Development of a transient network simulation to determine the temporal and local linepack

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ABSTRACT

The compressibility of natural gas forces a sufficient linepack within the pipeline network to fulfill delivery pressures and to compensate balances between feed-in and withdrawal. Therefore, the network operator needs a precise knowledge of the actual linepack distribution at any time. The scope of this paper is the development of a method to simulate and determine the linepack of a natural gas pipeline network.

The developed method uses a segmentation of the pipeline network and calculates the linepack for each segment separately. Additionally, it combines two transient approaches for network calculations to improve the computing time. For the initial solution, the method uses an existing Newton-Raphson approach.

The results demonstrate the realistic physical behavior of the developed method. Furthermore, the paper shows investigations for the temporal and local linepack distribution and proves that the approach is qualified to investigate the temporal and local linepack behavior in a complex pipeline network.

INTRODUCTION

In the context of the liberalized European gas market, the network operator of natural gas transport networks has the function to manage the gas transport of different actors [1]. Consequently, it is one of the central tasks of the network operator to fulfil the contractual delivery pressures of the customers and thereby deliver a given amount of gas at a given pressure. Based on the compressibility of natural gas, a sufficient linepack must exist in the network to maintain the required pressure level [2]. Because the pressure loss increases with increasing transport volume, the necessary linepack volume varies with each transport situation [3].

Because of forecast deviations, imbalances between natural gas feed-in and withdrawal occur often [4]. Therefore, the linepack also compensates imbalances between natural gas feed-in and withdrawal of different actors. For this purpose, the network operator has to know the local distribution of the linepack, because the linepack has limited compensation speed within the pipeline.

Due the aforementioned two important tasks of the network operator, a precise knowledge of the actual linepack at any time is required to ensure a safe and efficient transportation system operation. For this task, computer-aided simulations are necessary, in order to monitor the natural gas transport network and operate external balancing sources. Therefore, the scope of this paper is the development of a method to simulate and determine the linepack of a natural gas pipeline network. For this purpose, the temporal variation and the local variation of the linepack must be considered.

Therefore, the paper analyses the network characteristics and derives the requirements for the method. Afterwards, the paper introduces existing approaches and elaborates the particular benefits and disadvantages. This is the basis for the described development of a new method. Exemplary simulations verify the developed approach and demonstrate that the physical relationships are reproduced. The investigations of the load flow are also benchmarked using state of the art simulation tools. Thereafter, examples investigate and explain the temporal and local distribution of the linepack. Finally, the conclusion summarizes the main findings.

NETWORK CHARACTERISTICS

Physical properties

Most network simulations are depending on the two Kirchhoff’s laws [5]:

1. The algebraic sum of all feed-in and withdrawal is in every network node zero.
2. The sum of all pressure losses in a closed loop is zero.

However, the laws depend on a steady-state situation. In case of law one, a violation would cause an injection or withdraw in the network node. Deviations from law two would cause different pressure levels in one and the same network node. This would lead to equalizing gas flow rates, which would reduce the pressure difference [5].

Furthermore, Kirchhoff‘s laws are also valid in transient cases [5]. However, storage processes within the pipelines could occur, so the material-balance equation governs the mathematical description of the transient flow [6]:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho \cdot w)}{\partial x} = 0 \quad (1)$$

In the equation ρ describes the gas density and w the gas velocity. The mass flow rate $\dot{m}$ of a pipeline with a cross-sectional area A is written as [5]

$$\dot{m} = \rho \cdot w \cdot A = \rho \cdot \dot{V} \quad (2)$$

Alternative, the mass flow rate $\dot{m}$ is expressed by the flow rate $\dot{V}$. The flow can be different at the beginning of the pipeline $(x = 0)$ than at the end of the pipeline $(x = l)$ with pipeline length l. This difference, due to injection or withdrawal, leads to packing and drafting of the linepack within the pipeline and to a change of the gas density ρ over time t. Therefore, the gas flow rate in or out of the defined volume is variable, due to compressibility of the fluid [7].

The momentum equation is the second equation to describe transient cases [6]:

$$\frac{\partial(\rho \cdot w)}{\partial t} + \frac{\partial(\rho \cdot w^2)}{\partial x} + \frac{\partial p}{\partial x} + \frac{\lambda}{2 \cdot d} \cdot (\rho \cdot w^2) = 0 \qquad (3)$$

The equation is additional expressed by the pressure p, the friction factor λ and the pipeline diameter d. The momentum equation describes that the chronological change of the momentum of fluid-particles is equal to the sum of the related forces. As acting forces of the transient and steady-state flow acceleration, the pressure force and the power of resistance are taken into account [7].

Equations (1) and (3) are depending on the Euler equations for fluid dynamics, which are a simplification of the three Navier-Stokes equations. The third equation, which is the energy equation, is negligible, since heat exchange with the environment happens too slowly for measurable effects [8]. The equations also neglect the vertical height of the pipeline, because the considered pipeline networks are approximately horizontal [9]. Therefore, the calculation depends on the time t and the location x.

Linepack

Packing and drafting of the linepack occurs or is volitional in many cases. As the linepack is a temporary storage within the pipeline, the storage capacity is of interest. As for any storage, the geometrical volume V_{geo} of the pipeline is calculated by [5]:

$$V_{geo} = \frac{\pi \cdot d}{4} \cdot l \qquad (4)$$

The determination of the linepack needs the pressure additional to the geometrical volume. As stated before, the pressure within a pipeline is temporally and locally variable. Due to this fact, the integrated average pressure p_m is sufficient as an actual pressure value for a pipeline segment from location i to j [5]:

$$p_m = \frac{2}{3} \cdot \frac{p_i^3 - p_j^3}{p_i^2 - p_j^2} \qquad (5)$$

Applying formula (2), (4) and (5) the standard gas volume V_s of the linepack is:

$$V_s = \frac{m}{\rho} = V_{geo} \cdot \frac{p_m}{p_s} \cdot \frac{T_s}{T_m} \cdot \frac{1}{K_m} \qquad (6)$$

The integrated average pressure is related to the pressure under standard conditions p_s and the actual mean temperature T_m is related to the temperature under standard conditions T_s. Furthermore, the compressibility factor K_m is also a mean value along the considered pipeline segment. This assumption is valid for steady-state and transient cases if the segment size is small enough [5]. Furthermore, a method of segmentation allows a linepack location within a pipeline.

