Abstract

The fundamental equations which describe the flow through gas and liquid pipelines are formally identical. However, the wide gap between the compressibility ranges of gases and liquids leads to quite different transport characteristics for both kinds of media. While for oil pipelines and pump stations specific topics like batch operation, surges, and possible slack line scenarios have to be considered, a detailed design calculation for gas pipelines and compressor stations require substantial knowledge of real gas thermodynamics. The general relationship between pressure difference along a pipeline section and volume flow is given through the combination of mass conservation and the force balance. An extension of Bernoulli’s law applies to steady-state liquid flow with non-constant density profile (e.g. batch operation), whereas Ferguson’s formula is valid for gas flow through pipelines. The dynamic behaviour of a pipeline system is calculated by real time simulation of a complete model including all existing station elements like pumps, valves, etc. in terms of a one by one mapping of the real world. The energy equation is the link between flow mechanics and thermodynamics and is the basis for the temperature model which again is formally identical for liquid and gas pipelines. Especially for gas pipelines a realistic temperature model turns out to be essential. Heat exchange with the environment shows considerable differences for onshore and offshore pipelines.

This article briefly outlines some layout and design considerations for transport capacity and power consumption of oil and gas pipelines. The impact of uncertainties of assumptions on the results is shown with examples.
Basic data for a design study
From the technical point of view a design study for a pipeline requires at first the
designated route with an elevation profile along the line and the desired throughput.
Further the flow related physical properties of the fluid (liquid or gas) and an
adequate thermodynamic equation of state have to be determined. The design code
(e.g. ASME etc.) is the framework for layout mainly under safety aspects.

In addition to these general information demands all the specific boundary conditions
of the individual project have to be respected. Constraints due to environmental
protection are just one of such conditions.

Results of a design study
Diameter and wall thickness along the pipeline and the optimal placement of stations
are the main results that should be determined by the hydraulic study. The layout of
pump and compressor stations includes the determination of the expected power
consumption for operation later on. Most of these questions can be answered by
steady-state calculations.

The operation philosophy, the control concept and the indispensable instructions in
case of emergency are elaborated with a detailed model of the entire pipeline
including its stations. A leak detection and leak location system is mandatory for oil
and gas pipelines. The choice of the instrumentation and the SCADA system should
be part of the considerations from the beginning.

Common aspects for oil and gas flow
Basic equations
There are four equations which describe (1) the continuity of mass, the conservation
of (2) momentum and (3) energy, and finally (4) the equation of state. All four
equations have to be solved simultaneously to include all the hydraulic and
thermodynamic phenomena being relevant for flow through pipelines. The four
variables to be simultaneously calculated are flow velocity \(v\), pressure \(p\), temperature
\(T\), and the density \(\rho = \rho(p, T)\).

The set of equations is identical for liquids and gases except for the equations of
state. Especially for natural gases there are a variety of approaches toward a precise
thermodynamic description of their properties, which in general can be derived from
the individual gas composition.

General approach
A detailed pipeline model is the fundament for the reliable calculation of all steady-
state scenarios as well as the dynamic behaviour of the pipeline during operational
intervention or disturbances like accidents, breakdown of power supply and other
emergency cases.

The model is hierarchically structured like the pipeline itself. There are stations
connected by pipeline sections. The internal construction of the stations has to be
mapped into the model element by element. Each element then has to be
configured according to its actual parameters – characteristics of pumps and valves, closing times of valves, etc. Also the control sequences are fully included in the model simulation.

Figure 1 Overview of a pipeline model comprising detailed stations and pipeline sections. Visualisation of the simulation results via dynamic hydraulic profile.

Steady-state flow
Steady-state flow hydraulics yields the relation between pressure and throughput, finally the transport capacity of the pipeline. The alliance of continuity of mass and momentum (reduced to steady-state conditions) leads directly to the pressure-throughput-relation. Gases and liquids, however, are described differently. For liquids the pressure head is used instead of the pressure itself – which leads to the well known Bernoulli equation, here being extended for a non-constant density profile.

