

Heat Effects in Gas Systems

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Introduction

This paper is a small tutorial that addresses temperature issues in natural gas transmission systems. The paper does not present any new development or concept. It is simply an attempt to discuss heat effects in gas systems in a way that can easily be understood by someone not deeply familiar with thermodynamics and fluid mechanics. For example the thermodynamic concepts of 'enthalpy' and 'entropy', how useful they may be, have been carefully avoided here. Moreover, this paper has been kept 'formula-free'. For readers wishing to dig deeper into the subject, the paper contains a non-exhaustive bibliography of excellent theory papers.

Temperature impacts on a number of issues in gas transmission:

- Pipeline transport capacity and compression energy costs
- Formation of natural gas hydrates and hydrocarbon condensation
- Thermal stress on pipeline material, permafrost thawing, and similar

Gas temperature in a pipeline is affected by the conductive and convective transfer of heat in a radial direction, by the accumulation of heat in the surrounding soil, and by the Joule-Thomson effect. Compression adds heat to the gas, resulting in an increase in the temperature of the gas discharged by the compressor. Aftercoolers can help to decrease compression fuel costs and may be necessary to avoid damage to the pipeline's bitumen coating. Pressure reducers cause the gas outlet temperature to drop due to the Joule-Thomson effect. At low gas temperatures and other conditions, hydrates may form, or natural gas liquids may condensate.

The numerical examples presented here apply for a test pipeline that has 1m inner diameter and is 200 km long. It has a compressor station at the outlet to recover the pressure to the initial pipeline supply pressure 95 barg. These examples have been computed with SIMONE 5.6. Pipeline configuration data is documented in the Appendix.

Internal Energy, Heat and Work

'Internal energy' is the total amount of the kinetic and potential energy of the molecules confined in a gas volume. Internal energy can be changed from the outside world across the volume boundaries by adding or withdrawing energy in the form of work and/or heat. The gas temperature rises if internal energy is built up, and decreases if internal energy is reduced. This is true as long as the gas does not condense. As shown in Figure 1, this concept has already been known and applied for a long time.