Requirements for developed method

This section defines the requirements for the development of a method, which is capable of simulating and determining the linepack of a natural gas pipeline network. Since temporal and local changes in the linepack are never a steady-state phenomenon, the network calculation has to use the equations from formula (1) and (3). This requires transient models to make precise statements. Furthermore, the linepack physics have to be taken into account. Therefore, the method has to calculate the pressure of every location within the network, including pipeline segments. Moreover, because the pressure interacts with the gas flow rate, the method has to calculate the gas flow rate for every pipeline segment.

EXISTING APPROACHES

As the problems of transient calculations are known for many years, there exist already different approaches. Published papers present different models to determine the load flow in the network. The main approaches are the Method of Characteristics [8, 10, 11], the Difference Procedure [8, 9] and the Implicit Method [8, 10, 11]. Each of these methods uses as an initial solution a steady-state calculation [8]. Therefore, this section introduces first the steady-state calculation and afterwards the three approaches.

Steady-State Calculations

Under steady-state conditions, the gas flow rate under standard conditions $\dot{V}_s$ into a pipeline is equal to the gas flow rate out of a pipeline and within the system are no equalizing flows. This formulates Kirchhoff's first law (see section physical properties) as

$$\sum_{i \neq j} \dot{V}_{s,ij} + \dot{V}_{s,i} = 0 \qquad (7)$$

Where the sum of all standard gas flow rates $\dot{V}_s$ at network node i is zero [12]. In formula (7) the gas flow rate $\dot{V}_{s,ij}$ describes a flow from or to a node j and the gas flow rate $\dot{V}_{s,i}$ the feed-in or withdrawal at the node i. The common formula for pressure losses between the pressures p of node i and node j shows the relation between the pressures and the steady-state standard gas flow rate [12]:

$$p_i^2 - p_j^2 = \frac{16 \cdot \lambda \cdot \rho_s \cdot p_s \cdot T \cdot K \cdot l}{\pi^2 \cdot d^5 \cdot T_s} \cdot \dot{V}_{s,ij}^2 \tag{8}$$

The insertion of formula (8) in formula (7) generates for every network node a non-linear problem with the objective to find the zeros with unknown pressures $\vec{p}$ [12]:

$$\vec{f}(\vec{p}) = \vec{0} \tag{9}$$

It is not possible to solve the problem analytically. For that reason most approaches use the Newton-Raphson-Method as an iterative method [8].

Method of Characteristics

The Method of Characteristics uses the theory of ordinary differential equations to solve the formulas (1) and (3), which many papers [8, 10, 13] describe. As a first step, the formulas (1) and (3) are transformed to use the factor pressure p and mass flow rate $\dot{m}$. Thereby, the location x and the time t are independent variables. Subsequently, the eigenvalues are combined and by the use of the speed of sound c relaxed. The last step introduces a new factor $\bar{R}$, which pools all frictional factors in the equation:

$$\bar{R} = \frac{\lambda \cdot c^2}{2 \cdot d \cdot A^2} \cdot \dot{m}_{max}^{2-n} \tag{10}$$

The transient exponent variance n controls the impact of the local mass flow rate. These steps formulate a system of two characteristic equations and two straight lines [10]:

$$C_+ \begin{cases} \dfrac{dx}{dt} = c & (11) \\ \dfrac{dp}{dt} + \dfrac{c}{A} \cdot \dfrac{d\dot{m}}{dt} + \bar{R} \cdot \dfrac{c}{p} \cdot \dot{m} \cdot |\dot{m}|^{n-1} = 0 & (12) \end{cases}$$

$$C_- \begin{cases} \dfrac{dx}{dt} = -c & (13) \\ -\dfrac{dp}{dt} + \dfrac{c}{A} \cdot \dfrac{d\dot{m}}{dt} + \bar{R} \cdot \dfrac{c}{p} \cdot \dot{m} \cdot |\dot{m}|^{n-1} = 0 & (14) \end{cases}$$

The characteristic formulas (12) and (14) are only valid on their straight lines from formula (11) and (13). The mass flow rate and the pressure in the point of intersection of the straight lines P is then calculated by integration of the characteristic formulas depending on the points A and B and formulated by:

$$C_+: \; p_P - p_A + \frac{c}{A}(\dot{m}_P - \dot{m}_A) + \frac{\bar{R} \cdot \Delta x}{p_P + p_A} \cdot (\dot{m}_P \cdot |\dot{m}_P|^{n-1} + \dot{m}_A \cdot |\dot{m}_A|^{n-1}) = 0 \tag{15}$$

$$C_-: \; p_P - p_B - \frac{c}{A}(\dot{m}_P - \dot{m}_B) - \frac{\bar{R}\Delta x}{p_P + p_B} \cdot (\dot{m}_P \cdot |\dot{m}_P|^{n-1} + \dot{m}_B \cdot |\dot{m}_B|^{n-1}) = 0 \tag{16}$$

Hence, an orthogonal grid can be stretched. The axis of abscissae expresses the pipeline length and the axis of ordinates represents the time as show in Fig. 1.

