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Modelling of Oil Pipeline Networks

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Summary: The developed model facilitates the analysis of actual operational states of oil pipeline systems. In this context, it can also be used to significantly reduce the uncertainties of flow rate measurements. It incorporates oil properties, energy and mass balances, and geometric data of the pipeline. Analytic approaches for the calculation of the pressure drop inside the pipeline sections, and the temperature drop along the pipeline have been implemented in order to enhance the accuracy of the model.

Souhrn: Navržený model umožňuje analýzu skutečných provozních stavů systémů ropovodů. V této souvislosti může být tento model užit k významnému snížení nejistot měření průtoku. Model zahrnuje vlastnosti ropy, bilance energie a hmotnosti a geometrická data ropovodu. Analytické přístupy pro výpočet tlakové ztráty v potrubních částech a teplotních diferencí podél potrubí jsou zahrnuty, aby bylo možné zvýšit přesnost modelu.

1. Introduction

This paper presents the development of a mathematical model for the calculation of the actual operational state of pipeline systems for liquid fluids. The model has been developed to be used as an online monitoring system for a pipeline transporting crude oil from a pumping station to the receiving point. It facilitates the continuous analysis of the actual state of operation including the detection of potential leakages and quality control of the transported oil. Another advantage of the model is a significant reduction of uncertainty in the measured flow rate, which is one of the key parameters in pipeline calculations in economic respect.

The model is based on the Gaussian minimization approach and uses process data reconciliation in order to find an optimal solution for the given flow problem. Data reconciliation is a technology that uses all available information to achieve a complete and realistic performance analysis of the overall process from less accurate process variable measurements:

- flow rate [Nm^3/h]
- internal pressure [bar]
- temperature [K]
- density [kg/m^3].

In addition to the measured values, analytical approaches have been developed to calculate the pressure difference and temperature drop along the pipeline sections according to fluid properties and geometric constrains. The calculated values provide further information that can be used while finding the optimal solution for the given flow problem. The resulting over-determined set of equations that describes the actual state of operation of the pipeline system is used to correct all considered data in such way, that coherent mass and heat balances as well as accurate key performance indicators (KPI's) based on consistent information are obtained. The accuracy of the single measurements is increased, by being transferred into a redundant and inter-dependent network of information.

The flow rate in the evaluated pipeline system is approximately 600 Nm^3/h. Reducing the tolerance of the measured value by 50 % can translate into millions of Euros per year for the pipeline operator.

Not only an optimized determination of the flow rate, but also increased availability of the pipeline due to the swift detection of leakages and the switch to condition based maintenance contribute to the financial benefits of the pipeline network.

Last but not least, process data reconciliation serves as an invaluable tool for avoiding environmental damages.

2. Theoretical background

2.1 Data reconciliation

All measured values are subject to distortions caused by avoidable, systematic or random errors (DIN 1319). For more than 200 years, the Gaussian correction principle has been available as an estimation method in the statistical-mathematical sense and allows these errors to be detected by taking boundary conditions into account.

The basic idea of this method is to use not only the minimum quantity of measured variables required to obtain a solution but to use all accessible measured variables along with their respective variances and covariances. Additionally, the true values of the measured variables must meet the boundary conditions:

- mass balances
- energy balances
- material balances (stochiometric laws).

This method is described in VDI 2048, see [1] and [2], and is the best possible quality control method available to detect serious measurement errors. This methodology allows consistent estimations of the true of the measured variables to be derived from conflicting measured values. The consistently estimated values correspond to the true values with a 95% probability.

2.1.1 Gaussian correction principle

Corrections ν are made to the measured values x in accordance with equation (1) in order to obtain estimated values (reconciled values) $\overline{x}$.

$$\overline{x} = x + \nu \qquad (1)$$

The corrections ν must be determined in such a manner that the quadratic form

$$\xi_0 = \nu^T \cdot S_X^{-1} \cdot \nu \Rightarrow Min \qquad (2)$$

ξ_0 ... square form of errors

S_X^{-1} ... inverse empirical covariance matrix

becomes a minimum. The empirical covariance matrix S_x is the estimated value for the uncertainty of the measured variables X. This general formulation also covers the existence of covariances, i. e. the interdependencies of the measuring points. The improved covariance matrix $S_{\bar{x}}$ is calculated from the empirical covariance matrix S_x and the covariance matrix of the improvements S_v as follows:

$$S_{\bar{x}} = S_x - S_v \tag{3}$$

2.1.2 Quality control

As a quality-control measure, two criteria must be fulfilled for process data reconciliation based on VDI 2048. First, the square form of errors ξ_0 contained in equation (2) must be smaller than $\chi^2_{95\%}$ (95% quantile of CHI square).

