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Combining thermodynamic and fluid flow modelling for CO_2 flow assurance

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Abstract

The present paper concerns the importance of a combined modelling and experimental effort to develop physics-based combined thermodynamic and transient flow models for CO_2-transport pipelines. Such models need to handle both multiple components and two-phase flow, which can occur both during normal operation and transient situations, such as first fill and depressurization. Moreover, these models can provide useful input to risk analyses and design of mitigation actions of undesirable incidents like pipeline rupture and well blow-outs. This paper discusses various physical phenomena, design issues and solutions by using the experience from actual cases encountered by Vattenfall, Gassco and Statoil. Among the key issues are the minimum temperature in the pipe wall during depressurization and the magnitude of pressure oscillations during transient operation.

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Keywords: CO_2 transport; CO_2 mixtures; CFD; thermodynamics; fluid dynamics

1. Introduction

Much of the research effort within CO_2 capture and storage (CCS) has, so far, concentrated on CO_2 capture from power plants and industrial processes, and storage in saline aquifers. Nevertheless, more often than not, the site of capture and that of storage will be separated. Therefore, transport of the CO_2 between the two will be required, and this involves several research challenges. There are CO_2 onshore transport pipelines in operation today for enhanced oil recovery (EOR) purposes. However, in the International Energy Agency's two-degree (2DS) scenario from 2012, CCS will contribute to reducing the

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global CO_2 emissions by about 7 gigatonnes in 2050 [1]. Such a large-scale deployment of CCS will require the construction of very large pipeline systems, many of which will pass through or near populated areas or subsea. This implies constraints regarding health, safety and environment (HSE), including pipeline integrity. At the same time, for economic reasons it will be desirable to avoid oversizing and the use of expensive material qualities.

CO_2 has been transported for the purpose of enhanced oil or gas recovery for decades, particularly in the USA. Further, several CCS chains are currently in operation and more are planned. Thus, much knowledge exists on the topic of CO_2 transport and storage. Nevertheless, during the last few years, numerous research projects on CCS have concluded that there is a need to build new knowledge on the fundamental properties of CO_2 mixtures with impurities and their impact on the CCS chain operation, integrity and economics. Depending on the capture process, the transported CO_2 will contain various impurities. Several among them can significantly alter the thermodynamic and transport properties, as well as the phase equilibria of the fluid. Therefore, "CO_2" in this context really means "multicomponent CO_2-rich mixtures". Corrosion of the pipeline and formation of hydrates are also related to impurities.

The CO_2 pipeline transport will most often take place at a high pressure, where the CO_2 is in a dense (supercritical or liquid) state. A depressurization of the pipeline can occur due to an accident or planned maintenance. This will cause phase transition and a strong Joule-Thomson cooling of the pipe. If the temperature becomes low enough, the material in the pipe and any valves may become brittle or coatings may lose their function, with the risk of rupture, injury, material and infrastructure damage [2]. Studies performed by Gassco have shown that existing pipeline simulation tools struggle to estimate the fluid temperature close to the release points during CO_2 pipeline depressurization [3].

Near or in populated areas, running fracture of the pipeline must be avoided. A fracture can be initiated e.g. by corrosion or mechanical damage. The fracture may run if the fluid pressure at the crack tip is higher than a critical value. This is a coupled fluid-structure problem, involving such items as the crack-propagation speed versus the pressure-propagation speed (or sound speed) [4]. To calculate the latter, a flow model including an accurate thermodynamic description of the fluid is required.

A further HSE issue for CO_2 pipelines concerns noise and dispersion during a depressurization. Concept studies of noise and dispersion performed by Gassco [5] indicate that special care has to be taken in the design of the vents to avoid problems with noise and dispersion in the close vicinity of existing processing plants. Noise and dispersion models for CO_2 in the terrain are not considered in the present work, but it should be noted that to study both dispersion and noise, required inputs include the flow rate, liquid and gas volume fractions, temperature and pressure upstream from the point of release. Therefore, the coupled pipe flow and thermodynamic models we consider here provide necessary boundary conditions for dispersion and noise modelling.