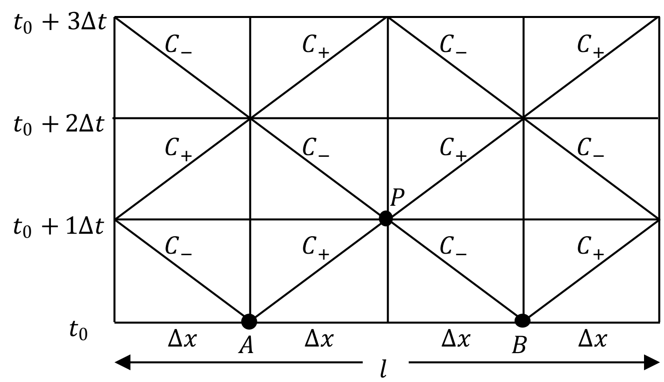

Fig. 1: grid of characteristic segments

Due to the limited velocity of propagation close to the speed of sound in formulas (15) and (16), the speed of sound describes the relation between Δx and Δt [10]:

$$\Delta x = \Delta t \cdot c \tag{17}$$

Therefore, the method has to choose the time step Δt in a way that Δx is a common divisor for all pipeline segments of a network. This leads to small time steps and accordingly, to higher computing time. On the other hand, the Method of Characteristics estimates all possible characteristics of a natural gas network like changes in the gas flow direction.

Difference Procedure

Formula (1) and (3) are the basis of the Difference Procedure. The method transforms them into a system of partial differential equations [9]:

$$\frac{\partial p}{\partial t} + z_1 \cdot \frac{\partial}{\partial x}(\dot{V}_s) = 0 \tag{18}$$

$$p \cdot \frac{\partial p}{\partial x} + z_2 \cdot \left(\dot{V}_s\right)^2 = 0 \tag{19}$$

Using:

$$z_1 = \frac{4 \cdot p_s \cdot K_m \cdot T_m}{\pi \cdot d^2 \cdot T_s} \tag{20}$$

$$z_2 = \frac{8 \cdot \lambda \cdot p_s \cdot \rho_s \cdot K_m \cdot T_m}{d^5 \cdot \pi^2 \cdot T_s} \tag{21}$$

The Difference Procedure determines stepwise grid points of a grid. The grid spans the field of observation in x-direction with step size Δx and in t-direction with step size Δt as shown in Fig. 2.

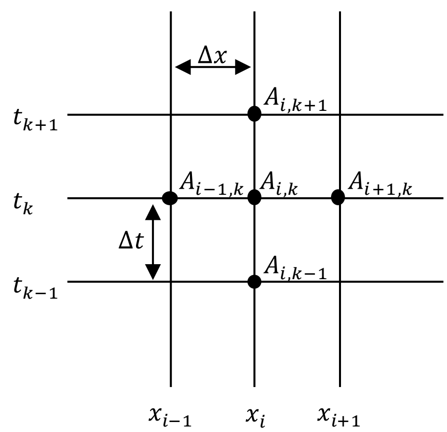

Fig. 2: grid of Difference Procedure

The use of the central difference quotient for the x-direction and the forward difference quotient in t-direction can be inserted into the system of partial differential equations from formulas (18) and (19) and yields the following equations, which are fast to calculate:

$$p_{i,k} = p_{i,k-1} + z_1 \cdot \frac{\Delta t}{2 \cdot \Delta x} \cdot \left(\dot{V}_{s_{i-1,k-1}} - \dot{V}_{s_{i+1,k-1}}\right) \tag{22}$$

$$\dot{V}_{s_{i,k}} = \sqrt{\frac{1}{2 \cdot \Delta x \cdot z_2} \cdot p_{i,k} \cdot \left(p_{i-1,k} - p_{i+1,k}\right)} \tag{23}$$

Concluding, the Difference Procedure has fast computing times, but a change of the gas flow direction is not possible, due to the square root function of the directed gas flow in formula (23).

Implicit Method

The Implicit Method bases on formula (1) and (3) and substitutes the density dependency and gas velocity dependency with a pressure and a mass flow dependency [10]. The frictional factors are pooled in the factor $\bar{R}$ known from formula (10) using the transient exponent variance n:

$$\frac{\partial p}{\partial t} + \frac{c^2}{A}\frac{\partial \dot{m}}{\partial x} = 0 \tag{24}$$

$$\frac{1}{2}\frac{\partial (p^2)}{\partial x} + \frac{p}{A}\frac{\partial \dot{m}}{\partial t} + \bar{R} \cdot \dot{m} \cdot |\dot{m}|^{n-1} = 0 \tag{25}$$

The use of difference quotients for a pipeline segment from location A to location B (as seen in Fig. 3) instead of the differentials from formulas (24) and (25) leads to the equations [10]:

$$f_1 = \frac{p_{A2} - p_{A1} + p_{B2} - p_{B1}}{2 \cdot \Delta t} + \frac{c^2}{A} \cdot \frac{\dot{m}_{B2} + \dot{m}_{B1} - \dot{m}_{A2} - \dot{m}_{A1}}{2 \cdot \Delta x} = 0 \tag{26}$$

$$f_2 = \frac{1}{2}\frac{p_{B2}^2 + p_{B1}^2 - p_{A2}^2 - p_{A1}^2}{2 \cdot \Delta x} + \frac{p_{A2} + p_{A1} + p_{B2} + p_{B1}}{4 \cdot A} \cdot \frac{\dot{m}_{A2} - \dot{m}_{A1} + \dot{m}_{B2} - \dot{m}_{B1}}{2 \cdot \Delta t} + \frac{\bar{R}}{4^n} \cdot (\dot{m}_{A2} + \dot{m}_{A1} + \dot{m}_{B2} + \dot{m}_{B1}) \cdot |\dot{m}_{A2} - \dot{m}_{A1} + \dot{m}_{B2} - \dot{m}_{B1}|^{n-1} = 0 \tag{27}$$