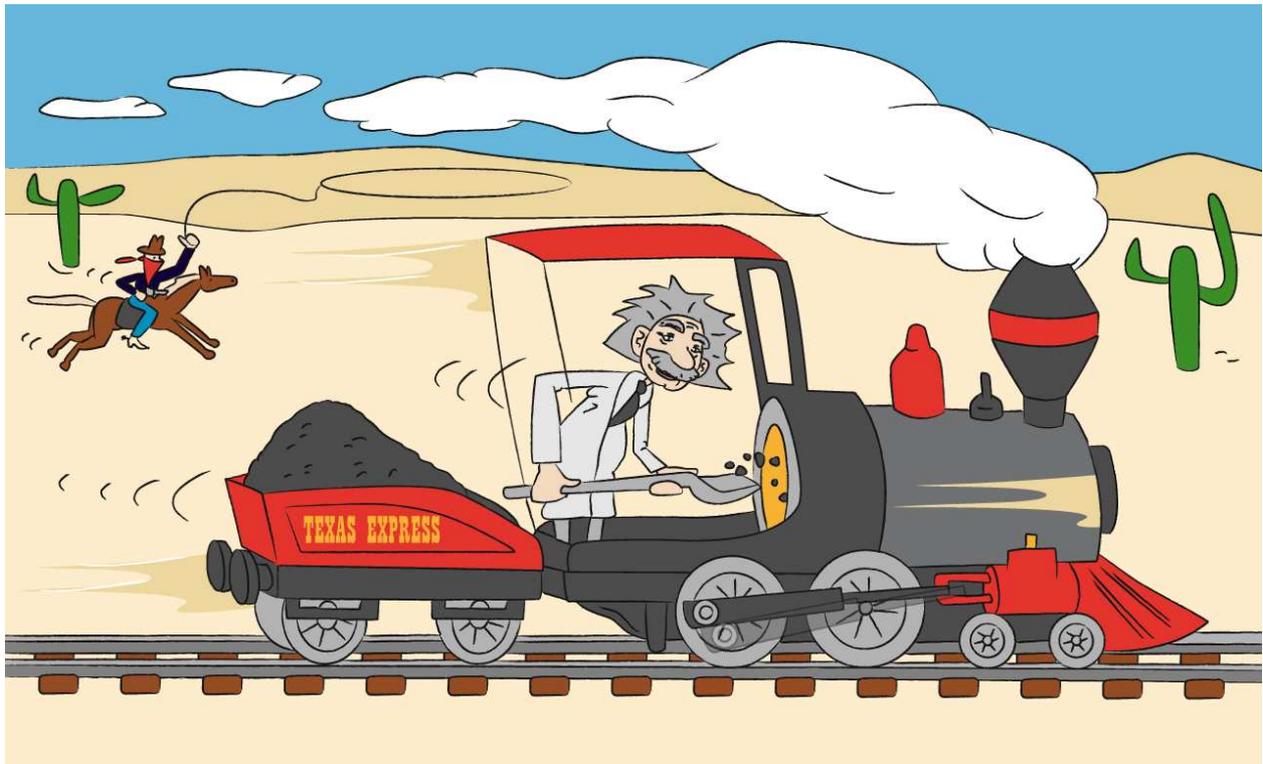


Figure 1 – Exchanging heat and work is not a new story

Heat can flow between adjacent bodies if there is a difference in temperature. The flow is always directed from the warmer to the cooler body. The resulting flow tends to level out the temperature difference. Therefore a heat flow from the outside into the confined gas volume will warm it up, while withdrawing heat from the gas will cool it.

Work is added to the gas by shrinking its volume against the gas pressure. Applying this compression work adds to the internal energy, and hence raises the gas temperature in the shrunk volume; likewise, withdrawing work from the gas (e.g. by expanding it through a turbine that drives a generator) reduces the gas temperature.

Joule-Thomson Effect

Typically, gas is expanded not by an expansion turbine (as just discussed), but by letting it flow through a pressure reduction valve. This kind of passive device does not withdraw (or add) work from (to) the gas; nor is heat exchanged, as the high flow speed in the valve does not provide sufficient time for a gas molecule in transit to absorb (release) a noteworthy amount of heat from (to) the outside world.

This could imply that the gas temperature will be unaffected by expansion through a pressure reduction valve. But that clearly contradicts observation, which actually shows a drop in the temperature of the expanded natural gas. This is called the 'Joule-Thomson effect'. Natural gas (being a 'real gas') does in fact perform work internally during expansion against the attractive molecular forces (repulsive molecular forces may be present in other gases, which make the temperature rise at expansion). This work enlarges the average distance between the gas molecules. This expansion work is converted into 'chemical energy', which is another constituent of internal energy. All in all, the internal energy of the gas remains constant when passing through a pressure reduction valve, while its temperature drops.

