H_s = resulting calorific value
 V_1 , V_2 = volume of stream #1, #2
 H_1 , H_2 = calorific value of stream #1, #2
 Q_i = flow of stream i (= dV/dt)

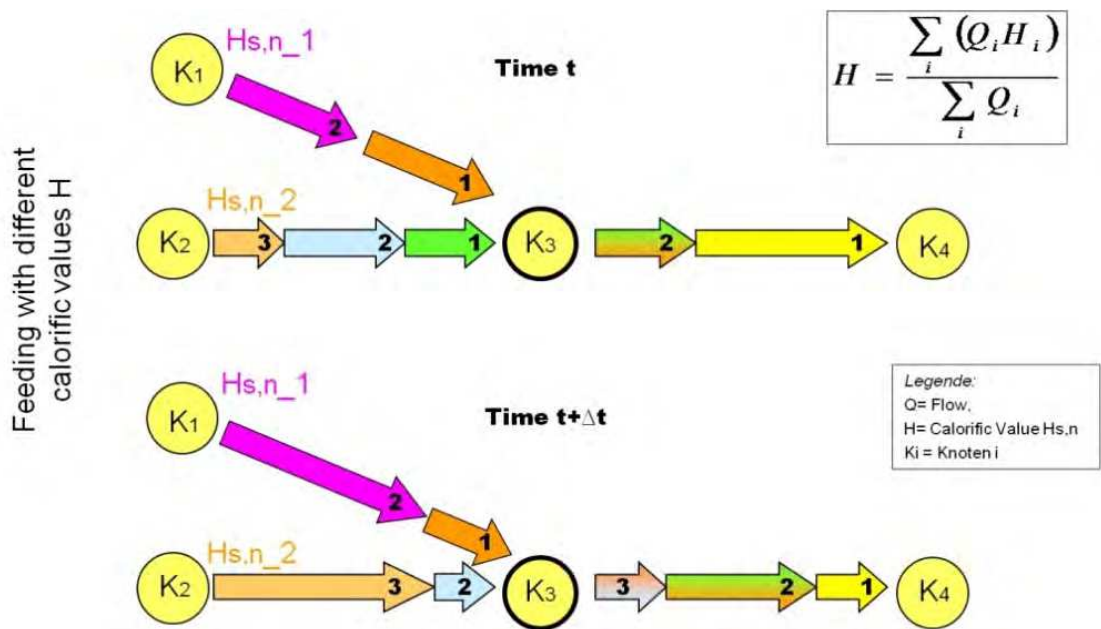
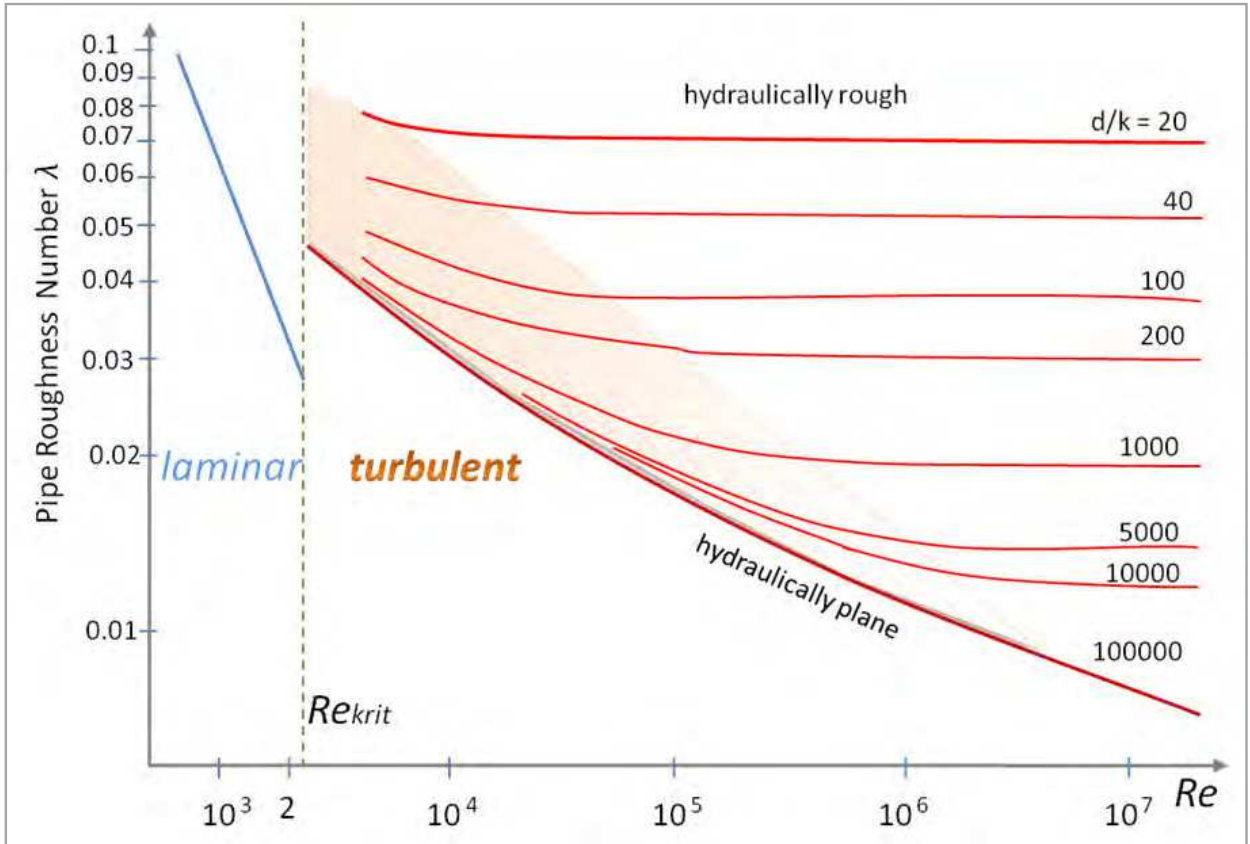