The description of gas flow at typical pipeline pressure and throughput requires a complete real gas thermodynamic treatment. The large compressibility of gases leads to spatially varying density due to the pressure drop along the line and due to the elevation profile. The latter effect was first introduced by Ferguson.

The basic equation of the pressure(head)-throughput-relation is given by (cf. the “Glossary” for the notation):

\[ \rho \cdot v \cdot \frac{\partial v}{\partial x} = - \frac{\partial p}{\partial x} - \rho \cdot g \cdot \frac{\partial z}{\partial x} - \frac{\rho \cdot \lambda}{2 \cdot D} \cdot v^2 \]  

\[ \text{Eq. 1} \]

Bernoulli’s and Ferguson’s equations can both directly be derived from Eq. 1. Usually the flow velocity is replaced by the throughput, i.e. the volume flow rate \( Q = \pi D^2 \cdot v / 4 \).
**Ferguson’s equation with extension**

The gas density in Eq. 1 is replaced by the real gas equation of state using the so called compressibility factor $K = K(p, T)$. $K$ is the fraction of the real gas $Z$-factor $Z(p, T)$ and the $Z$-factor at normal conditions (typically 1 atmosphere and 0 °C). Its values for each pair of $p$ and $T$ have to be calculated for every individual gas composition. The above mentioned replacement and some further algebraic rearrangements yield the following partial differential equation

$$\frac{\partial p^2}{\partial x} + 2 \cdot g \cdot \frac{\rho_N \cdot T_N}{p_N \cdot K} \cdot \frac{\partial Z}{\partial x} \cdot p^2 = -\frac{8}{\pi^2} \cdot \frac{\lambda}{D^5} \cdot \rho_N \cdot Q_N^2 \cdot \Omega_{TD}(p, T, \ldots)$$

Eq. 2

Eq. 2 has a well defined solution, if the expressions $A$ and $B$ are properly averaged between each two adjacent numerical grid points. In Ferguson’s original paper the thermodynamic function $\Omega_{TD}$ is simply $2 \cdot \rho_N \cdot R_N \cdot K \cdot T$, but in detail it is more complicated. Ferguson’s equation (i.e. the solution of Eq. 2) expresses the flow induced pressure drop along the pipeline by a difference of quadratic pressure at the inlet and outlet of the pipeline section.

$$p_{out}^2 = p_{in}^2 \cdot e^{-\langle A \rangle \cdot \Delta x} + \left( \frac{B}{A} \right) \cdot \left( e^{-\langle A \rangle \cdot \Delta x} - 1 \right)$$

Eq. 3

A typical pressure profile calculated from Eq. 3 is sketched in the following figure.

**Figure 2 Typical pressure profile along a gas pipeline**

The factors $A$ and $B$ depend on pressure and temperature. Hence, a temperature model has to be used simultaneously with the pressure-throughput-relation (see chapter “Energy equation and temperature model” below).

**Bernoulli’s equation with extension**

For liquids, which are nearly incompressible, the pressure in Eq. 1 is usually replaced by the pressure head which is defined as

$$H = z + \frac{p - p_{atm}}{\rho \cdot g}$$

Eq. 4

With this definition Eq. 1 can be rearranged to a simple equation:

$$\frac{\Delta(p \cdot g \cdot H)}{\Delta x} = \left( -\frac{8}{\pi^2} \cdot \frac{\lambda \cdot Q^2}{D^5} \right) + \left( f(Q, \ldots) \right) \frac{\partial p}{\partial x}$$

Eq. 5
The brackets above denote spatial averages between adjacent numerical grid points \((x \rightarrow x+\Delta x)\) along the pipeline. \(f\) is an extension to the standard Bernoulli equation that takes the compressibility of liquids into account. Noteworthy contributions from the 2\textsuperscript{nd} term on the r.h.s. of Eq. 5 appear for narrow scale density variations at batch interfaces and/or steep temperature gradients. A simple approach is to use \(f = 0\) but with a loss of accuracy.