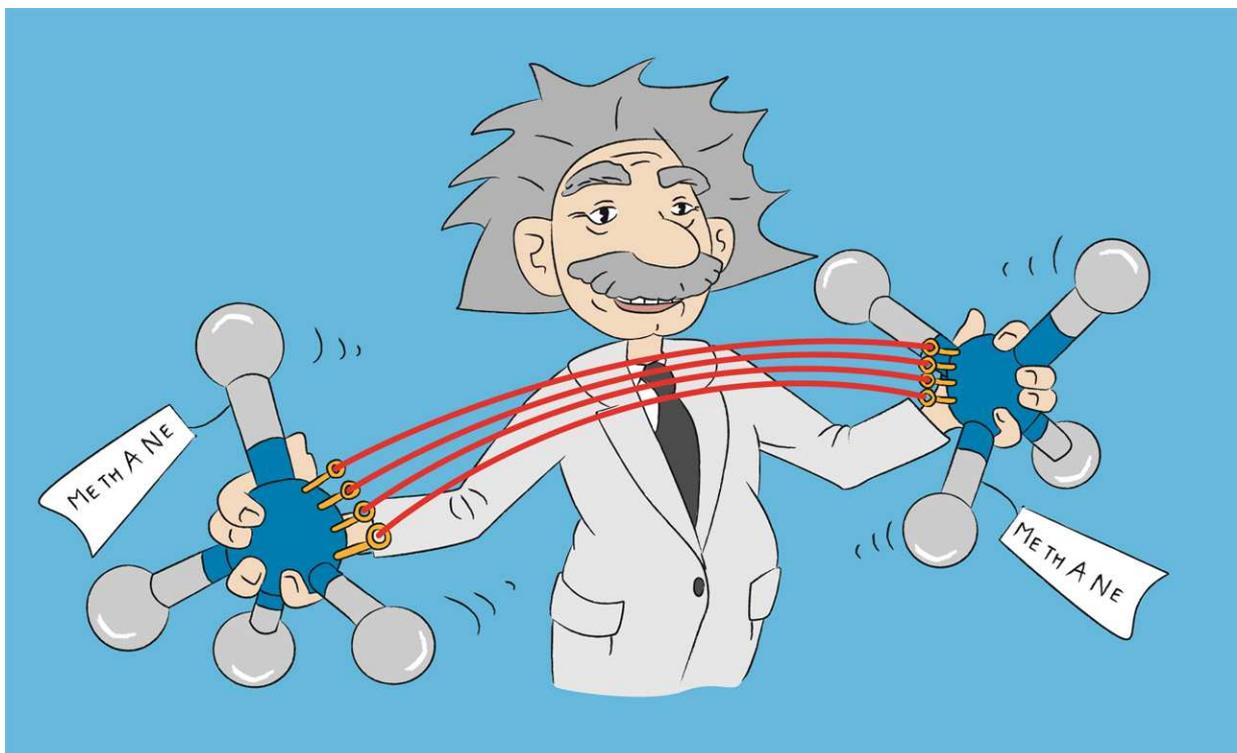


Figure 2 – Working against attractive molecular forces

Friction

Flowing gas rubs against the pipe wall. Therefore the gas flow is slowed down near the boundary surface. The resulting radial flow speed gradient induces shear forces, as do flow turbulences occurring in the gas stream. Gas is viscous, so it resists these shear forces. The viscous resistance causes a frictional pressure loss in the flow direction.

It is common experience that friction converts mechanical energy into heat, and so the gas temperature should rise. But this conclusion is not correct. Assuming a thermally insulated pipeline and ideal gas (e.g. no Joule-Thomson effect), the internal energy remains unchanged over the pipeline length, since no work and no heat are exchanged with the outside world. The gas does in fact work against the friction, but this work is internally withdrawn from the internal energy 'account', and at the same time, added to it again in the form of frictional heat. All in all, energy-wise this is a zero-sum game that hence leaves the gas temperature unchanged. But friction is a conversion of 'useful' pressure energy into 'un-useful' heat. Thus the gas needs to be compressed at the next downstream compressor station to recover the initial pipeline pressure again. The compression work requires fuel energy to drive the compressor to set off the frictional pressure loss in the upstream pipeline.

Heat Transfer

The assumption of a thermally insulated pipeline is not that realistic because the pipe wall surface permits heat to flow from or to the gas. Usually the temperature of the gas entering a pipeline is considerably higher than the temperature of the surrounding soil or sea water. The temperature difference drives a radial heat flow across the pipe wall into the soil or sea water. The heat flow is proportional to this temperature difference. The gas thus cools down along the mileposts in the flow direction. Therefore, the heat flow density gradually reduces as well in the gas flowing direction, which makes the gas temperature drop asymptotically along the mileposts towards the surrounding soil or sea water temperature.

The Joule-Thomson effect can also be noticeable in pipelines. Friction causes the pressure to drop in the flow direction. The pressure drop induces the Joule-Thomson temperature drop. In the case of a high flow pipeline, Joule-Thomson cooling can even drive the gas temperature below the undisturbed soil or sea temperature, so that the heat transfer then reverses from soil to gas.

Figure 3 shows the temperature profile along the test pipeline operating at 40 barg delivery pressure, resulting in 2.141 mil. Nm³/hr net transport capacity plus the 19,750 Nm³/hr fuel gas flow for the turbine driving the downstream compressor. Besides the gas and the undisturbed soil temperature,

the figure also includes a simulated 'artificial' temperature by neglecting the Joule-Thomson effect. This is just to demonstrate how strongly the Joule-Thomson effect may impact the gas temperature.