Fig. 3. Mixing and dynamic tracking of gas parameters at point K3

The mixing of the flows and thus the resulting value is not perfect in the vicinity of the mixing point. This is due to the pipe dimensions which may be large or different and the flow characteristic: laminar or turbulent. The mixing process is better and faster if the flow is turbulent. If the flow is laminar mixing may take a long way and time as even a layering effect may occur. In order to speed up mixing in such cases static mixer pipes, which have small obstacles inside to provoke little turbulence, will be built in the line.

3.3 Laminar vs. turbulent flow

Streams of gas and fluids show a typical behaviour when the flow changes from laminar state to the turbulent state (see figure 4). The areas of the flow type are described by the Reynold number (Re). Beyond Re= 2300 the flow switches suddenly from laminar to turbulent. But he transition spreads over a range and is dependent on physical and technical parameters. In pipeline systems the main parameters are pipeline inner diameter and roughness value which determine the flow type inside. Generally spoken, smaller diameters and higher roughness values lead to turbulent flow (but also to a higher pressure loss which is not really wanted).



(Re is defined as: $Re = v d / \nu$, (v = velocity, d = pipe diameter, ν = dynamic viscosity))

Fig. 4. Laminar and turbulent flow in Reynold number vs. pipe roughness number (source /1/)

3.4 Gas conditioning, process optimization

Gas conditioning is required in biogas plants in order to provide gas of near or equal quality of natural gas when it is fed into the network. Many consumers, especially industrial

consumers need gas with stable calorific value and/or Wobbe-Index. The allowed tolerance in Germany/Europe is $\pm 2\%$, only.

By means of propane gas which has a higher calorific value (28.1 kWh/m³, approx.) the biogas will be mixed (conditioned) by special equipment to an appropriate final calorific value. The final value is selected and continuously controlled by the network operator depending on gas type (H or L), network structure, flow situation and consumer requirements.

The conditioning of gas is a high extra cost for the network operator (operational cost and propane, especially). An optimization of gas conditioning means that propane gas usage and cost should be minimized. This can be achieved in the conditioning equipment by selecting and setting the set point of the final calorific value to an acceptable low value. But this value must still be compatible with the calorific values in the surrounding network which - of course - must be known. Appropriate measurements, the mixing equations and simulation help to solve the optimization and set point problem, even on-line.

In gas network the gas flow may have a number feeder points - including different gas qualities - and in addition the intermeshed network structure contains potential mixing points at every pipe crossing or branch. Normally, insight of the gas flow and calorific value at certain interesting points in the intermeshed network is only possible by many measurements (e.g. gas chromatography) and/or network computation and simulation.

4. Measurement and data requirements for network computation

Any computation of a gas network is based on a model for the network structure and equipment accompanied by many data for the place and time of interest. These are data of materials, parameters of the medium, physical states, flow data (input and output) and controlling equipment. The sources of these data are shown schematically in table 2.