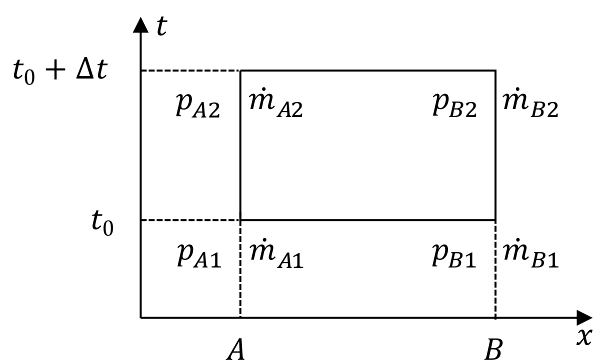

Fig. 3: implicit segment

As shown in Fig. 3 and in formulas (26) and (27) the differential equations are transformed to non-linear equations with four unknowns. As neighboring segments have common unknowns, the network node formula (7) is valid and the feed-in and withdrawal of the nodes are known, there are enough equations to determine the unknowns. Furthermore, the variables with index 1 are known for the next time step with the index 2.

The time step Δt is variable in the Implicit Method, but it has to calculate all equations for a pipeline network concurrent, as introduced above. This leads to very high computing times. However, the Implicit Method estimates all possible characteristics of a natural gas network like changes in the gas flow direction.

Preliminary Conclusion

Contrary to the Difference Procedure, the existing approaches of the Method of Characteristics and the Implicit Method fulfil the requirement resulting from the linepack determination. However, both methods have the disadvantage of high computing times. The Method of Characteristics as a result of the fixed segment size for every pipeline and the Implicit Method as a consequence of the dependency of all equations on each other. Therefore, this paper develops a method by combing the advantages of these two methods by simultaneously removing the disadvantages.

DEVELOPED METHOD

All existing approaches share the shortcoming that they do not take into account the linepack. Therefore, this paper develops a method to calculate the linepack. Furthermore, the developed method improves the existing approach through combination from the Method of Characteristics and the Implicit Method.

Every transient gas flow rate calculation needs an initial solution for the actual pressure values and the gas flow rate within the network. Therefore, existing methods use a steady-state simulation. For this purpose, the developed method uses also a steady-state calculation for the first time step. For this, the approach chooses an existing method using a Newton-Raphson method, which is developed by the Institute of Power Systems and Power Economics (IAEW) at RWTH Aachen University [14].

Approach

After the first time step, the steady-state constraints like same feed-in and withdrawal are no longer valid. As the approach models the pipeline network as network nodes in connecting pipelines, the feed-in or withdrawal for every node must be known by considering mass controlled networks.

The time step Δt determines the accuracy of a transient gas flow rate calculations. As shown in formula (17), the time step Δt is related to the segment size Δx in the Method of Characteristics and the method configures segment size Δt by the common divisor of the pipelines. The use of the Implicit Method can counterbalance this disadvantage, because the segment size Δx_i is variable. Since the choice of the time step Δt defines the segment size Δx, the random choice of Δt would probably result in a segment size, which is not a common divisor of every pipeline. Accordingly, a segment smaller than Δx would remain. By putting an implicit segment into the last segment, the complete pipeline could be modeled [10]. By putting the implicit segment into the middle of the pipeline, as shown in Fig. 4, the method decouples the implicit segment from other implicit segments. This decoupling leads to advantages in computing time, because the method determines single implicit segments independently [10].

According to the explanations from Fig. 1 and Fig. 3, the combination results in Fig. 5, which is the standard case of pipeline with a length longer than $2 \cdot \Delta x$. Furthermore, many special cases could occur. These could be a pipeline with one characteristic and one implicit segment, a pipeline depending only on one implicit segment or of course branches and feed-in or withdrawal network nodes.

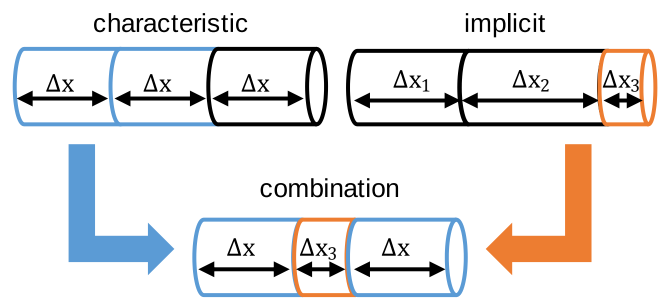

Fig. 4: segment combination – demonstrative

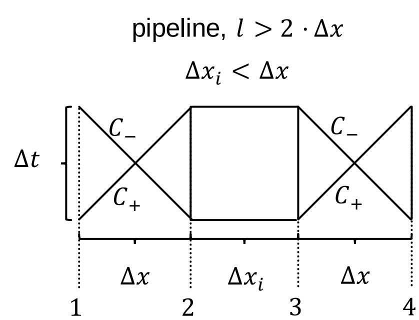

Fig. 5: segment combination - mathematical

Linepack determination

As the paper introduced before, the linepack can be calculated by the use of the integrated average pressure (formula (5) and (6)). As the developed method calculates the pressure at the beginning and the end of every pipeline segment, it uses the formula for every segment. In this way, the developed method determines the local distribution of linepack and by summing up of all segments the total amount of linepack within the pipeline network. The calculation in every time step also allows the investigation of the temporal change of the linepack.