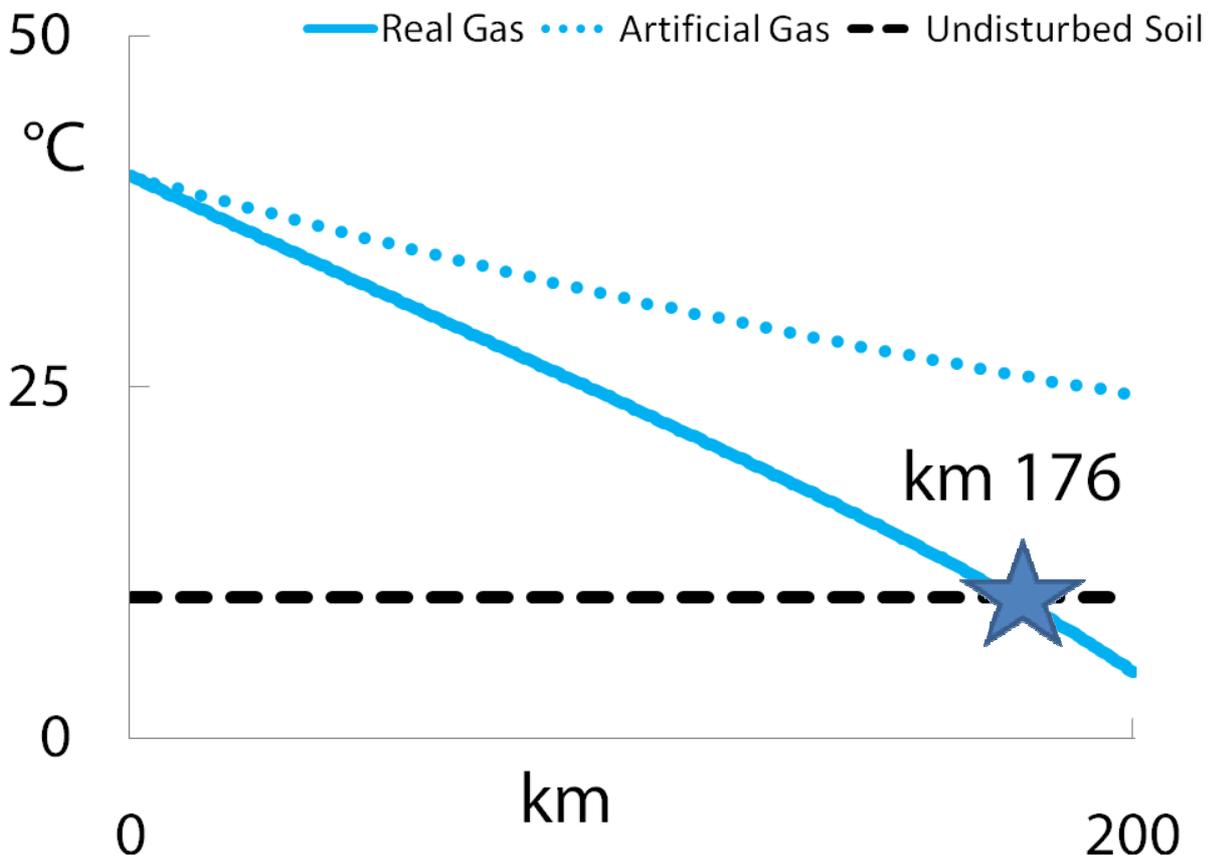


Figure 3 – The temperature of a heavily loaded pipeline can even fall below the undisturbed soil temperature

The soil surrounding an onshore pipeline can hold a considerable amount of heat. In steady-state pipeline flow, soil heat capacity can simply be neglected, as heat is neither buffered in, nor taken out, of the storage. The radial heat flow in steady state is entirely governed by the heat conductivities of the pipe wall, the surrounding insulation, and the soil.

In a transient situation, additional heat flows appear that fill or deplete the distributed heat storage around the pipe. As heat capacities are quite large, and heat conductivities are moderate to small, the time required to change the temperature distribution in the pipeline surroundings will be considerably higher compared to the fast gas flow transients in the pipeline. The radial distribution of heat capacities and conductivities means that more than one time constant must be taken into consideration when modeling this dynamic system - shorter time constants account for the faster

thermal transients in the pipeline's vicinity, and longer ones model the slower transients farther away from it. This is like taking an egg out of boiling water, and then quenching it under cold water. The egg shell temperature drops quickly, but when removed from the cold water the shell temperature rises again as heat starts to flow from the still hot large inner egg with a high heat capacity to the outer shell. The various time constants must not be mistaken for the relaxation time it takes for the gas temperature to come close to its final steady state. The relaxation time also depends on the temperature difference that drives the radial heat flow. The temperature difference, and hence the radial heat flow will be smaller at higher mileposts. Therefore, gas temperature transients die out more slowly as the pipeline milepost increases.

Heat transfer for an offshore pipeline is governed by convection which conveys heat from the concrete casing directly into the sea water. Therefore, heat conductivity is higher, heat capacities are lower, and so the thermal time constants are shorter than they are with soil-buried onshore pipelines. The sea water temperature thus considerably determines gas temperature, which in turn determines pipeline flow capacity.

Aftercooling

The higher the compression ratio and the warmer the gas on the suction side, the hotter the discharged gas from the compressor. However, typical pipeline insulation materials withstand only moderate temperatures of some 50 °C. Therefore aftercooling is a must if a high pipeline loading or a wide spacing of the compressor stations forces a high compression ratio. Aftercoolers can also further cool the discharged gas, and so either increase transport capacity, or reduce compression energy costs. The costs associated with aftercooling are, besides the capital expenditures of the cooling equipment, the additional compression costs to make up the gas pressure loss across the cooler, as well as the electric power for driving the air fans.