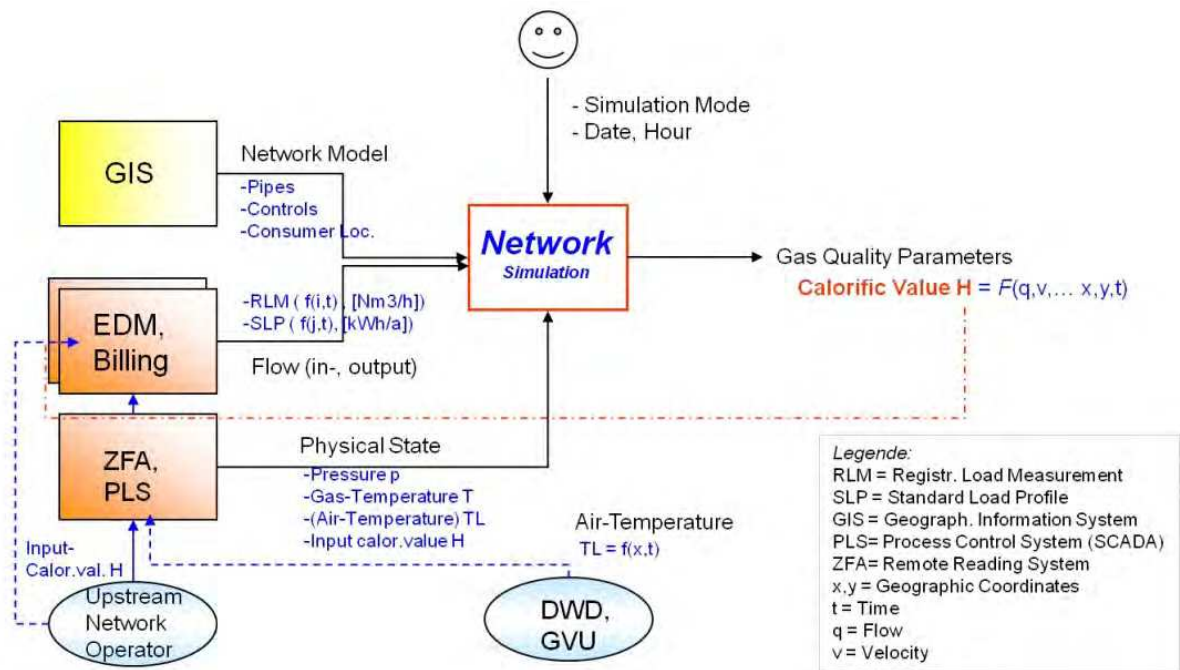


Fig. 5. Schematic data flow of reconstruction simulation for gas parameters/calorific value and feed back

4.1 Data types, accuracy, positioning, time scale/acquisition cycles

The data types and sources are summarized, collected and described in the following table to give a short overview:

Data Type	Data Detail	Source	Accuracy	Time Scale
Pipe	Inner diameter, Length, Roughness, Material class, ...	Geogr. Information System (GIS)	0.1 mm 1 m 0.01 mm	actual as possible
Node	Geographic (schematic) coordinates, node type (branch, ...)	GIS	1 m	
Control equipment	Valve (open/closed) Regulator (pressure/flow control operation mode), (max./min. flow, pressure)	GIS SCADA		hour, minute
Medium	Gas density, Gas temperature, Law of pressure loss	PGC		
Physical State	Pressure Flow (intake)	SCADA	0.001 bar 0.1 - 1 m ³	per hour per hour
Consumer	Flow (output), Type: RLM, SLP	SCADA, EDM	0.1 m ³	per hour, per month, per year
Other/ Derived	Outside air temperature, Consumption history/forecast, planned intake flow		° C (1 m ³)	per hour

Table 2. Data types required for control and simulation

The network model must be as actual as possible and should be updated whenever changes occur in reality. Very sensible with regard to the computation result is the information of actual or historical valve positions (open/closed); its tracing is indispensable, because wrong position will cause wrong/deviating results. The size of the network model may extend from some 1000 pipes up to 700 000 pipes (transport system to large distribution system including the transport system). The pressure range of larger networks may go down in several levels from 100 (84) bar to 0.020 bar finally at distribution level.

The data sources of different systems and their type of data which are necessary to build up a network model for simulation is shown schematically below (see figure 5). When computing the calorific value for each node (geographic position x,y) over time (t) the resulting value will be used to support the billing process.

4.2 Control system, full and sparse measurement coverage

In reality the gas networks are operated and surveyed by control systems (SCADA) consisting of a control center and remote control stations including remote control and data transmission. In general, a lot of data is acquired transmitted and stored but there is not always a full coverage for each point in the network. One can rely on:

- Input points: flow, pressure, gas quality
- Output points: flow of consumers (registered continuously)
- Intermediate points: flow, pressure (sparsely)

Intermediate points in the network are sparsely equipped or positioned, strongly depending on operational needs. Transport networks have a more detailed data view than distribution networks.

4.3 Consumer data (home, standard load profiles; Continuous registration)

Consumer data, especially small “home” consumers, are read once a year, only. When executing computations with small consumers their hourly values are deduced from yearly readings using standardized methods (standard load profiles, SLP). In all computations – when SLP’s are involved – it must be kept in mind that this method influences the accuracy of the computing results when a short time period is considered. Opposite to the former small consumers the big consumers are measured and registered continuously; so computations can be made very accurate even in short periods.

5. Operational aspects

5.1 Smooth operation goal

Network operators favor smooth operating conditions for a number of reasons:

- Avoid sudden pressure changes (could generate shock waves, higher gas velocity)
- Avoid bigger and many flow changes (leads to pressure changes, regulator instability and wear out)
- Deliver/provide constant gas quality (i.e. calorific value), (operate within allowed limits).

In reality more or less big changes are likely to occur each hour (minute) due to changes of the consumption, scheduled feed-in according to delivery contracts, natural variation of gas quality of gas sources/production fields.

5.2 Local biogas flooding

In wintertime gas consumption is high and normally biogas is a smaller amount of the total consumption causing normally no transportation problems. But in summertime when the gas consumption is very low some areas face the situation that biogas production is higher than the total consumption in a distribution (sub-) network. In effect, biogas floods the network but could not be consumed, even if the regulating devices would have been changed to different settings to retain natural gas flow. So the exceeding or all biogas must be transported to other areas via additional pipes which have to be provided by the network operator.