An additional complexity which may be a practical challenge for the future CO_2 storage projects is that some power plants with CO_2 capture are likely to operate with varying load, which leads to a varying CO_2 production over time [6]. This can be both rapid and slow fluctuations. Depending on the infrastructure setting, the fluctuations can be more or less difficult to handle for the downstream operation of pipelines and injection wells. We will illustrate this by an example from Vattenfall's Nordjyllandsværket.

A final issue for current research and development (R&D) is transient CO_2 flow in wells, of which planned well shut-ins and an uncontrolled depressurization represent the extreme cases. In the latter it is likely that CO_2 in the well will flow out, rapidly followed by the formation water. The speed is dependent on, among other things, the difference between the hydrostatic and the storage reservoir pressure.

To be able to predict and control the above-mentioned issues with experimentally validated modelling tools, can be called CO_2 flow assurance. Many of those tools are currently under rapid development in various stages of R&D. One example is the CO_2 Dynamics project which aims at combining thermodynamic and fluid flow modelling for CO_2 with impurities, and this will be discussed in the following.

2. Some of Statoil's experiences from Snøhvit and Sleipner

2.1. Experimental verification of depressurization and heat transfer

During design, one needs to establish methods and procedures for depressurization of CO_2 pipelines and CO_2 compression equipment. The reasons can be regular maintenance, planned stops or undesirable accidents. However, for CO_2, the triple and critical point are located in the operational window of such depressurizations. Compared to natural gas, CO_2 depressurizations can become significantly colder in less time due to evaporation of liquid CO_2 and the higher Joule-Thomson coefficient. CO_2 is handled routinely in the beverage industry which has developed methods for depressurization. But CO_2 capture and storage (CCS) handles significantly larger volumes of CO_2 than the beverage industry. Hence the effects of depressurization become more expressed. Eagleton [7] was one of the first to describe these issues. The depressurization challenge for onshore CO_2 pipelines is solved by regular vent stations. However, such vent stations are not possible for long offshore pipelines with injection wells from subsea templates. Hence, depressurization can only be done at the compression site and it can take a long time to safely depressurize and keep the temperature above design limits. If the temperature becomes low enough, the material in the pipe and any valves may become brittle or coatings may lose their function, with the risk of rupture, injury and material damage. Inspired by the construction of CCS at the LNG plant for production from the Snøhvit gas field [8], Statoil and SINTEF started R&D on depressurization of CO_2 pipelines. It was acknowledged that the pipeline system could be built and operated safely, but that experimentally verified models could decrease cost and improve safety even more. Two different physical phenomena were chosen for experimental verification. The first one was logically the simultaneous evaporation and Joule-Thomson cooling of CO_2 inside the pipeline. The second one was the heat transfer outside the pipeline. It was found in the first modelling attempts that the heat transfer coefficient is very important for the total depressurization time. During a depressurization, the pipeline usually gets colder than its environment. For pipelines, the outer heat-transfer coefficient is usually lower than the inner one, and it therefore determines the heat transfer to the surroundings. When a pipeline is surrounded by water, it can be challenging to estimate the outer heat-transfer coefficient. Below 0 ˚C an ice layer can form and grow which introduces a transient heat transfer coefficient. The results until now of this R&D have been described in References [9,2,10,11]. The current status is that several experimental campaigns have been executed and compared to models. The next step for further maturing the models for commercial use is to tune them with the experiments, while continuously improving the fundamental base of the models.

2.2. Two-phase flow

This Section will discuss two-phase flow of CO_2 by using the Sleipner CO_2 injection as an example. A good reason for this discussion is claims that two-phase flow should be avoided in CO_2 pipelines [12]. On the Statoil operated Sleipner offshore platform in the North Sea, CO_2 is captured from natural gas, recompressed, transported and injected via a platform well into the Utsira saline aquifer. The first estimates of the flow conditions were published by Hansen *et al.* [13]. Their compression train and wellhead flow is described in a pressure-enthalpy diagram, see Figure 1. The flow leaving the last cooler and going into the well was touching the two-phase line, but not entering. This estimate was in line with the uncertainties of the reservoir pressure and temperature at the time. But knowledge on the reservoir has increased [14], which leads to better understanding of the flow conditions in the well. A more likely behaviour is given by the line with the square symbols, which assumes, for simplicity, adiabatic flow in the well. The pressure at the wellhead is assumed to be 65 bar. The flow at the wellhead is now clearly in the two-phase area and there is a gradual phase change inside the well. The figure also shows the phase envelope for a CO_2 mixture with 5% CH_4, which can occur at natural gas sweetening plants like Sleipner. The CH_4 even increases the pressure-enthalpy envelope where two-phase flow exists.