$$\text{VDI 2048 criterion 1:} \quad \xi_0 \quad < \quad \chi^2_{95\%} \tag{4}$$

The 95% quantile of CHI square is a statistical measure for the number of model redundancies and is included e.g. in [3] as a table. The number of model redundancies is dependent both on the number of equations contained in the model and on the number of embedded measured values and reflects the over-determined character of the system. The relationship between the square form of errors and CHI square is referred to as the reconciliation quality, see equation (5). Generally, the following applies: The smaller the reconciliation quality, the better is the quality of the model/measured values.

$$\text{Reconciliation quality} = \xi_0 \;/\; \chi^2_{95\%} \tag{5}$$

Additionally, the value of the individual penalty must be smaller than the statistical coefficient of 1.96. The value of the individual penalty of a measuring point is the ratio of the square of the improvement v_i to the difference between the estimated uncertainty of the measured value $s_{x,ii}$ and the calculated standard deviation of the reconciled value $s_{\bar{x},ii}$, see equation (6).

$$\text{VDI 2048 criterion 2:} \quad \frac{|v_i|}{\sqrt{s_{x,ii} - s_{\bar{x},ii}}} = \frac{|v_i|}{\sqrt{s_{v,ii}}} \leq 1.96 \tag{6}$$

This criterion must be fulfilled for all measured values *i*. If it is not fulfilled, a serious error exists in the corresponding measuring point *i* or in the estimated value of the associated uncertainty.

In this case, the reconciled value as well as the measured value itself is questionable. If both of the above criteria are complied with, the reconciled measured values $\bar{x}$ correspond to a 95% probability of the true physical state variables.

2.1.3 Consequences for an industrial process

When process data reconciliation based on VDI 2048 is applied to an industrial process, measured temperatures, mass flows and pressures lose their singular character. The physical relationships between the measured parameters generated via secondary conditions such as mass balance and energy balance result in a process image that corresponds to the physical basis of the process as closely as possible. The relationships thus generated can be represented via the correlation coefficients that result from the improved covariance matrix; see [1].

2.2 Calculation of the pressure gradient

The pressure gradient Δp along a pipeline section consist of two major components - friction and altitude difference - which are derived in the following chapters.

$$\Delta p = \Delta p_f + \Delta p_a \tag{7}$$

2.2.1 Pressure gradient due to friction Δp_f

In isothermal horizontal pipe flow at moderate velocities (> 0.5 m/s in the evaluated pipeline), the main cause of energy loss is the friction between the pipe wall and the moving fluid. The pressure loss due to wall friction can be expressed in terms of the friction factor λ which can be found in [4] and [5]. Also, it has been shown, that for low Reynolds numbers (*Re*) the friction factor is a function of *Re* only, whereas for sufficiently high *Re* the friction factor becomes a function of the wall roughness only. The formula of Colebrook [6], see equation (8), is valid for both cases as well as for the transitional regime in between.

$$\lambda = \frac{1}{\left[2\log\left(\frac{2{,}51}{\mathrm{Re}\sqrt{\lambda}} + \frac{0{,}27}{d/\varepsilon}\right)\right]^2} \tag{8}$$

d ... pipe diameter [m]
ε … surface roughness [m]
Re … Reynolds number.

It relates to pipes with technical surface roughness and is consistent with experimental data.

According to [7], the pressure gradient Δp_f between inlet and outlet of an evaluated pipeline section can now be calculated by using the following equation (9):

$$\Delta p_f = \frac{\lambda l \rho v^2}{2d} \tag{9}$$

l ... length of the pipeline section [m]
v … velocity of the fluid [m/s]
ρ … density of the fluid [kg/m^3]
d … pipeline diameter [m].