Simulation sequence

Fig. 6 demonstrates the simulation sequence. In the first step, the method reads the input data, like the network topology or the feed-in and withdrawal, and calculates the initial steady-state solution. Then the methods divides the pipeline into characteristic and implicit segments depending on the chosen time step, before the gas flow rate calculation starts. As described before, the method calculates every segment independently, which leads to improved computing times. Depending on the calculated pressure level and gas flow rate for every segment, the method determines the linepack. Afterwards, the pressure and gas flow rate for every node are calculated. In the last step, the calculation of the gas flow rate saves the data as input for the next time step. At the end of the sequence, the developed method exports the results as time and location depending pressures, gas flows rate and linepack.

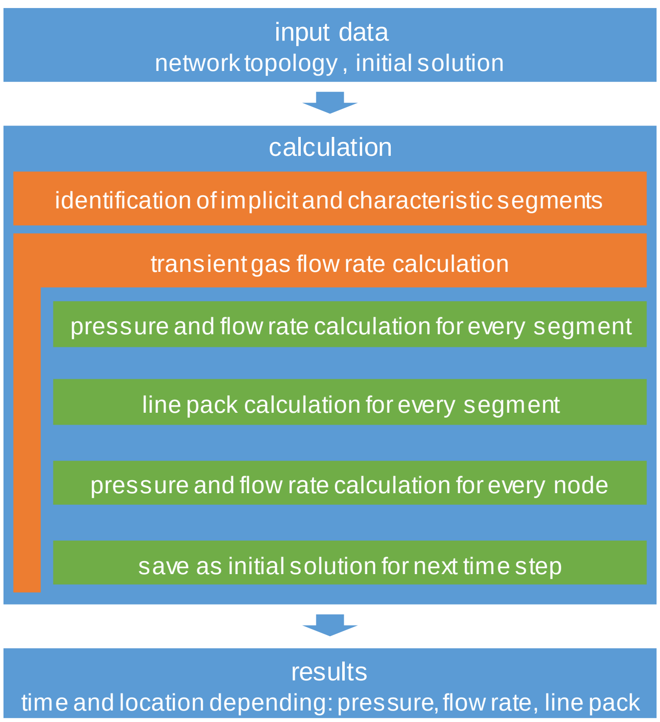

Fig. 6: simulation sequence

EXEMPLARY RESULTS

The exemplary results proof the physical behavior of the developed method and benchmarks them to an existing method. Afterwards the paper investigates the local and temporal linepack for different examples.

Input Data

The exemplary results use for the calculations an exemplary test network, which is shown in Fig. 14 in the annex. The network contains of a total pipeline length of 550 km. The pipeline diameter at the feed-in nodes are 0.8 m and decreases with increasing distance. The calculations use a time step Δt=15 s, which leads to a pipeline segment size Δx of 5025 m.

Fig. 7 shows the considered situation of the gas flow rate depending on the four feed-in nodes (see Fig. 14) and the withdrawal at the other nodes. The feed-in and withdrawal are in balance over the day. This means the injected volume is equal to the withdrawn volume. Additional to the situation of gas flow rate, the investigations consider a natural gas power plant, which generates power about six hours in the morning and has, to that effect, a gas withdrawal, as shown in Fig. 8. As a storage supplies the power plant, there is additional feed-in at the storage node. In scenario 1 the storage only injects gas over the day. The gas volume corresponds to withdrawal of the power plant. Fig. 8 shows these equal areas of injection and withdrawal. In addition, the paper considers a second scenario. In the second scenario, shown in Fig. 8, the storage injects more gas to the network than needed by the power plant in the morning. For that reason, the storage withdraws the additional gas volume in the evening hours.

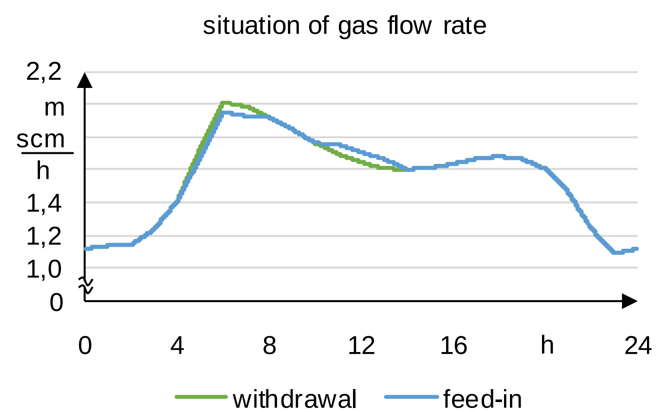

Fig. 7: situation of gas flow rate

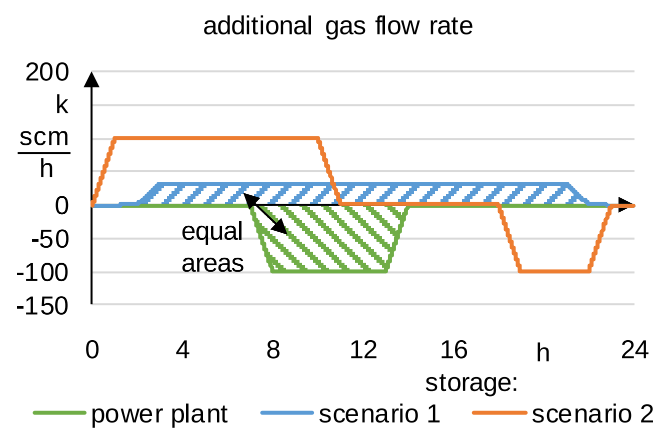

Fig. 8: additional gas flow rate

Verification of Approach

For the verification of the developed method, the paper considers the pressure at the beginning and the end of the storage pipeline and the gas flow rate within the storage pipeline. Fig. 9 shows that the dependency between pressure level and gas flow rate in the pipeline is correct. By consideration of the simplified formula (8), the pressure behavior becomes clear. In scenario 1 the injection rate of the storage is less than in scenario 2. Therefore, the pressure difference between the beginning and the end of the pipeline is smaller. Due to the fact that in scenario 1 the storage only injects gas, the pressure at the end of the pipeline is at all times smaller than at the beginning of the pipeline. Of course, the pressure is equal in the hours without any feed-in. The storage operation changes between feed-in and withdrawal in scenario 2. At times of withdrawal, the pressure at the beginning of the pipeline is smaller than the pressure at the end of the pipeline, as shown in Fig. 9 and as expected. In addition, the equal pressures during the hours without feed-in or withdrawal in scenario 2 are seen clearly. Thus, the investigation confirms the realistic physical relationships of the developed method.