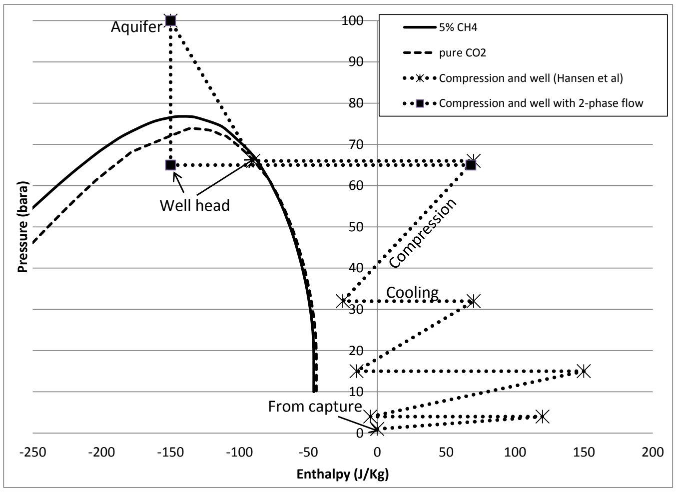


Figure 1. Pressure enthalpy diagram for pure CO_2 and CO_2 with 5% CH4 showing two compression and well paths at Sleipner (SRK Peneloux (T) in PVTSim 19.0 by CalSep was used)

Sleipner is not the only CCS site with the two-phase flow. Henninges *et al.* [15] documented two-phase flow in the demonstration well at Ketzin, Germany. So, it is likely that at two-phase flow is in operation at least two CCS sites. For building up a sufficiently dense column in the well, two-phase flow may even be unavoidable in high-permeability shallow CO_2 storage reservoirs. As a final note, both the two-phase flow occurrences at Sleipner and Ketzin have in common that transport distances are short and no rotating equipment is installed.

3. Vattenfall onshore pipeline project

Most thermal power plants are designed for base load operation with a relatively small number of starts and stops per year. Taking Denmark as an example, more than 25% of the electricity today is produced by wind turbines, with a high variation in actual market contribution. The boundary conditions for thermal power plants are thereby changing towards an increasing need for cyclic loads and operation involving frequent starts and stops. Further improvements on reduction of minimum load, shortened time for start-up and shut-down and increased load change rate will lead to increased load-flexibility over time. The same conditions will apply for CCS.

In 2009, Vattenfall shelved plans on a CCS demonstration project at the coal-fired power plant Nordjyllandsværket. The project included a post-combustion capture plant with up to 1.8 million tonnes of CO_2 per year and storage at an onshore saline aquifer with 24 km pipeline transportation. The power plant operates today such that the electricity output can be varied by the market prices for electricity. The CCS preparations included work with the objective to improve the understanding of the pressure, temperature and related phase behaviour of the CO_2 flow during different operational phases and to evaluate the impact that this has on the technical design.

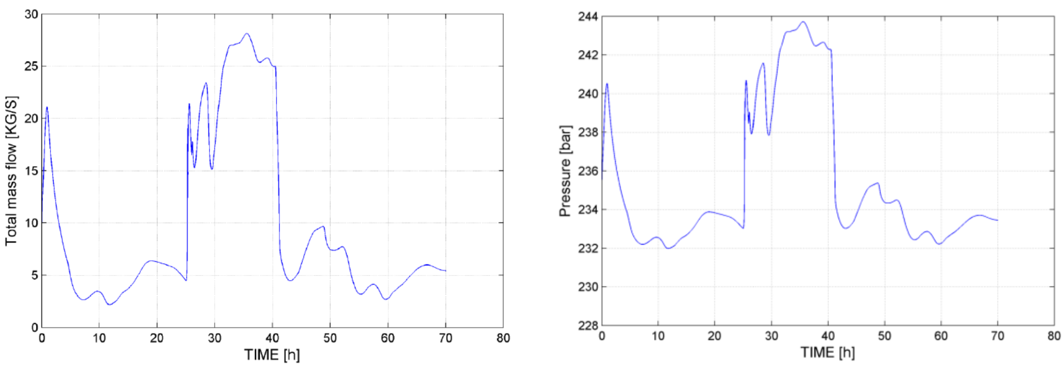
Part of the work investigated the effect of transient operational scenarios imposed at the plant on the flow in the pipeline and well/reservoir [6]. A main concern was loss of injectivity due to rapid change/oscillations in bottom-hole pressure. The impact of changes in CO_2 injection rate due to start-up, shut-down, compressor trip at the capturing plant as well as load changes during operation, such as ramp-down-ramp-up was modelled using the multiphase thermo-hydraulic simulation tool OLGA (version 6.1) from SPT Group [16]. The recently developed CO_2 single component module of OLGA [11] was used, which utilizes the Span-Wagner Equation of State (EOS) for pure CO_2 [17]. Several operational scenarios were simulated. Here we consider ramp-up-ramp-down (from 18% to 100% load and back). The boundary conditions were as follows:

- Mass flow rate at the pipeline inlet as a time series, with 77.5 kg/s @ 100% load)
- Fluid temperature at the pipeline inlet: 40°C
- Reservoir pressure at a reference depth: 231 bar
- Well injectivity index, II: 2.21296×10^{-5} kg/s/Pa
- Ambient (air) temperature for the pipeline: 8°C
- Linear ambient temperature profile in the wells

The ramp-up-ramp-down simulations starts to operate at a flow rate of 18% load for 25 h. Steady state is not reached yet (Figure 2a), but at this time the flow rate is increased to 100% and kept for 15 h before decreasing the flow to 18% again. During the ramp-up the bottom-hole pressure (Figure 2b) first increases rapidly from 233 to 240.7 bar (about 0.5 h after the ramp-up was initiated at the inlet, at 25 h), then goes through a couple of oscillations around 239.5 bar before rising to the peak value of 243.8 bar (about 10 hours after initiation of ramp-up) and then decreasing just above 242 bar during the high-flow-rate period. The high inlet rate is kept for 15 h, but this is not sufficiently long to obtain a steady state in the bottom-hole (Figure 2a). At ramp-down (initiated at 40.45 h) the bottom-hole pressure goes rapidly down from just above 242 bar to about 233 bar and oscillates around this value with roughly 1 bar amplitude the remaining period of the simulation.

The simulations indicate that phase change to gas phase occurs in the first part of the pipeline during the low-flow-rate periods (see also Section 2.2 on two-phase flow). This increases the complexity of the transient system and is a part of the reason of the irregular oscillating flow behaviour.

The results show that the bottom-hole pressure (and pressure in the reservoir in the near well area) reacts almost instantaneously to sudden changes in the CO_2 injection. These changes are not considered to be dramatic, though the impact from continuation of these changes over time should be assessed on the well and the near-well reservoir.



(a) Total mass flow (b) Pressure

Figure 2. The Nordjyllandsværket ramp-up ramp-down case. Simulated results at the well bottomhole.

4. Gassco's Mongstad project

The Norwegian Ministry of Petroleum and Energy (MPE) has requested Gassco to evaluate solutions for subsea pipeline transportation of captured CO_2 from flue gas emitted by the Combined Heat and Power (CHP) plant at Mongstad into suitable locations on the Norwegian Continental Shelf. The pipeline from the planned CO_2 capture plant at Mongstad is designed to transport at least 3.3 megatonnes of CO_2 per year.

Four possible storage locations have been evaluated resulting in four different CO_2 pipeline routes. All four routes share a common subsea pipeline route through the more than 500 m deep Fensfjorden. From Mongstad landfall down towards Fensfjorden it is proposed to have the pipeline laid in a borehole, which will be filled with water. For the two longest routes, the distance to the subsea template is 110 km and in order to transport the required amount of CO_2, a 12" pipeline (ID = 0.2889 m) will be required. At the subsea template, the CO_2 will enter a 2700 m deep injection well (ID = 6.1"). The reservoir conditions are given in terms of an estimated injectivity.

As part of this study, Gassco has modelled the transport of CO_2 along the entire pipeline including the onshore part at Mongstad, the offshore pipeline towards the template, the flow in the well and the injection into the reservoir. Capacity estimates, as well as detailed analysis of different transient scenarios like shut-in, settle-out, water-hammer effects and blow down, have been an important part of the work. For this purpose we have used OLGA, version 5.3.2, with the single-component CO_2 module as mentioned in the previous section.