2.2.2 Pressure gradient due to altitude difference Δp_a

The density of the evaluated crude oil is approx. 840 kg/m^3. Therefore the pressure gradient over a pipeline section is mainly influenced by the difference in altitude Δh of section inlet and outlet. Following the Bernoulli equation given in [8], the pressure gradient Δp_a can be written as

$$\Delta p_a = \frac{v_2^2 - v_1^2}{2}\rho + \Delta h\, \rho\, g \tag{10}$$

g … gravitational constant [m/s^2]

Because it is assumed that no leakage flow occurs along the pipeline section, flow velocity at the inlet v_1 and outlet v_2 must be equal in order to close the mass balance over the pipeline section. Therefore equation (10) simplifies to

$$\Delta p = \Delta h \; \rho \; g \tag{11}$$

2.3 Calculation of heat transfer

Another important factor for the determination of the actual state of operation is the expected heat loss along the entire pipeline. This heat loss depends on a number of factors, such as inlet and outlet temperatures of the fluid, thermal conductivity and heat transfer coefficient of the used materials, different ambient conditions the pipeline is exposed to, the location of the pipeline below the ground, etc. An exemplary cross-section of a pipeline is shown in Figure 1.

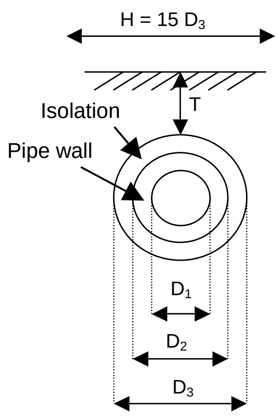

Figure 1: Pipeline cross-section

According to [9] the heat transfer rate $\dot{q}$ can be calculated by

$$\dot{q} = \frac{\pi \; L \left(t_{av} - t_{ambient}\right)}{\dfrac{1}{\alpha_{oil} \; D_1} + \dfrac{1}{2\lambda_{steel} \; \ln\left(\dfrac{D_2}{D_1}\right)} + \dfrac{1}{2\lambda_{insulation} \; \ln\left(\dfrac{D_3}{D_2}\right)} + \dfrac{1}{\lambda_{soil} \; \dfrac{2\,\pi\,L}{\cos^{-1}\left(\dfrac{2\,T}{D_3}\right)}} + \dfrac{\pi}{\alpha_{air} \; H}} \tag{12}$$

t_{av} … temperature difference between inlet and outlet [K]
$t_{ambient}$ … ambient temperature [K]
L … length of pipeline section [m]
a … heat transfer coefficient [W/m^2 K]
λ … thermal conductivity [W/m K]
T … buried depth [m]
Nu … Nusselt number based on D_1 or H.

Equation (12) includes the convective heat transfer coefficient of the crude oil, the resistance due to the pipe wall, isolation and soil (assuming heat transfer over 15 diameters) and finally the outside convective heat transfer coefficient of the air above the pipeline.

Heat transfer coefficients of crude oil and air are calculated according to the following equations (13) and (14).

$$\alpha_{oil} = \frac{Nu_{D_1}\ k_{oil}}{D_1} \tag{13}$$

$$\alpha_{air} = \frac{Nu_H\ \lambda_{air}}{H} \tag{14}$$

The determination of Nusselt number *Nu*, respectively Prandtl number *Pr* is described in [10]. Nusselt number based on D_1 is given by

$$Nu_{D_1} = 0.012\ \left(\mathrm{Re}_{D_1}^{0.87} - 280\right)\left(1 + \left(\frac{D_1}{L}\right)^{2/3}\right) \tag{15}$$

where the Reynols number based on the pipe diameter D_1 is expressed by equation (16).

$$\mathrm{Re}_{D_1} = \frac{4\,m}{\pi\ D_1\ \mu} \tag{16}$$

For the Nusselt number based on *H* equation (17) is valid:

$$Nu_H = 1.967\ \ \mathrm{Re}_H \left(\ln\left(\mathrm{Re}_H\right)\right)^{-2.584}\ \ \mathrm{Pr}^{1/3} \tag{17}$$

with

$$\mathrm{Re}_H = \frac{\rho\, v\, H}{\mu} \tag{18}$$

$$\mathrm{Pr} = \frac{c_p\ \mu}{\lambda} \tag{19}$$

c_p … specific heat of fluid [J/kg K]
L … length of pipeline section [m]
λ … thermal conductivity of fluid [W/m K]
μ … dynamic viscosity of fluid [kg/m s]
m … mass flow rate [kg/s]
ρ … density [kg/m^3]
v … wind velocity [m/s].