5.3 Reverse feeding to high pressure trunk lines

So called “Reverse Feeding” to the transportation network is required to solve the problem of excess biogas production in a local area. An extra pipeline leads the biogas that has been previously compressed to an appropriate point (nearest one) of the transportation network. The level of compression depends on the pressure level of the transportation system (occasionally this can be up to 80 bar).

5.4 Odorization and deodorization

If biogas is fed into a distribution network it must be odorized before. Odorization adds the typical alarming and disgusting smell to the gas that warns human beings in case of leakage. If in the situation that excess biogas exists in a network area odorized biogas must be deodorized before entering the transportation network that has no odorized gas (odorization will be added downstream at the distribution level, only).

6. Network modeling, simulation

Building a network model is a complex task. It starts first with data extraction from the geographical information system (GIS) via a special interface. This will include and deliver all pipe data, node geographic coordinates and equipment forming the basic network structure. Control equipment such as valves and controlling regulators are read or derived from GIS data; regulator devices often must be connected manually or corrected afterwards.

Next the inputs and outputs of the network have to be introduced. Aside from feeder points or underground gas storage the outputs - better said the outflows - are modeled by consumers. Each consumer (up to hundreds of thousands) has his individual set of data, static or dynamic. Static data are used for long term planning for a certain scenario, dynamic data is used for short term planning (i.e. some days). When the simulation finally starts the correct pressure data - at least for the most important points - must be given to the simulator. Consumer data, valve position and pressure data must be taken from different IT-systems: Energy Data Management (EDM) system and Process Control system (SCADA).

6.1 Transport networks

Transport networks are designed to transport gas over longer distance. They are equipped with remote control which transmits all relevant data to the control centre. From the point of view of modeling these networks have an excellent information base for a moderate number of pipes and nodes (measurement points) making modeling straightforward and easy. The network structure of a transport system tends to be sparsely intermeshed.

6.2 Distribution networks

Distribution networks are designed to transport gas over shorter distance, e.g. within a city. They are equipped also with remote control, but only important data is transmitted to the control center. The amount of data handled may be subject to changes in the future when for each customer Smart Metering and on upper level Smart Grid will be introduced. From the point of view of modeling the distribution networks have an acceptable information base for

all pipes but moderate number of measurement points making modeling an intensive work. The network structure of a distribution system tends to be strongly intermeshed. Distribution networks may have also a smaller trunk transportation system at a higher pressure level (e.g. 25, 16, 10 or 4 bar) while most of the pipes in the final distribution area are operated at 0.022 to 0.8 bar depending on the required flows.

6.3 Influence of intermeshing

Intermeshing is a basic concept in pipeline/network planning: it provides intrinsic redundancy for gas delivery in case of trouble/break at single points of pipeline. It supports continuous operation and pressure of the system; as it is most important to keep the whole pipeline system under pressure all the time (if the pressure would drop to zero, oxygen could enter the pipeline system exposing some areas or the system to the risk of explosion). Exaggerated use of intermeshing lead to higher investment cost in pipes and decrease a cost-efficient network structure in principle (besides, an item of passionate discussions among planners). Intermeshed networks need, because of their complexity, simulation support to get detailed insight into physical state and variables of the pipeline system.

6.4 Online- and offline-simulation

An advanced feature of simulation or operating mode is online-simulation. Here the simulation is coupled with a SCADA system and is executed corresponding to the cycle of the data acquisition (minutes to hours). It is a good tool to watch and control the network by additional detailed information almost in real time. This type of simulation is very demanding as it requires correct and complete data all the time what must be carefully prepared. Offline-simulation is the normal application it can be executed when needed - at arbitrary time.

6.5 Static vs. dynamic simulation

Static simulation means to execute a simulation for a fixed time; it is therefore good and often used for checking a set of scenarios or planning alternatives. Dynamic simulation reflects the changes of variables over time. This can be applied for historical data or for the future (based on forecasts). In case of reconstruction and tracking of certain values in the network (e.g. gas quality, calorific value) dynamic simulation is required. The typical time scale for simulations are hours which correspond well to most of the measurement cycles which are read from the field devices.

6.6 Tracking of gas quality parameters in the network

Online-simulation is used for tracking of gas quality parameter in the network. This method saves measuring equipment (gas chromatographs) in the field giving a much more detailed view of the way, value and distribution the gas quality parameters (see figure 6). Most often it will be applied for tracking the calorific value for all nodes on an hourly base (if used with historic data it will be called a reconstruction run). If the computed results shall be applied for billing purposes, then an official acknowledgement/permit of the technical authority (board of weights and measures) is required and a permanent surveyance system has to be installed.