One of the reasons why for liquid flow the pressure head is used instead of the pressure itself is the fact that the pressure head \(H\) is very close to a straight line along any arbitrary pipeline section (cf. Figure 3 below).

**Figure 3 Pressure head profile along a liquid pipeline**

![Pressure head profile](image)

Both, the density and the volume flow rate depend on pressure and temperature. Hence, a temperature model has to be used simultaneously with the pressure-throughput-relation (see chapter “Energy equation and temperature model” below).

**Specific transportation costs**

One of the important conclusions displayed in Figure 2 and Figure 3 is the fact that a given throughput requires a defined pressure difference between inlet and outlet. This pressure difference is proportional to the energy that has to be provided in order to operate the pipeline. Long transport lines require more than one pump or compressor station.

**Figure 4 Transport pipelines for gas and oil (or liquid)**

![Transport pipelines](image)
The optimal placement of stations along the line does not only depend on hydraulic aspects, but also on other local conditions like geological, environmental, political, infrastructural conditions etc.

The required energy per mass unit of transported medium is proportional to the specific transportation costs and has the following dependency:

\[
\frac{\text{Energy}}{\text{Mass}} \sim \frac{L}{D^5} \frac{\Delta H}{\eta} \quad \text{(for liquid)} \quad \frac{\text{Energy}}{\text{Mass}} \sim \frac{L}{D^5} \frac{\Delta p}{\eta} \quad \text{(for gas)} \quad \text{Eq. 6}
\]

Eq. 6 leads to a general relation between energy/mass and throughput. For the case of having replaced \( \Delta p \) and \( \Delta H \) by the pressure-throughput-relation, the result is given in Figure 5.

**Figure 5** Specific transportation costs (energy/mass) for given diameter

The optimal diameter of the pipeline has been found, when the curve of energy/mass shows a minimum at the desired throughput.

**Variation of parameters**

During real pipeline operation some design parameters can still vary with time. The actual diameter and the roughness are such parameters. Both have a direct impact on the hydraulic resistance of the pipeline sections. In crude oil pipelines depositions of heavier crude components can lead to variations of the internal diameter or cross section. All sources of impact on the hydraulic resistance of a pipeline section are here expressed by the single parameter “roughness”. In fact, by this way it looses its original physical meaning, but the parameter roughness then is a direct (and simple) measure for the hydraulic resistance.

Figure 6 shows results of an investigation in connection with an optimisation of pig runs for a crude oil pipeline under batch operation. The parameter “roughness” was
calculated from Eqs. 5 and 7 (see below) in an inverse manner using direct measurements (process data) as boundary conditions.

Figure 6 Varying hydraulic resistance (or “roughness”; blue curve) of a pipeline section due to different crude oils with different grades of deposition of heavier crude components

Two interesting results are displayed in the above diagram. (1) After a pig run the pipeline shows a significantly reduced hydraulic resistance (green arrow) and (2) the resistance is varying with different crude oil qualities. Heavier crude oils raise the hydraulic resistance in the course of time, probably by deposition of heavy components (reduction of available cross section). Light crude oils obviously dissolve these depositions and lead to a slow reduction of the hydraulic resistance. Hydraulic resistance and actual power demand are tightly correlated, which offers the possibility for optimisation.

Energy equation and temperature model
The energy equation couples mechanic and thermodynamic aspects. Heat as one form of energy is expressed by temperature and heat capacity. Heat will be exchanged with the environment, if there is a temperature difference between the medium in the pipeline and the environment.