In this section we will focus on challenges related to depressurization of the subsea pipeline, and in particular, uncertainties in the temperature predictions. From a pipeline integrity point of view, it is well known that depressurization of CO_2 can lead to very low temperatures within the pipeline. If the depressurization is performed too fast, the CO_2 might even reach the triple point (5.2 bar, –56.6 °C) resulting in the formation of dry ice and subsequent blockage of the stream and making the steel walls become brittle.

The simulations of the Mongstad pipeline show that it is possible to depressurize the pipeline through a 3" orifice keeping the temperature of the CO_2 above –20°C almost everywhere (minimum design temperature of offshore pipeline). However, according to the simulations, the temperature of the CO_2 will drop below the minimum design temperature along the first 250 m of the borehole. Thus, Gassco has proposed to rerate the relevant parts of the pipeline to handle this. Using stainless steel with a minimum design temperature of –45°C would resolve this issue, however, at an increased cost.

The borehole also possesses another challenge; it contains water, and during depressurization, the low temperatures of the CO_2 might lower the water temperature below the freezing point (0 °C). In the blow-down simulations, the OLGA model of the pipeline was refined by dividing the surrounding water in the borehole into four layers of concentric rings. The simulation results show that during the first fifteen hours of depressurization, only the water layer closest to the pipeline wall will freeze.

There are indications that the current version of OLGA is conservative in predicting the CO_2 temperature. In a previous study, we have used OLGA to simulate depressurization of an existing 50 km, 24" pipeline in the USA [3]. This study showed that the minimum simulated temperature upstream of the release was more than 12 K lower than the measured minimum temperature, see Figure 3. This observation supports that the risk of water freezing over in the borehole of the Mongstad pipeline is even lower than indicated by the OLGA simulations.

From Gassco's extensive work on the Mongstad CO_2 pipeline it is clear that improved and experimentally validated simulations tools for CO_2 transport are capable of reducing risk, as well as cost. Thus, it has been proposed that the above mentioned issues should be investigated further in the next phase of the Mongstad project. These investigations should aim at verifying that the heat transfer models implemented in OLGA provide accurate-enough predictions for challenging transient cases. It is advised to conduct simulations using the OLGA Finite Element Method (FEM) module, other third party Finite Volume software, as well as utilizing recently developed models obtained in on-going CO_2 projects like CO_2 Dynamics. Future investigations should also include lessons learned from experimental work on heat transfer, like the on-going work involving the CO_2 heat transfer rig of Statoil [2].

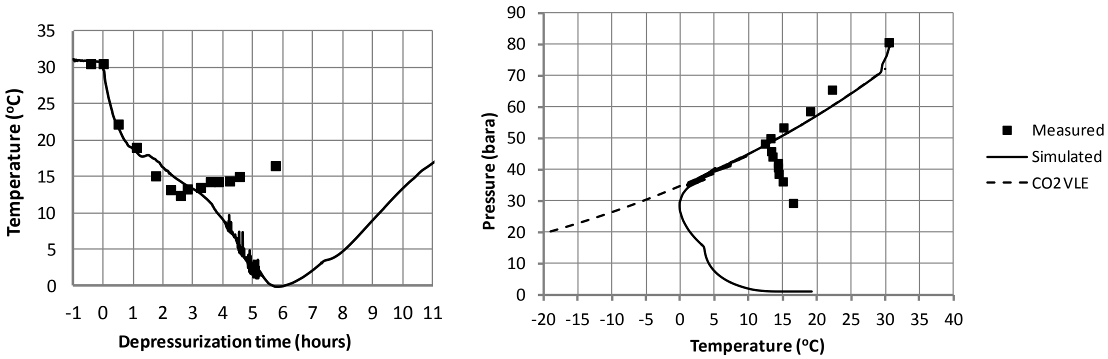


Figure 3. Measured and simulated temperature development upstream the vent opening versus time for an on-shore US pipeline (left). The corresponding pressures and temperatures plotted in a (P,T) diagram together with the CO_2 Vapor-Liquid-Equilibrium line (VLE) (right). Both figures are taken from [3].