Situation **old** - **new**

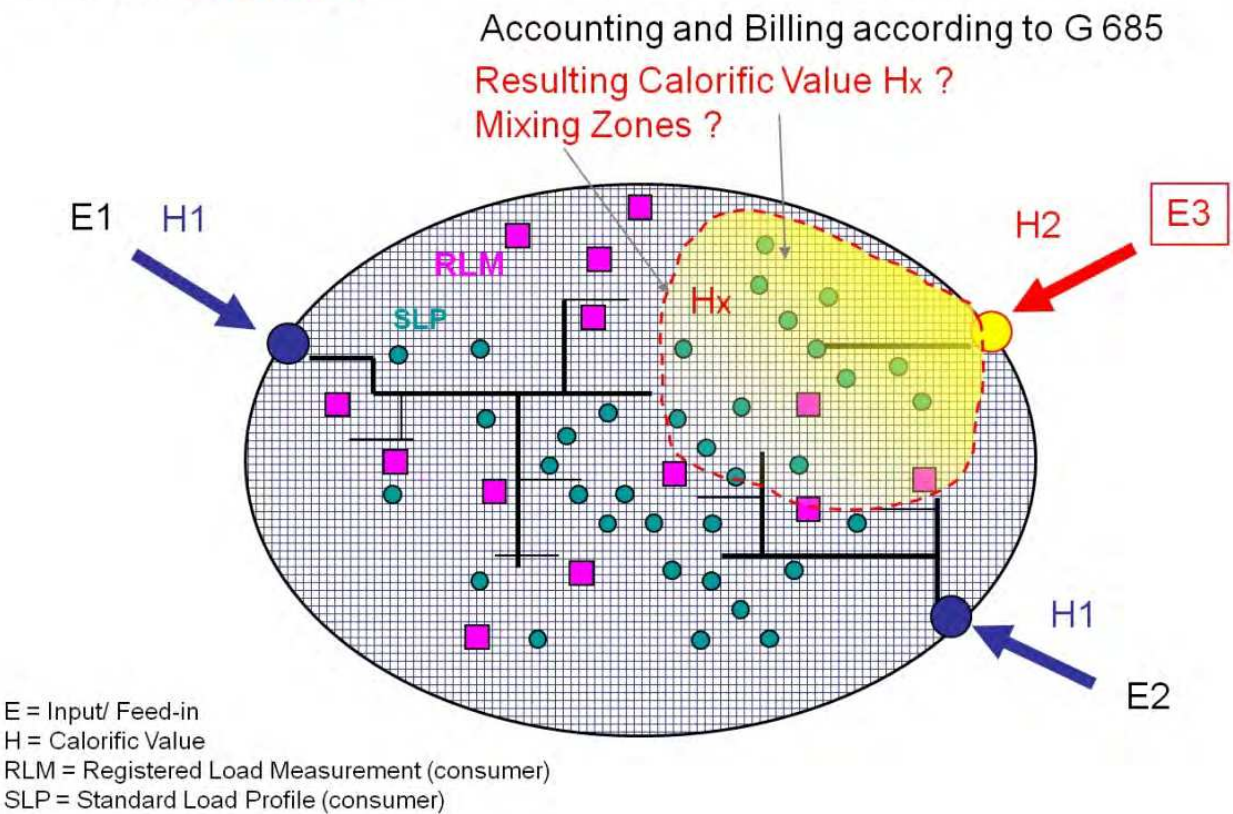


Fig. 6. Schematic view of areas of influence from different input of calorific values at feeding points

6.7 Examples

The following example demonstrates the results of a simulation which tracked the calorific value with historic data for 24 hours (reconstruction simulation) in a smaller city with a medium sized distribution network with some trunk lines (see figure 7).

There are six feeder points in total; in the north and the west are equal calorific values, in the south there is one point with different calorific value. (The different calorific values are made visible by different colors on the pipe segments, arrows indicate flow directions). In the middle of the network there is a mixing area (blue and pink) while near the southern feeder point the initial value dominates (dark yellow); the eastern branch of the grid shows a moderate mixed value (red). The small diagrams aside the network lines show the variable flow at the feeder points.