For steady-state flow the energy balance shows a simple structure:

$$\frac{\partial T}{\partial x} + X \cdot (T - T_G) = F + S \tag{Eq. 7}$$

with the factors:

- $X =$ heat exchange with the environment of the pipe,
$F = \text{frictional heat, and}$

$S = \text{thermodynamic change of state along the pipeline.}$

Eq. 7 is an ordinary differential equation with a well defined solution, if the temperature of the environment of the pipe $T_G$ is reasonably constant along the section under consideration. The long range behaviour of the temperature profile is given by the following asymptote:

$$T \to T_G + \frac{F + S}{X}$$  \hspace{1cm} \text{Eq. 8}

Gas and liquid pipelines differ significantly on this issue. While for liquids the flow induced thermodynamic changes of state can be neglected ($S \approx 0$), for gases it is the Joule-Thomson effect that causes the factor $S$ to be negative and even to over-compensate the frictional heat term $F$.

Therefore, the asymptotic behaviour of the long range temperature profiles of gas and liquid pipelines differ as shown in the next two figures.

**Figure 7 Asymptotic temperature profile for gas pipelines**

![Asymptotic temperature profile for gas pipelines](image)

The Joule-Thomson effect causes such a strong temperature drop (correlated with the pressure drop) along the pipeline that the temperature tends to a level below the temperature of the environment of the pipe.

**Figure 8 Asymptotic temperature profile for liquid pipelines**

![Asymptotic temperature profile for liquid pipelines](image)

$$X > 0$$

$$F > 0$$

$$S < 0$$

$$|S| > |F|$$

$$\frac{F + S}{X} < 0$$

$$X > 0$$

$$F > 0$$

$$S = 0$$

$$|S| \ll |F|$$

$$\frac{F + S}{X} > 0$$
For liquids of sufficiently high viscosity (like crude oils) the flow induced heat production leads to an asymptotic temperature level well above the temperature of the environment of the pipe.

The mechanisms of heat exchange with the environment depend on how the pipeline will be laid. Buried pipelines exchange heat by heat conduction through the soil (cf. Figure 9, left). Offshore pipelines are lying on the bottom of the sea and are circulated by the sea water (cf. Figure 9, right and Figure 10). In this case the advective heat transport is dominating. The latter is also true for pipelines that have been laid above the ground – here radiation of heat has to be considered in addition.

**Figure 9** Buried pipeline (left) and freely circulated pipe (right). The mechanisms of heat exchange are heat conduction (left) and heat advection (right)

![Figure 9](image)

The heat exchange rate for offshore pipes depends on the usual insulation and the details of the flow pattern around the pipe. The relation between heat exchange and flow patterns can be calculated e.g. by the theory of similarity.

**Figure 10** Flow pattern around a circulated pipeline lying on the bottom of the sea

![Figure 10](image)

All the parameters which define the heat exchange – like heat conductivity of the soil, flow velocity of the sea water etc. – can vary significantly for different sections. In addition to that they can also vary with time. Seasonal changes, day and night variations, rainfall, etc. will more or less affect the temperature profile. For model calculations and reliable predictions all these influences are the predominant source of uncertainties. Checking the sensitivity of the model with respect to these parameters is the only way to make right conclusions and reliable predictions.

Real gas thermodynamics starts with an analysis of the individual gas composition. From this information three ingredients have to be calculated first: (1) the norm density, (2) the compressibility factor $K(p,T)$, and (3) the specific heat capacity $c_p(p,T)$, the last two as functions of pressure and temperature. The next figure shows the various dependencies of thermodynamic calculations. Deficient accuracy in one variable or function causes errors in the dependent variable.
Figure 11 Dependencies of thermodynamic functions and variables

The next figure shows an example for a 40'' natural gas pipeline carrying $36 \times 10^6$ norm m$^3$ per day. The simple “geology” of the artificial model emphasises the typical behaviour within the different sections. The line colours are assigned to the displayed scale units: pressure in bar abs. (red), density in kg/m$^3$ (blue), temperature in °C (orange), and flow velocity in m/s (magenta).