5. Thermodynamic and fluid dynamic modelling

As illustrated in the previous sections, new knowledge can help in the design and operation of safe and efficient CO_2-transport systems. The knowledge required spans the range from basic-oriented research to pilot plants. The CO_2 Dynamics project[†] is set up to close some of the more basic knowledge gaps within fluid dynamics, thermodynamics and numerical methods, and they will be briefly discussed here.

Several of the pipe flow simulators in use in the oil and gas industry have been developed mainly with mass transport in mind. The need also to simulate e.g. depressurizations requires robust and accurate numerical methods, due to the difference in scale between the relatively slow-moving mass waves and the fast-moving pressure waves [18,19,20,21]. In CCS, the CO_2 to be transported is not going to be pure. Even small amounts of some impurities can significantly influence the thermophysical properties of the CO_2, and hence also the decompression behaviour [18].

In two-phase flow modelling, it is not uncommon to assume that the two phases have the same pressure, temperature and chemical potential at all times, that is, instantaneous mechanical, thermal and phase equilibrium. However, this assumption leads to the prediction of a discontinuous speed of sound in the limit of single-phase flow [22]. This is not considered physical. A better understanding is required in this area in order to physically model non-equilibrium flows. However, it is already clear that the assumptions on equilibrium affect the speed of sound predicted by the model [23,24,25,20,26,27]. In particular, an equilibrium model will predict a lower speed of sound than a non-equilibrium (relaxation) model [28]. Here it is necessary to bear in mind that while the speed of sound is a thermodynamic property for a single-phase fluid, it is a function of both thermodynamics and flow topology in a multiphase flow.

[†] http://www.sintef.no/co2dynamics

The constitutive relations occurring in multiphase-flow models have been studied for a long time, but there is still no canonical formulation being both physically realistic and mathematically well-posed, see e.g. Ref. [29]. One contribution towards the latter goal is by Flåtten and Morin [30], who found that a thermodynamically reversible model possessing real eigenvalues must include some sort of virtual-mass terms. In a more practical study, Aakenes [31] compared experimental data for frictional pressure-drop for steady-state two-phase flow of pure CO_2 (see also [2]) to data calculated using models from the literature. It was found that a model developed specifically for CO_2 is not enough in itself; a broad experimental base is also required. Hence more work is needed, both in modelling and experiments, regarding physically validated and mathematically sound models for the flow of CO_2-rich mixtures in pipelines. In particular, the interplay between thermodynamics and fluid dynamics deserves more attention.

Thermodynamic models, such as equations of state (EOS), are normally associated with a numerical algorithm to find e.g. solutions for phase equilibria. When included in computational fluid dynamics (CFD) calculations, such algorithms are required to be particularly robust, accurate and efficient – more so than what is normally needed in e.g. process simulations. The stiffened-gas (SG) equation of state is widely used in the CFD literature, and efficient algorithms have been made [32]. However, for many applications, the SG EOS is too simple to provide realistic-enough results. At the same time, reference EOS'es like the one of Span and Wagner [17] for pure CO_2 are computationally expensive [33]. The extended corresponding-state approach like the one of SPUNG [34,35] may constitute a good compromise between computational speed and accuracy.

The development of accurate thermophysical models requires accurate experimental data. Regarding CCS-relevant data for CO_2-rich mixtures, there are significant gaps both regarding thermodynamic [36] and transport properties [37]. In particular, more data and model development are needed for vapour-liquid equilibria, density, speed of sound and viscosity.

6. Conclusions

The design and safe operation of CO_2-transport pipelines can benefit from physics-based and validated models for flow and depressurization. Two or multiphase flow can occur both during normal operation and during such situations as start-up and shut-down. Further, models need to account for the mixture properties of CO_2-rich mixtures. The calculation of the speed of sound in two-phase flow where condensation and evaporation can occur is subject to research. It is of particular relevance for pipeline depressurizations and pipeline integrity assessments. The common assumption of full mechanical, thermal and phase equilibrium leads to unphysical predictions of the speed of sound.

Physics-based combined thermodynamic and transient flow models for CO_2-transport pipelines can provide useful input to risk analyses and design of mitigation actions of undesirable incidents like pipeline rupture and well blow-outs. Future research should span the range from basic-oriented work to more practical tests in order to address the current knowledge gaps.

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