3. Pipeline model

3.1 Geometry and Layout

The length of the pipeline system analyzed in this paper is approx. 350 km. Its diameter is 700 mm and there are no tappings. It is divided into single sections by 54 line valve stations. The surface roughness of the used steel inside the pipeline is defined to be 0.3 mm. The altitude over sea level varies between 200 m and 600 m. The difference in amplitude of the pumping station at the inlet and the receiving station at the outlet is about 140 m. In Figure 2 the overall altitude profile of the pipeline is shown.

Three booster and three main pumps build up a working pressure of 65 bar at the pumping station, where the flow rate is measured by two serial ultrasonic flow meters. At the receiving station, a control valve adjusts the flow rate, which is again measured by two serial ultrasonic flow meters. The transport volume of the pipeline is approx. 600 Nm^3/h.

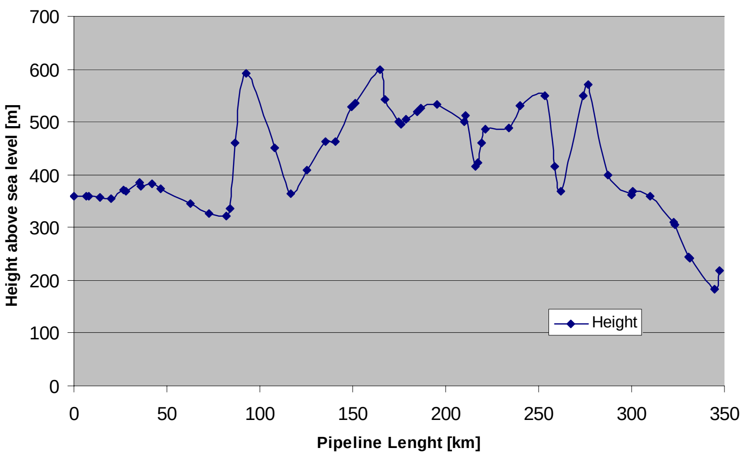

Figure 2: Altitude profile of the pipeline

3.2 Location and uncertainties of the measurements

The pipeline system is equipped with multiple measurement devices. Back and working pressure of booster and main pumps is available. The ultrasonic flow meters measure not only the flow rate but also temperature and density. The line valve stations provide data for the inlet pressure of the stations and in some cases inlet temperature. The measurements are implemented into the model with relative uncertainties as described in Chapter 2.1.

- 1 % for pressure
- 0.25 % for temperature (relating to Kelvin)
- 5 % for volume flow rate
- 5 % for electrical power
- 1 % for density
- 10 % for pressure gradients due to friction and amplitude differences, see chapter 2.2.

The temperature calculation described in chapter 2.3 is not included into the model yet, because of missing values for the ambient temperature.

4. Results

Figure 3 shows the local solution for pipeline section 14. There is only a small correction of the pressure value at the inlet of LV14, because the difference between the pressure gradient based on the measurements and the gradient according to chapter 2.2 is only 0.93 %. The measured temperature is not corrected at all, because the calculated temperature drop according to chapter 2.3 is not taken into account.