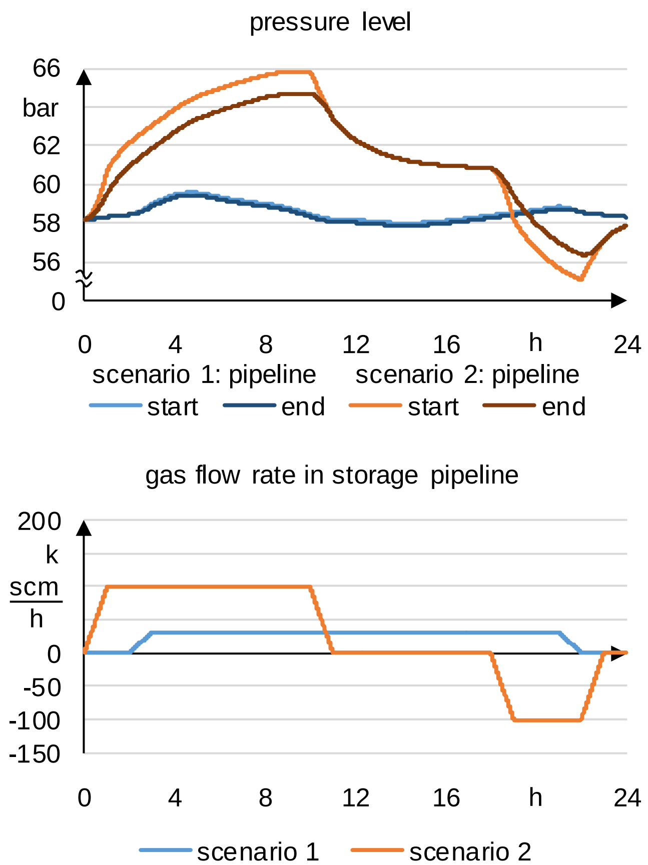

Fig. 9: dependence between pressure and gas flow rate

In addition, the exemplary investigation benchmarks the results of scenario 1 with a state of the art simulation. Firstly, the paper considers the pressure levels at the feed-in 1 node and the power plant node (see Fig. 14 in annex). Fig. 10 shows that the pressure profile at both nodes is almost equal. The small difference can be explained by the different time-steps of the simulation between 15 s in the developed method and 1 h in the state of the art simulation.

Secondly, the benchmark of the total linepack calculation proofs the quality of the developed method. Fig. 11 shows that the results of both methods are almost equal. Furthermore, the total linepack at the beginning of the time is equal to the total linepack at the end of the time. This is consistent with the balanced feed-in and withdrawal of the input data.

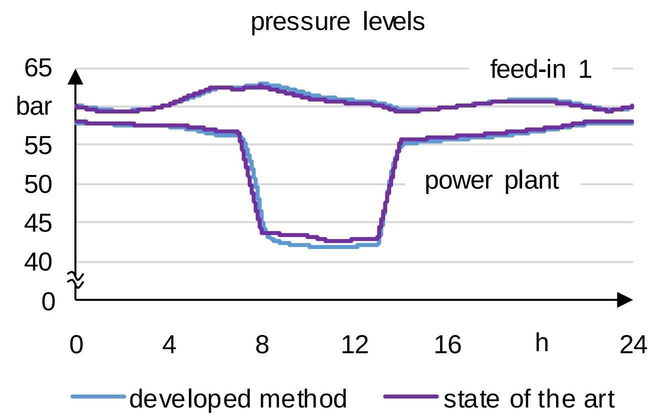

Fig. 10: pressure levels

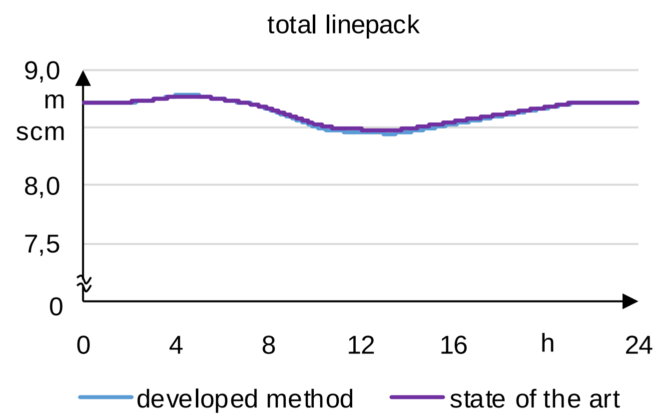

Fig. 11: total linepack of network

The verification investigations show that the developed method simulates a realistic physical behavior of a natural gas network. In addition, it is consistent to other calculation methods. Therefore, the approach is qualified to investigate the temporal and local linepack behavior of a complex pipeline network.