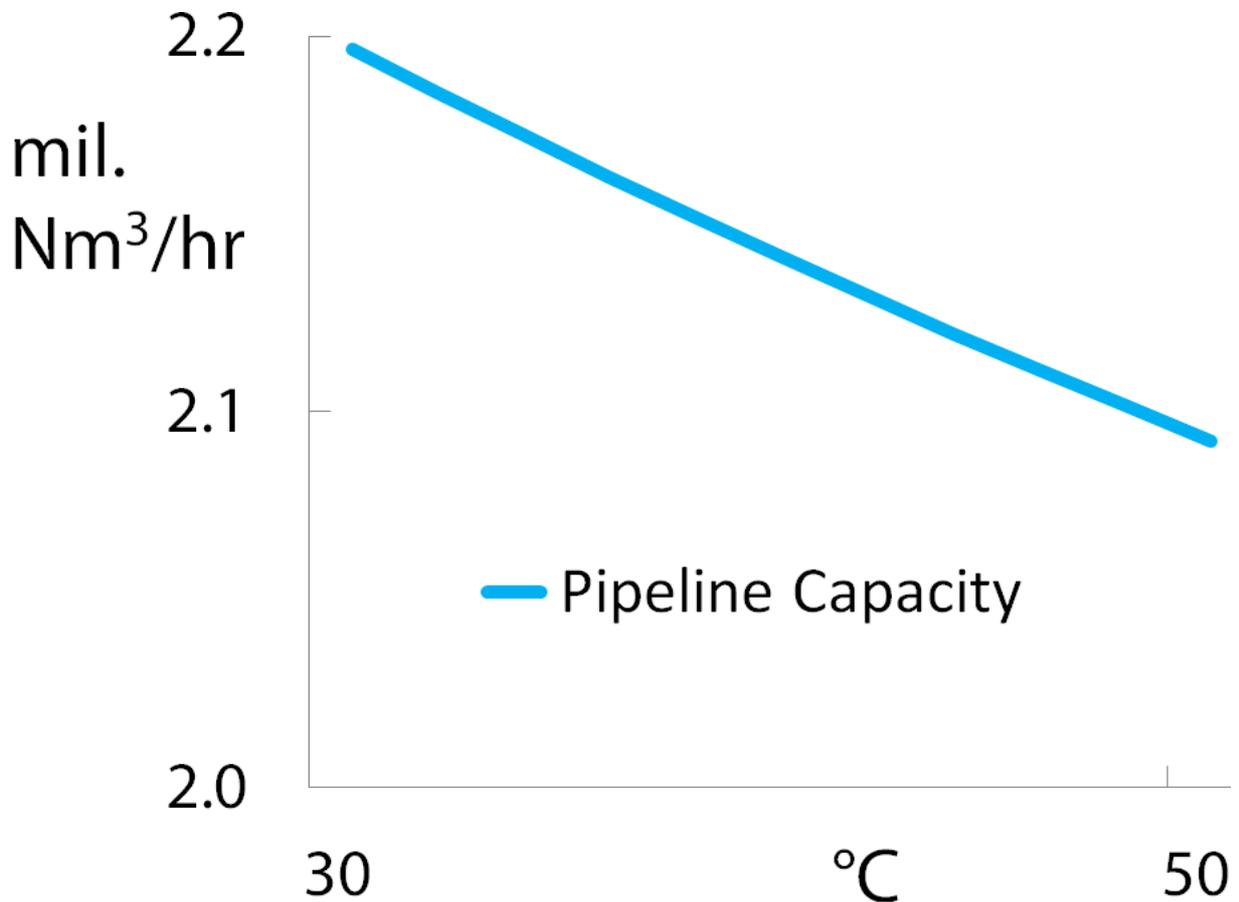


Figure 4 - Aftercooling increases transport capacity

The capacity of the test pipeline increases by just 5.0 % with intensified aftercooling, starting at 50 °C down to 30 °C (Figure 4).

However, the effect of using aftercooling to improve fuel efficiency is much more dramatic. For the test pipeline at 2.141 mil. Nm³/hr net transport, the fuel gas required to drive the downstream compressor is 47 % higher if the gas is supplied to it at 50 °C as opposed to 30 °C (Figure 5). The electric power to drive the air fans is just a fraction of the saved compression horsepower (provided, of course, the air temperature is well below the gas temperature at the cooler outlet).