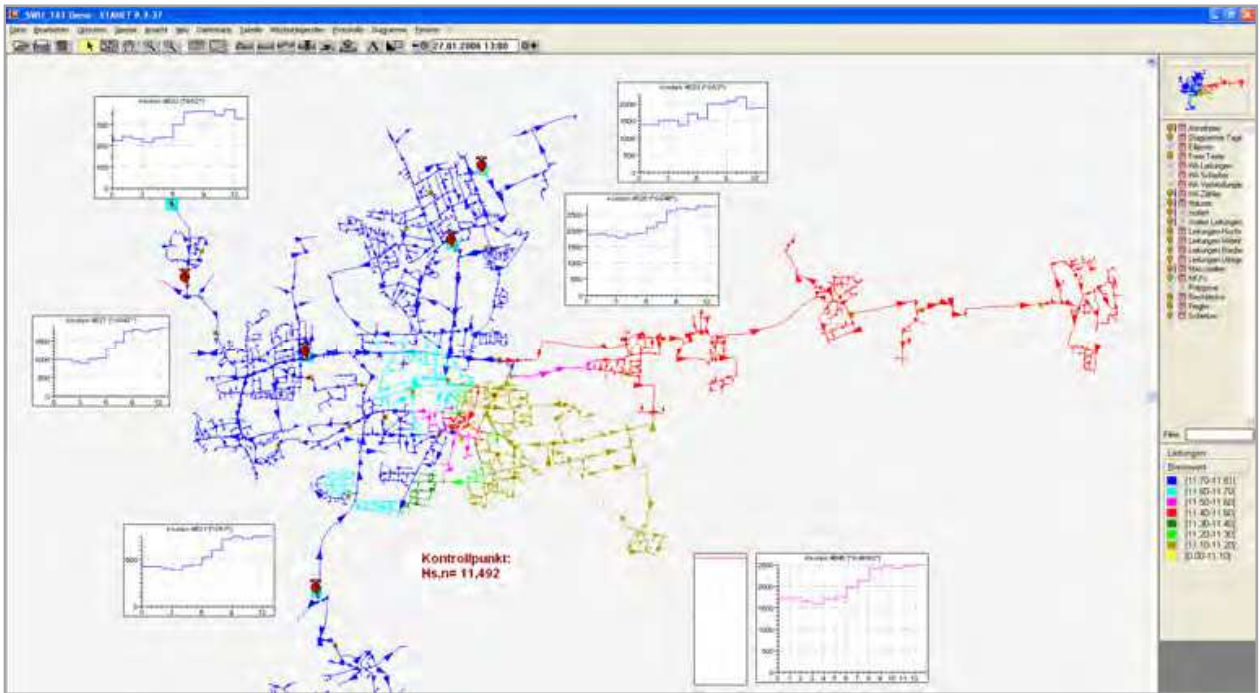


Fig. 7. Result of calorific value tracking in a distribution network; distinction by color scale (courtesy of STANET)

Figure 8 shows a detailed view of the distribution of the calorific value in the middle area of the network, figure 9 demonstrates the area of influence from the different feeder points in the same network by different colors in the background.



Fig. 8. Detailed view of calorific value distribution in the inner city area network (distinction by color)

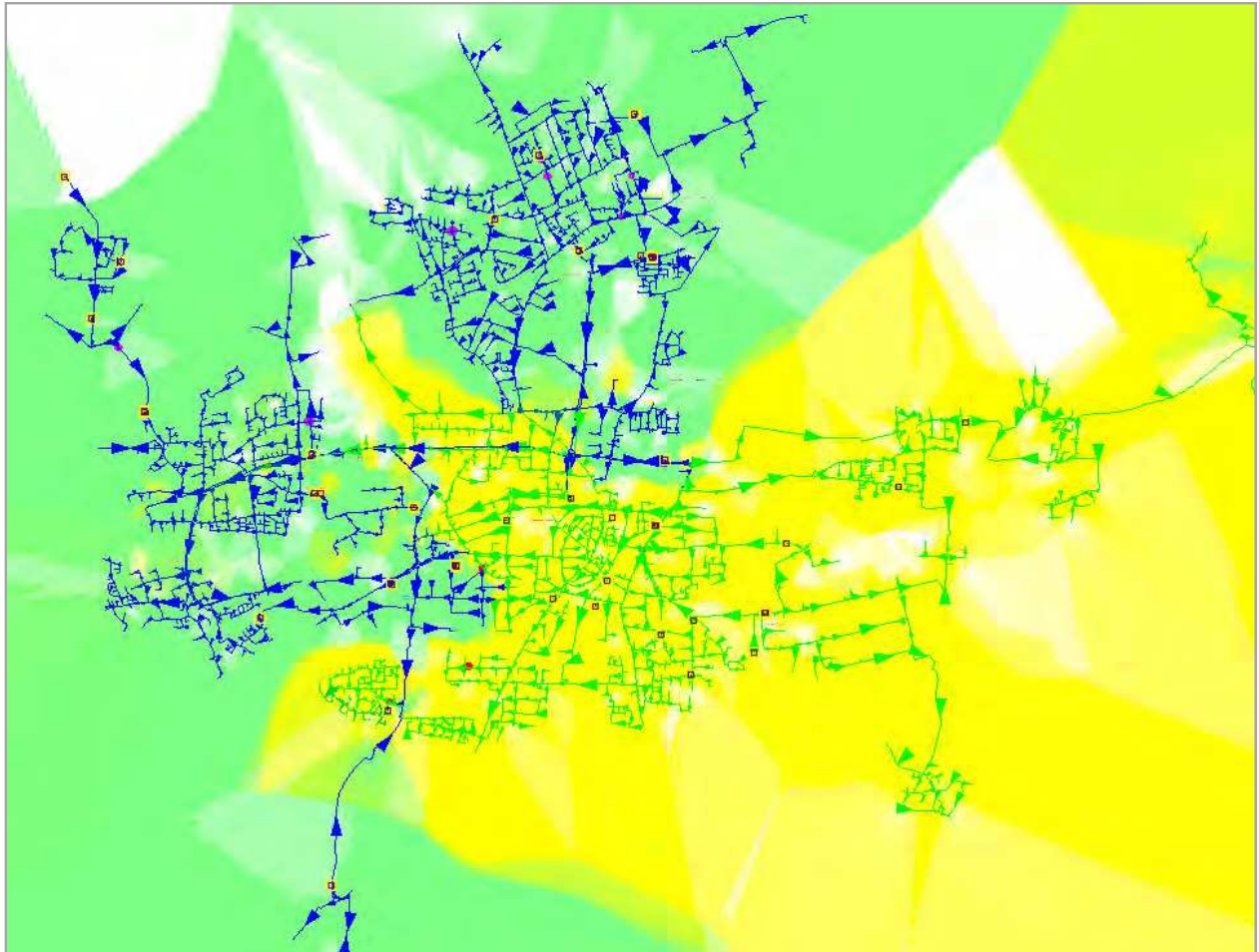


Fig. 9. Areas of influence of the feeder points (calorific value distribution distinct by colored borders in the background: yellow/ green)