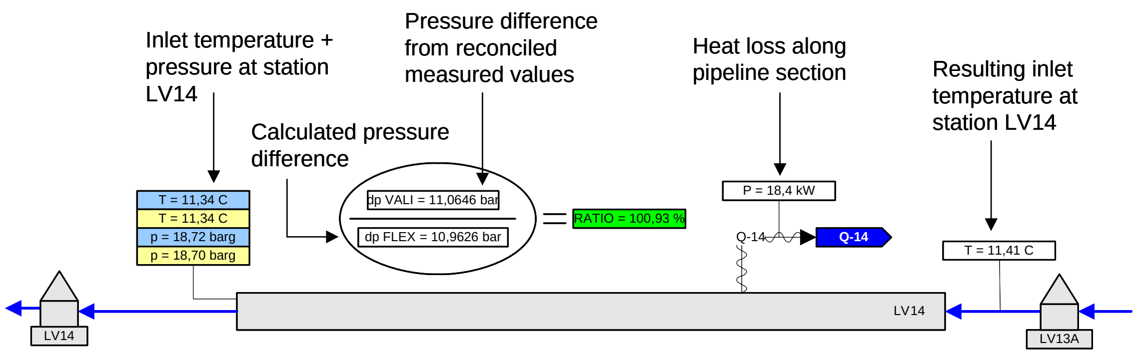

Figure 3: Results for pipeline section 14

In Figure 4 the measured and reconciled flow rate for the flow meters at the pumping station are displayed. Fluctuations of the measured values from the receiving stations (RS) are much higher compared to the pumping station (PS). Because all measurements have the same uncertainty (3 %), the fluctuations are reflected in the reconciled values. Furthermore, the correction of the measured values from PS is not as high as the correction of RS values. The reconciled uncertainty of the flow rate is 1.44 %, so the measured uncertainty is reduced by more than 50 %. The solution for the complete pipeline system is shown in Figure 5.

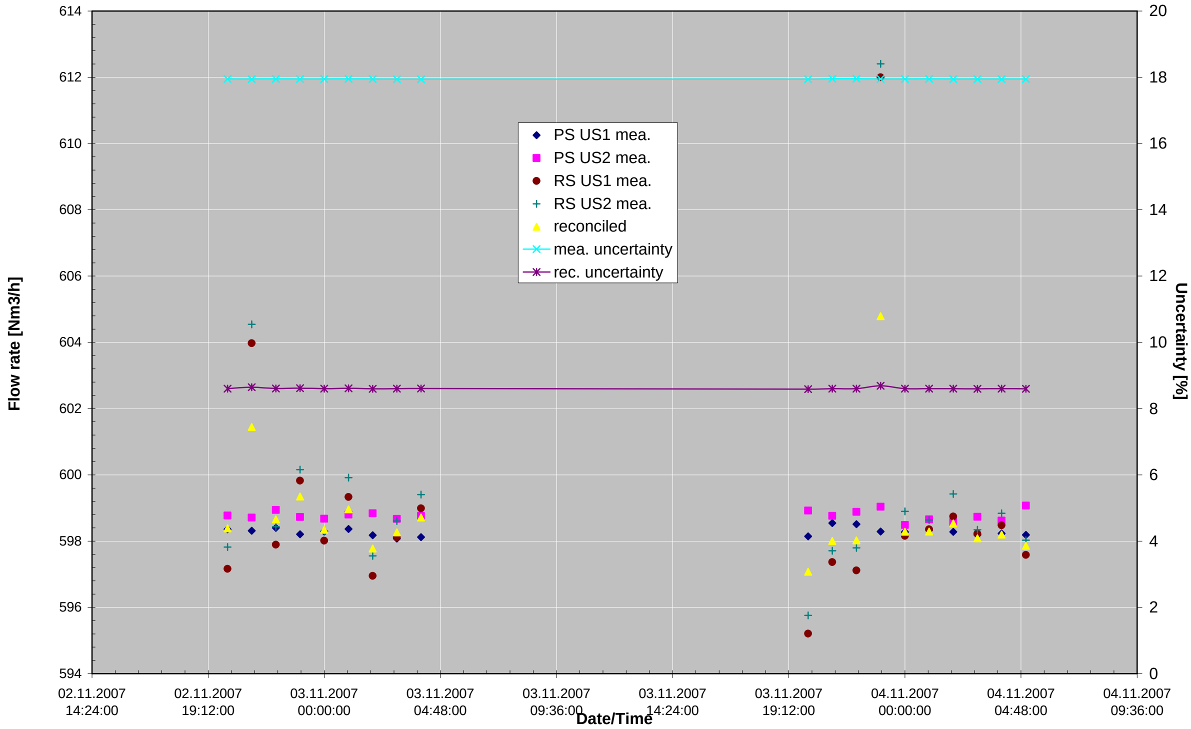

Figure 4: Measured and reconciled flow rate

In the case of ambient temperature at the different pipeline sections is available, the temperature drop along the pipeline could be calculated as shown in *Figure 6*. In this case, an estimated value of the ambient temperature is used that varies between 7° and 12°C. Facing a total length of 350 km and a variation of altitude above sea level in a range between 200 m and 600 m, the changes of the ambient temperature are reasonable. In the near future, new measurement devices will be installed along the pipeline, and values of the ambient temperature will be available to validate this approach and to further increase the accuracy of the model.