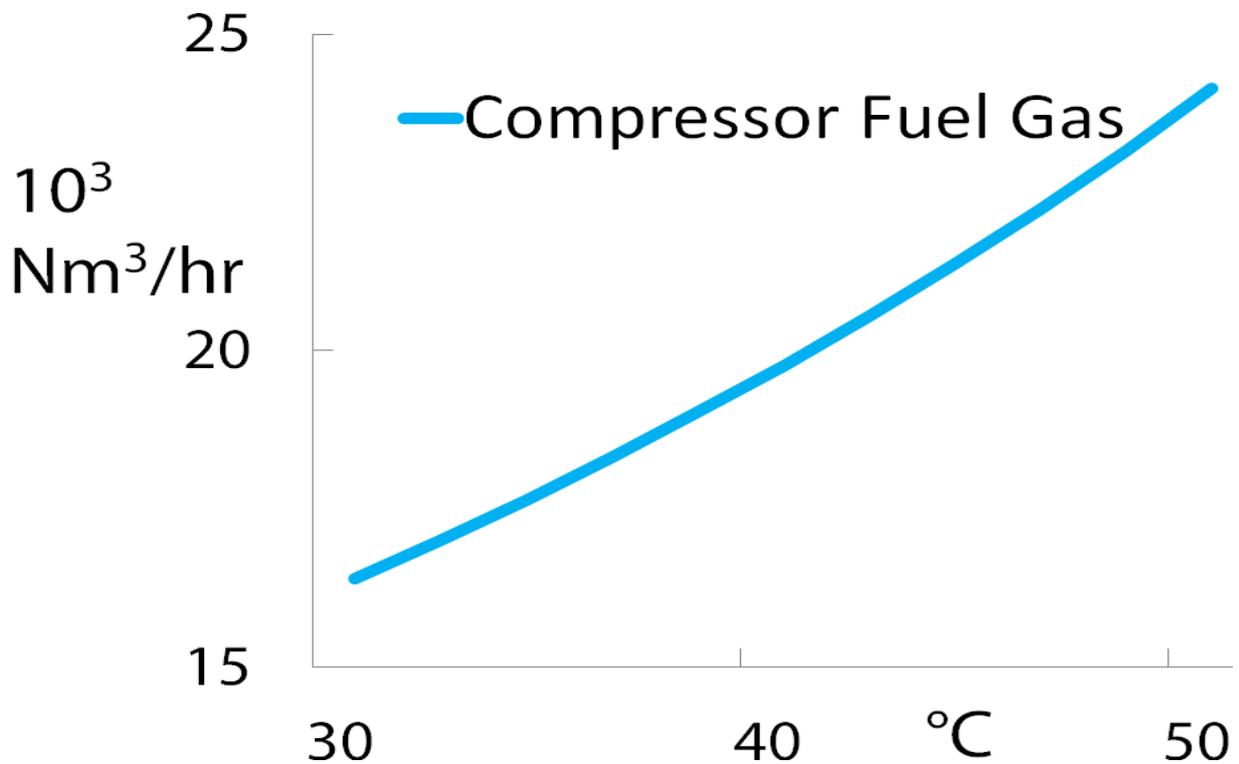


Figure 5 – Aftercooling increases transport efficiency

Hydrate Formation

To keep pipeline pressure losses small, the fluid should remain in the gas phase. However, under certain temperatures and other conditions this may not be achievable. Hydrates may form in the presence of water under low temperature and high pressure. These are ice-like compounds of hydrocarbons and water. Natural gas hydrates may form in a wet gas (i.e. water is present) if the fluid temperature drops below both the water dew point temperature and the hydrate equilibrium temperature. The water dew point temperature depends on pressure, water concentration and gas composition. The hydrate equilibrium temperature depends on pressure and gas composition; it may be reduced by adding an inhibitor, such as methanol or glycol.