Linepack Investigations

The paper examines two scenarios with different storage operation, shown in Fig. 8, for the linepack investigations. Therefore, the first investigation describes the total linepack in dependence of the storage operation. Fig. 12 shows that the linepack in scenario 1 begins to decrease with the power plant operation and then increases after the power plant operation. In scenario 2 the storage injects more gas into the linepack than the power plant needs. Therefore, the linepack increases in the first hours. When the storage starts to withdraw, the linepack decreases again. The pressure level of feed-in 1 reflects this, because the increasing linepack leads to a higher pressure level. As the feed-in and withdrawal are balanced in both scenarios the linepack ends at the level from the beginning, such as the pressure level.

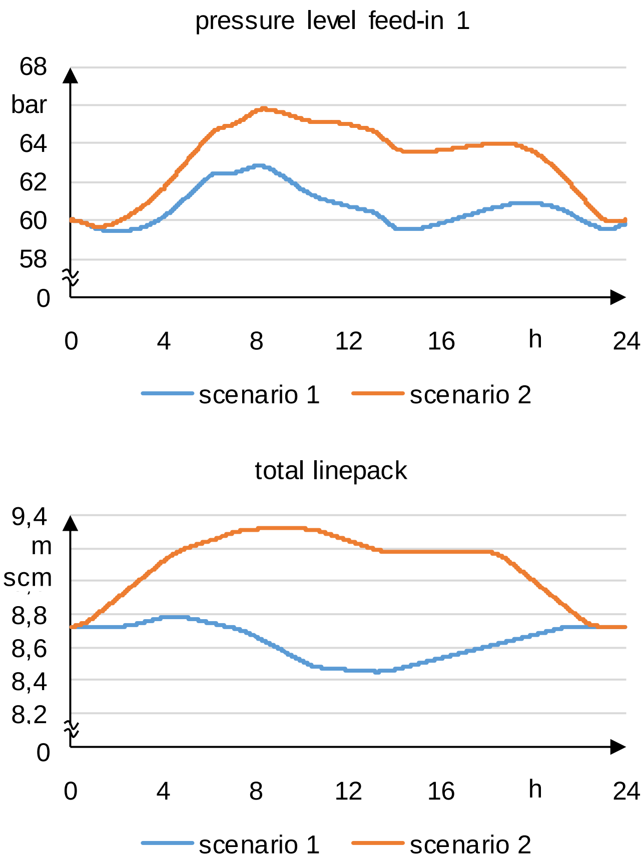

Fig. 12: dependence between pressure and linepack

The investigation of the power plant node shows more details. As seen before the increase of the total line pack increases the pressure level. Fig. 13 shows that this behavior is also seen in the network node of the power plant. Associated with this, the temporal line pack of the supply pipeline of the power plant also increases during the increase of the total line pack. Furthermore, a comparison between the pressure and the linepack of the power plant illustrates the correlation between pressure level and linepack.

Fig. 13 displays also the local linepack distribution. Due to the different segment sizes of the supply pipeline of the power plant, the linepack of the segments is standardized to the linepack per m. When the power plant does not operate, it needs no gas. Therefore, there is no gas flow rate within the supply pipeline and that is why there is no pressure difference between the end and the beginning of the pipeline. Thus, the pressure is the same throughout this pipeline. The linepack per m is consequently in every pipeline segment identical.

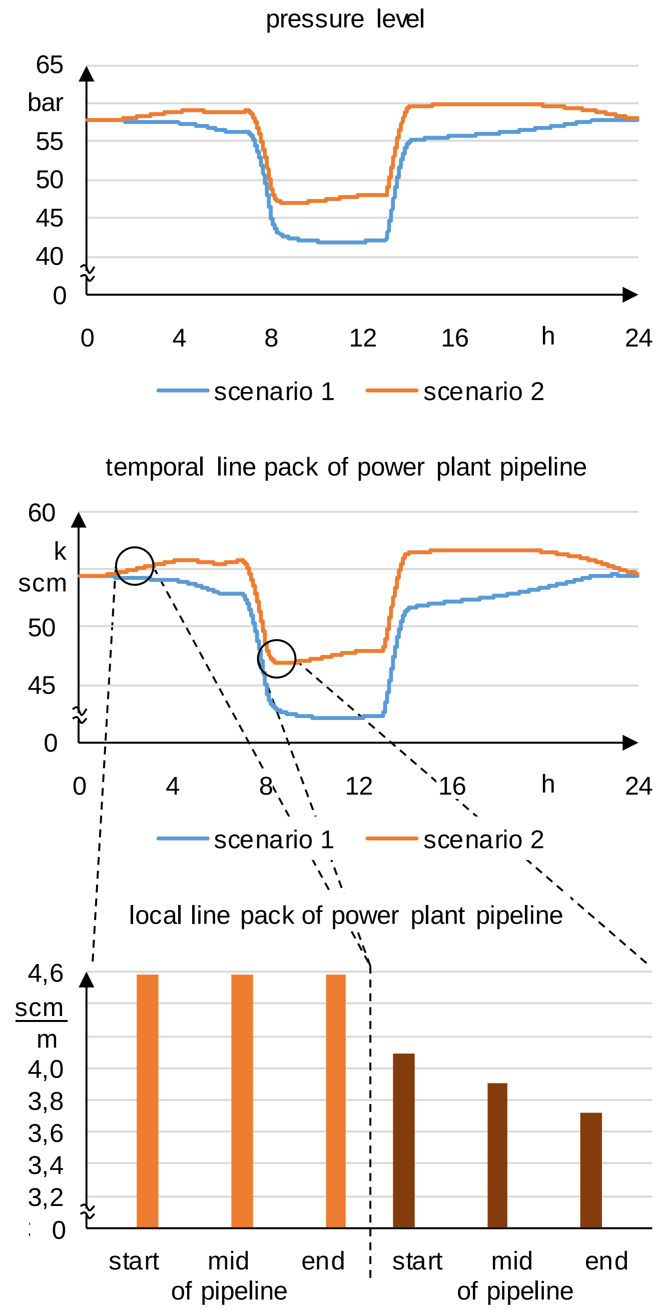

Fig. 13: linepack behavior

In an operating situation of the power plant, the linepack distribution is different. Firstly, the pressure level is lower. This leads to less linepack in the supply pipeline. Secondly, there is a gas flow rate through the pipeline, because the power plant needs gas to operate, as seen in Fig. 8. For this reason, there are pressure losses between the beginning of the supply pipeline and the end of the supply pipeline. Because the pressure at the beginning of the pipeline is higher, the linepack in the first segment is higher, too. This derives from the higher compressibility under higher pressure. Analogical, the linepack at the end segment is lower.