The next example shows the result of the tracking of the calorific value for high pressure network (see figure 10). Here two biogas plants feed into the network at different points; the three feeder points from other upstream transportation systems (not shown here) are equipped with process gas chromatographs ensuring complete information of the incoming gas qualities. The pipelines are color coded according to their calorific value. As the calorific value changes with time there are different values which are transported downstream in the pipes (visible in simulation only, not in this snapshot at a distinct time). Apart from the transport of different calorific values the areas of influence are discernable (e.g. blue colored pipes).

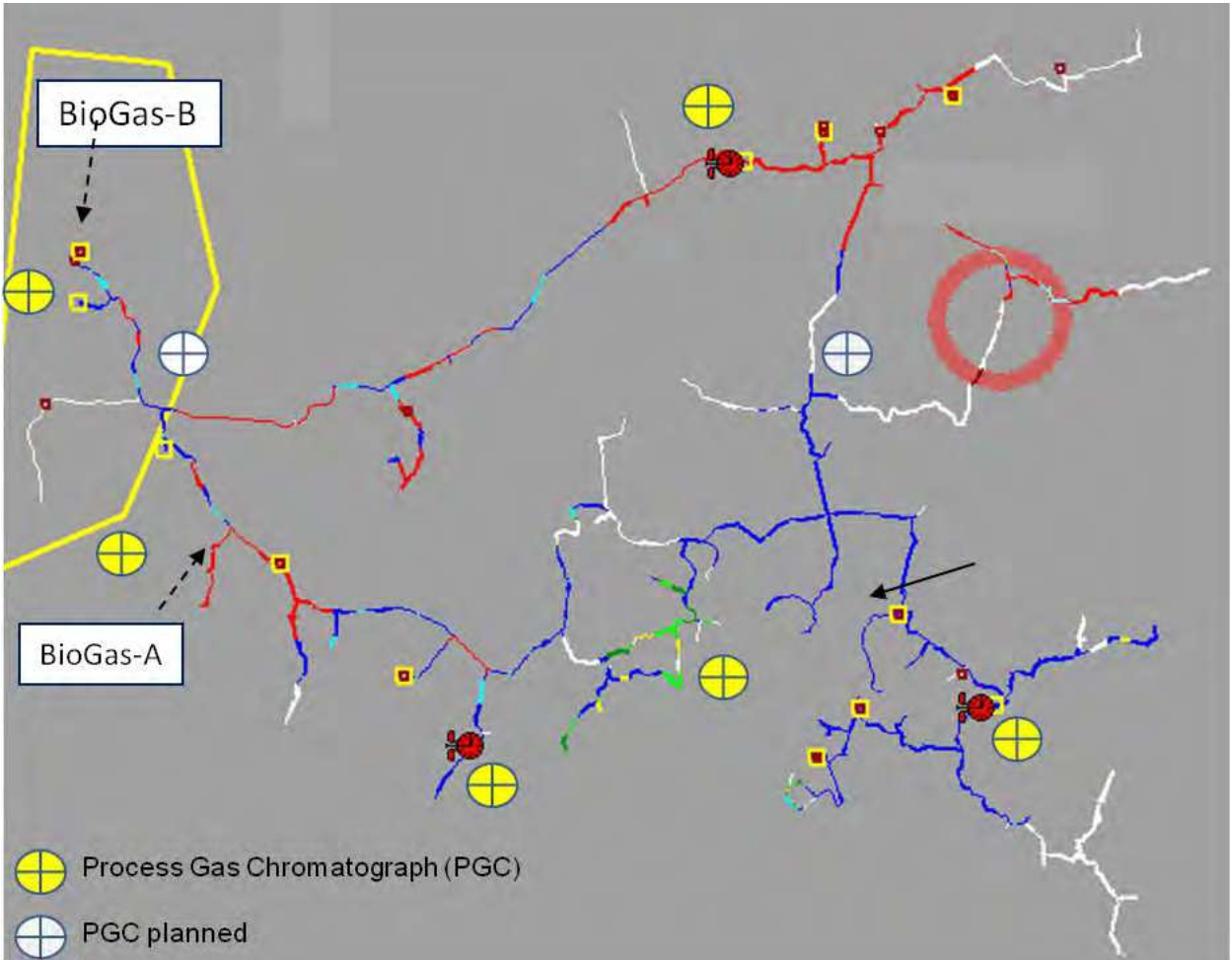


Fig. 10. Tracking off the calorific value in a high pressure transport network and biogas feedings (A, B)