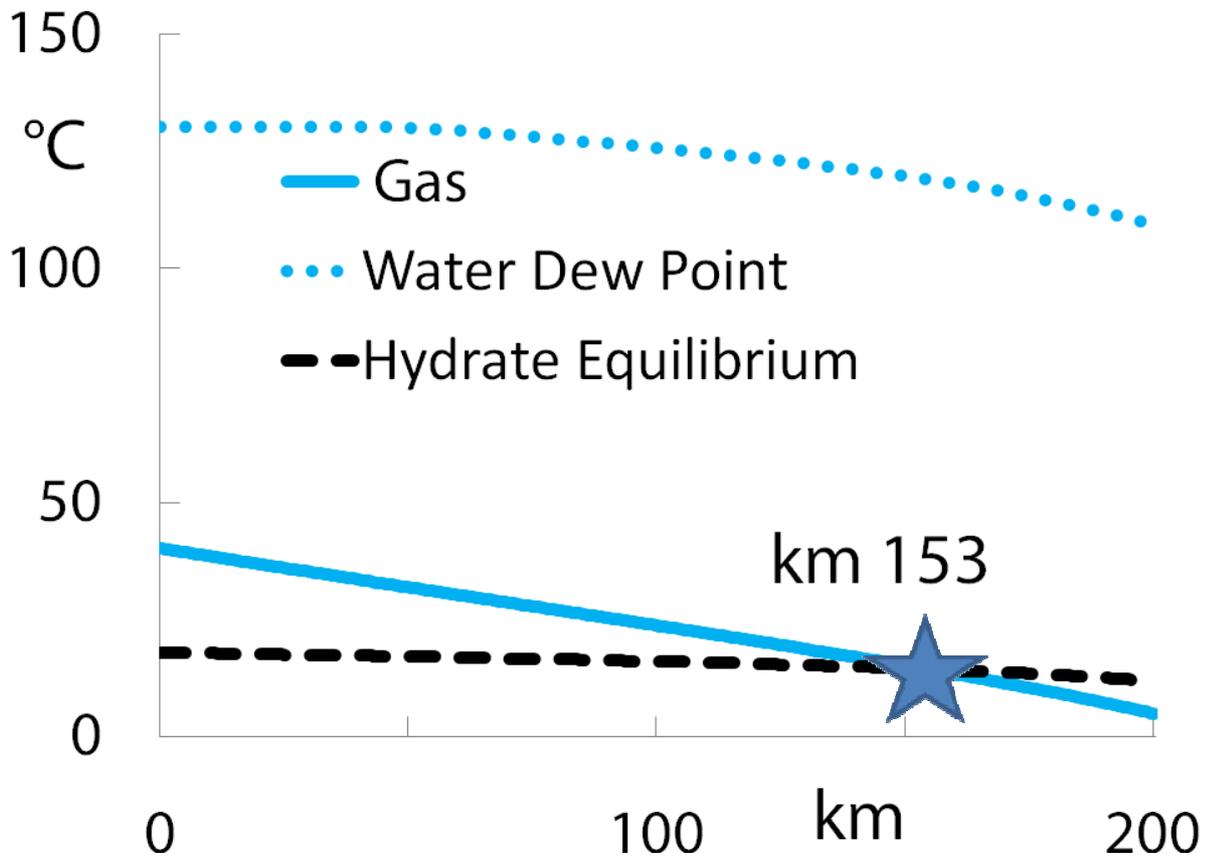


Figure 6 - Hydrates may form downstream km 153

Figure 6 shows the simulated water dew point, gas and hydrate equilibrium temperature profiles on the test pipeline at 30 g/m^3 water concentration and at 40 barg offtake pressure. Condensed water exists all along the pipeline since the gas temperature is below the water dew point. From km 153 on downstream, the gas gets cooler than the hydrocarbon equilibrium temperature. So, in this part of the pipeline, hydrates may form.

Hydrocarbon Condensation

Natural gas is a mixture of various hydrocarbons. The heavier the component, the higher its dew point temperature at which it starts to condense. Natural gas liquids start to drop out if the fluid temperature gets below the hydrocarbon dew point, which depends on the fluid temperature and pressure. At the hydrocarbon dew point, the heaviest component of the hydrocarbon mixture starts to condensate.