Figure 12 Example of a 1000 km natural gas pipeline with an offshore section and 3 compressor stations
The onshore sections of the above example are modelled as buried, non-insulated pipes laid in soil at a ground temperature of 12 °C near sea level and down to 4 °C at the mountain peak. The offshore section is an insulated pipe, laid on the bottom of the sea, passing through water layers of different temperature and assuming an average circulation velocity of 1 m/s.

Special attention has to be directed to the temperature profile. In the above example there are two regions where the temperature nearly drops down to the freezing point of water which could cause problems in case of wet gas. The model parameters (insulation, diameter, etc.) should be locally changed in order to avoid such low temperatures.

**Summary**

Hydraulic studies which shall cover all operating scenarios and boundary conditions require a detailed pipeline model. SIR 3S ® is such a powerful tool for modelling and simulation of oil and gas pipelines.

Special and important details of calculations differ significantly for oil and gas pipelines even though the fundamental equations are identical.

A detailed thermodynamic treatment and a temperature model are essential – especially for gas pipelines.

The impact of uncertain or temporarily varying design parameters on the actual operation later on has to be considered from the beginning. A sensitivity analysis of the model with respect to those parameters should be mandatory.

Just applying tools is not sufficient. In addition to the proper utilisation of powerful tools it is the engineer’s skill and experience that provides reliable results.
Glossary

Variables

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<tr>
<th>Variable</th>
<th>Description</th>
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<tbody>
<tr>
<td>A</td>
<td>numerical factor, see text</td>
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<tr>
<td>B</td>
<td>numerical factor, see text</td>
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<tr>
<td>D</td>
<td>diameter [m]</td>
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<tr>
<td>F</td>
<td>“frictional heat” term in the energy equation</td>
</tr>
<tr>
<td>f</td>
<td>extension factor for the Bernoulli equation (see text)</td>
</tr>
<tr>
<td>g</td>
<td>gravitational acceleration (9.8… m/s²)</td>
</tr>
<tr>
<td>H</td>
<td>pressure head [m] or metres of liquid column [mlc]</td>
</tr>
<tr>
<td>K</td>
<td>compressibility factor ( K = \frac{Z(p, T)}{Z_N} )</td>
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<tr>
<td>L</td>
<td>length of a pipeline section</td>
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<tr>
<td>p</td>
<td>pressure [Pa] (or [bar])</td>
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<tr>
<td>Q</td>
<td>volume flow [m³/s] (or [m³/h])</td>
</tr>
<tr>
<td>R</td>
<td>gas constant [m²/s² K]</td>
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<tr>
<td>S</td>
<td>“thermodynamic change of state” term in the energy equation</td>
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<tr>
<td>T</td>
<td>(absolute) temperature [K] (or [°C]; 0 °C = 273.15 K)</td>
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<tr>
<td>V</td>
<td>Volume</td>
</tr>
<tr>
<td>v</td>
<td>flow velocity (averaged over entire cross section)</td>
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<tr>
<td>X</td>
<td>“heat exchange” between medium and environment</td>
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<tr>
<td>x</td>
<td>axial coordinate along the pipeline (section) [m] (or [km])</td>
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<tr>
<td>Z</td>
<td>real gas Z-factor</td>
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<tr>
<td>z</td>
<td>geodetic elevation (altitude) [m]</td>
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<tr>
<td>η</td>
<td>efficiency</td>
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<tr>
<td>λ</td>
<td>friction factor of the pressure-throughput relation</td>
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<tr>
<td>ν</td>
<td>kinematic viscosity [m²/s] (or [cSt]; 1 cSt = 10⁻⁶ m²/s)</td>
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<tr>
<td>ρ</td>
<td>mass density [kg/m³]</td>
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<tr>
<td>Ω_{TD}</td>
<td>thermodynamic extension factor for the Ferguson equation</td>
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Indices

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<td>outlet of a pipeline section</td>
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<td>at normal conditions</td>
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<td>G</td>
<td>ground or environment of the pipe</td>
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<td>atm</td>
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