7. Tools, programs

7.1 Features of available simulation programs, short overview

Simulation programs are available as stand-alone versions or as integrated versions in a SCADA system. The best known and well reputed simulation programs for gas in Europe/Germany are summarized below highlighting some features:

Program Name	Producer	Features	Remarks
GANPRODA	PSI AG, Berlin	Integrated in SCADA; (GANESI based); online + offline simulation; tracking/reconstruction of calorific value	Medium: gas; static + dynamic computation
SIMONE	Liwacom, Essen	Stand-alone version; online + offline simulation; tracking/reconstruction of calorific value	Medium: gas; static + dynamic computation
STANET	Fischer-Uhrig Engineering, Berlin	Stand-alone version; online + offline simulation; tracking/reconstruction of calorific value, quality parameters	Medium: gas, water, steam, electricity; static + dynamic computation
Stoner SPS	Advantica/ German Lloyd, Hamburg	Stand-alone network calculation	

Table 3. Programs for simulation and gas quality parameter tracking

7.2 IT-systems requirements

The simulation programs can be executed already on a powerful PC; for big networks which have more than 100,000 pipes a powerful server type of computer with fast and large storage capacity is recommended. Computing time for static simulation ranges from seconds to few minutes (10,000 pipes about 20 s, 200,000 pipes about 150 s); dynamic simulations will take time according to the length of the period to be simulated.

8. Shortcomings, limitations

Unfortunately there are some limitations which should be known and considered when one will work and plan with simulation results:

8.1 Calibration aspects for network model and verification

In order to verify the computing results the network should be calibrated first. This means in the initial phase the simulation results must be compared with and validated against measurements taken in the field, e.g. pressure at selected (better many) control points. In most cases the network points which have appropriate measurements are sparsely installed. Calibration is a project that needs an extra effort and maybe temporary installation of additional measurements. If calibration is omitted then the computed/simulation results could be uncertain at a (small) percentage in a specific area (of few measurement points). Pipeline roughness value is another value that is often not really known but estimated, only. Instead, an “integral” roughness value is used for the pipes which averages individual values and some small scale effects on flow (e.g. sharp bendings).

8.2 Consumer behavior and data acquisition cycles

The small consumer's individual daily behavior is not known exactly; only an aggregation of all consumers can be calculated. This is due to the fact that consumption values are normally read and collected once a year. For computing purposes a yearly value has to be deduced to a daily or even hourly value by standard load profiles which have implicit uncertainties, of course. One day this shortcoming will be overcome stepwise when Smart Metering will be widely introduced and used.

8.3 Accuracy, cost-efficiency

Many measurements which are useful from the technical or simulation point of view may not be useful for economic reasons. Additional measurements cost extra money: equipment, erection, survey and maintenance, etc. So, in fact any computation will have to cope with less data points and less accuracy than desired or theoretically possible.

8.4 Technical board acceptance procedure

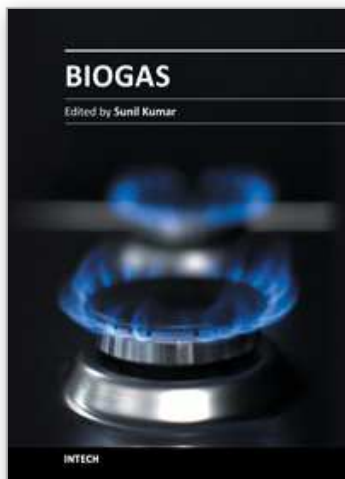
Introduction and use of quality parameter tracking systems (for calorific value) require an individual technical acceptance procedure from the Technical Board and a special operating permit. The required accuracy of the computed result must be better than $\pm 2\%$ in the network area or $\pm 0.8\%$ from total measuring range. In addition, a number of permanently recorded control measurements are requested to prove the correctness and integrity of the used data for the Technical Board authority.

9. Conclusion, benefits

Calorific value tracking is a most useful simulation tool in order to derive detailed information all over the network for every node and not only at distinct points. This method replaces many costly measurements in the network. Applying historical data to this tool helps to reconstruct all gas parameters and physical states of the past. Using the forward-looking method it enables even optimization of the gas conditioning for all biogas injections into the network. Aside from existing limitations the precision of the computed calorific value is high. Based on these data billing can be made fair as each consumer could get to know his energy consumption the best way possible.

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Biogas

Edited by Dr. Sunil Kumar

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This book contains research on the chemistry of each step of biogas generation, along with engineering principles and practices, feasibility of biogas production in processing technologies, especially anaerobic digestion of waste and gas production system, its modeling, kinetics along with other associated aspects, utilization and purification of biogas, economy and energy issues, pipe design for biogas energy, microbiological aspects, phyto-fermentation, biogas plant constructions, assessment of ecological potential, biogas generation from sludge, rheological characterization, etc.

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University Campus STeP Ri
Slavka Krautzeka 83/A
51000 Rijeka, Croatia
Phone: +385 (51) 770 447
Fax: +385 (51) 686 166
www.intechopen.com

InTech China

Unit 405, Office Block, Hotel Equatorial Shanghai
No.65, Yan An Road (West), Shanghai, 200040, China
中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
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