The linepack results demonstrate that the developed method simulates the linepack behavior accurately. They show also the dependency between linepack, pressure level and gas flow rate. This qualifies the developed method to make linepack investigations in natural gas pipeline networks. For example, the optimization of the interaction between linepack increase or decrease and the use of balancing energy.

CONCLUSION

The central task of the network operator is to fulfil the contractual delivery pressures of the customers. Based on the compressibility of natural gas, a sufficient linepack is needed, which varies with each transport situation. Additionally, the linepack has to compensate imbalances between natural gas feed-in and withdrawal. Correspondingly, the network operator has to know the local linepack distribution as well as the temporal line pack change. Therefore, the aim of the paper is the development of a computer-aided method to simulate and determine the linepack of a natural gas pipeline network.

Since temporal and local changes in the linepack are never a steady-state phenomenon, the network calculation requires transient models to make precise statements. As all existing approaches for transient calculations share the shortcoming that they do not take into account the linepack, this paper develops a method to calculate the linepack. The developed method uses a segmentation of the pipeline network and calculates the linepack for each segment independently. Furthermore, the developed method improves the existing approach through combination of the Implicit Method and the Method of Characteristics. For the initial solution, the method uses an existing Newton-Raphson approach.

The developed method shows realistic physical relationships and provides good matches with a state of the art simulation. The linepack investigations demonstrate the linepack behavior, such as the temporal and local distribution. Therefore, the approach is qualified to investigate the temporal and local linepack behavior in a complex pipeline network. Consequently, the method can investigate interactions between linepack increase or decrease and the use of balancing energy or other.

NOMENCLATURE

Formula Symbols

λ	friction factor
ρ	gas density
A	cross-sectional area
c	sound speed
C	characteristic equation
d	pipeline diameter
K	compressibility
l	pipeline length
$\dot{m}$	mass flow rate
p	pressure
$\bar{R}$	pool of frictional factors
t	time
T	temperature
V	volume
$\dot{V}$	gas flow rate
w	gas velocity
x	location
z	defined factor

Subscripts/Superscripts

$+$	direction
$-$	direction
A	grid Point
B	grid Point
geo	geometric
i	location
j	location
k	time step
m	integrated average
n	transient exponent variance
P	grid point
s	under standard conditions

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ANNEX

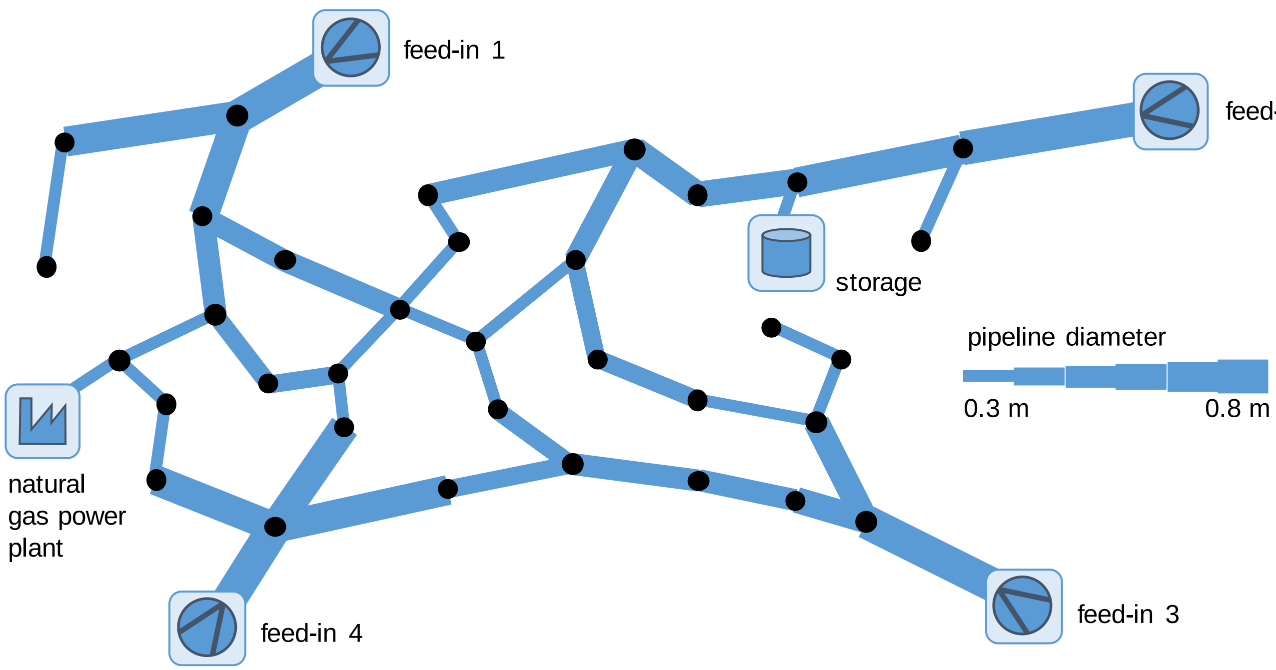

Fig. 14: considered network