5. Conclusions

Process data reconciliation is a new approach in the field of pipeline calculation. It regards the process as a whole, continuously closing energy-, mass- and material balances. Additional analytical approaches to determine the pressure and temperature drop along the pipeline sections have been included to further increase the accuracy of the model. This way, the uncertainties of the flow rate measurements can be significantly reduced by more than 50 % without the need of additional measurement instrumentation.
Continuous analysis of the actual state of operation leads to an optimized availability of the pipeline. It enables the switch to condition based maintenance and contributes to the financial benefits of the pipeline network.

Figure 5: Result of the complete pipeline system

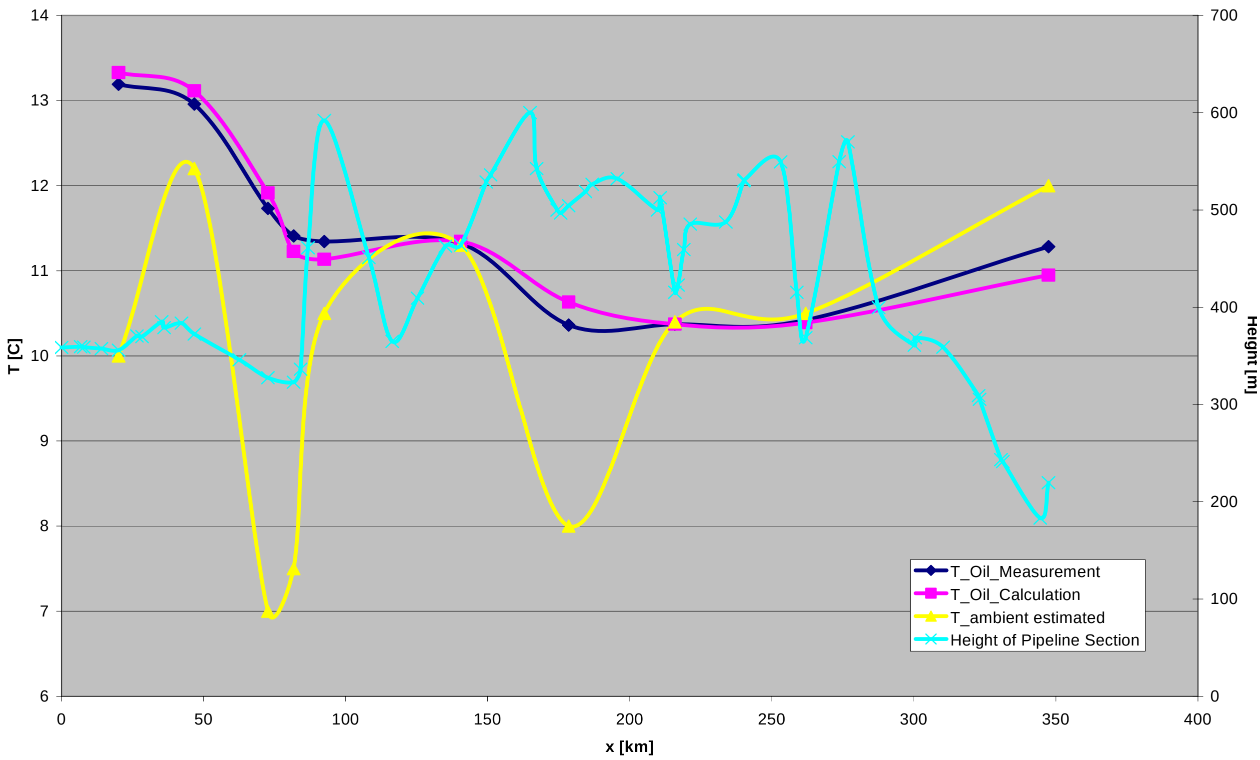

Figure 6: Temperature drop along pipeline

5. References

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