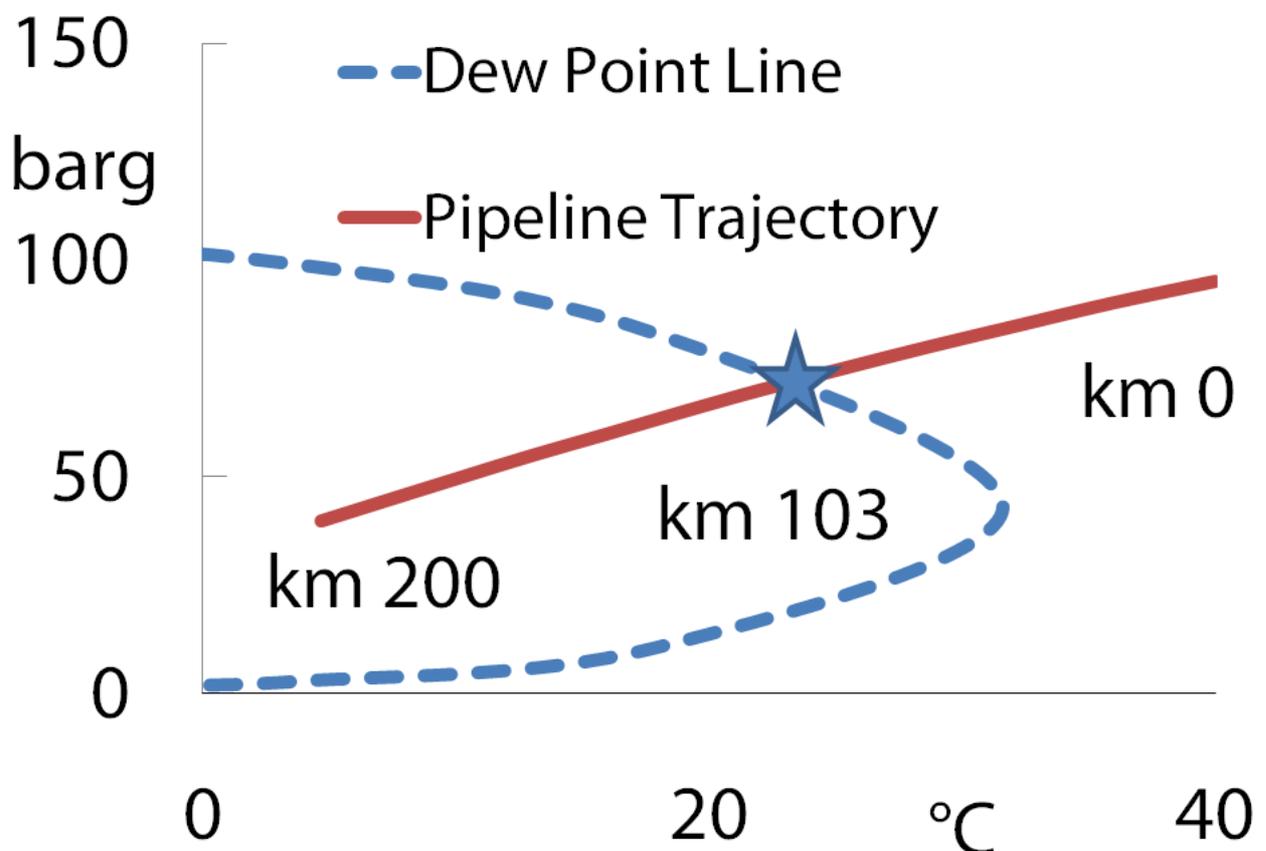


Figure 7 - Phase diagram with pipeline temperature/pressure trajectory

The state of a given hydrocarbon mixture as a function of temperature and pressure is shown in a phase diagram (Figure 7). In the area enclosed by the dew point line, gas and liquid phases coexist. To the right of the dew point line, all components are in the gas phase. The phase diagram Figure 7 applies for a gas containing heavier components than the test pipeline gas (as specified in the Appendix), so that already at normal pipeline conditions liquids start to drop out. This is demonstrated by drawing the temperature/pressure trajectory of the test pipeline, operated at 40 barg outlet pressure. Starting with 100 % gas from a high supply temperature and pressure the

trajectory crosses the dew point line at km 103, so that further downstream hydrocarbons may drop out. The heaviest components will start to condense first, but since their concentration is small, the liquid drop out will be small. The deeper the trajectory cuts into the 2-phase region, the more condensate will form, as now the higher concentrated lighter hydrocarbons will start to condensate, yielding larger liquid volumes.

Conclusions

The concept of internal energy has been used to explain temperature changes in a gas transmission system due to compression, expansion, Joule-Thomson effect, friction and heat transfers. The effect of aftercooling the gas discharged by a compressor on flow capacity and energy efficiency has been addressed. The temperature-dependant occurrence of gas hydrates (solids) and hydrocarbon condensates (liquids) have been discussed.

References

1. Modisette J.: Pipeline Thermal Models. 34th PSIG Annual Meeting, Portland, Oregon, 2002.
2. Vostrý Z., Závorka J.: Heat Dynamics in Gas Transport. 3rd SIMONE Congress, Espoo, Finland, 1995.
3. Osiadacz A., Chaczykowski M.: Comparison of Isothermal and Non-Isothermal Transient Models. 30th PSIG Annual Meeting, Denver, Colorado, 1998.
4. Dupont T., Rachford H.: How Required Compression Depends on the Thermodynamics of Rich Gas Flow. 24th PSIG Annual Meeting, Corpus Christi, Texas, 1992.

Appendix: Test Pipeline Configuration

The test pipeline has a compressor at its outlet to boost the pressure back to its initial level.

Pipeline inlet

Supply pressure	95 barg
Supply gas temperature	40 °C

Pipeline parameters

Length	200 km
Inner diameter	1000 mm
Roughness	10 μm
Heat transfer coefficient	1.56 W/m ² /K
Undisturbed soil temperature	10 °C

Compressor station parameters

Compressor isentropic efficiency	80 %
Gas turbine energy efficiency	30 %

Gas composition in mol %

Methane	86.0
Ethane	8.5
Propane	2.3
i-Butane	0.7
Nitrogen	1.0
Carbon dioxide	1.5

Standard volume

Nm ³	@ 1.01325 bar / 0 °C
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Fluid modeling

Equation-of-State (EOS)	SGERG-88
Friction factor	Colebrook-White (Hofer)
Viscosity	Lee-Gonzalez-Eakin
Specific heat	derived from EOS
Isentropic exponent	derived from EOS
Joule-Thomson coefficient	derived from EOS