Dynamic simulation of CO_2 flow through pipelines

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Carbon dioxide mixtures from separation plants contain usually some impurities. Major impurities include nitrogen, argon, hydrogen and oxygen, depending on the capture technology The mixture composition determines operating conditions the values of critical pressure and critical temperature in turn, the limits of dense phase/supercritical.

Carbon Capture and Storage (CCS) faces a number of challenges, which include transportation CO_2

Pipelines are the preferred mode of transportation for CO_2 when large volumes of captured CO_2 are to be stored in geological formations at some distance from the capture location.

Generally, CO_2 should be transported either as liquid or as a supercritical/dense phase fluid . Dense phase is a preferable condition for transporting CO_2
in pipelines. This state is characterized by fluid viscosity similar to that of a gas, but a density closer to that of a liquid.

The main purpose of this work was to examine the hydraulic parameters of the CO_2 pipeline by solving the single-phase, compressible fluid flow model.

The model is represented by one dimensional version of the Euler equations with terms representing <u>viscous dissipation</u> of energy and <u>heat transfer</u> to the surroundings.

Pipeline model

The basic equations are derived from the conservation principles.

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

$$\frac{\partial(\rho w)}{\partial t}+\frac{\partial\left(p+\rho w^2\right)}{\partial x}=-\frac{f\rho w|w|}{2D}-\rho g\sin\alpha$$

$$\frac{\partial}{\partial t}\left[\left(u+\frac{w^2}{2}\right)\rho\right]+\frac{\partial}{\partial x}\left[\left(h+\frac{w^2}{2}\right)\rho w\right]=\rho q-\rho w g\sin\alpha$$

Pressure, temperature and mass flow rate
- the dependent variables, since the above parameters are typically measured and used in pipeline operations. We assume that the transmission pipeline is operated with given CO_2 production rate and with the assumption of maintaining the storage site minimal delivery pressure

h_{conv}

For pipe with depth *H* below the ground surface and the surroundings of the pipe we obtain the following formula for the ground resistance

$$k_L = \left(\frac{1}{\pi D_1 h_{\text{conv}}} + \sum_{i=1}^{m} \frac{1}{2\pi\lambda_i} \ln\left(\frac{D_i}{D_{i-1}} \right) + R_{\text{ground}} \right)^{-1}$$

The overall linear heat-transfer coefficient for onshore pipelines is calculated from the expression:

$$R_{\text{ground}} = \frac{1}{2\pi\lambda_{\text{ground}}} \ln\left(\frac{H}{D} + \sqrt{\left(\frac{H}{D}\right)^2 - 1} \right)$$

Compressor model

The required work input to a compressor for a defined control period:

$$W_{comp} = \int_{t_0}^{t_1} \dot{W}_{comp,i} \cdot \mathrm{d}t$$

The power input to all stages of compression:

$$\dot{W}_{comp,i} = \sum_{i} M \cdot \left(h_d - h_s\right)$$

The exit enthalpy of the i-th stage is calculated using isentropic efficiency of the compressor:

$$h_d = h_s + \left(h_{is,d} - h_s\right) / \eta_{comp}$$

Numerical results are given for CCS project in Bełchatów power plant.

The plant will capture carbon dioxide coming from the flue gas stream leaving the 858 MW power generation unit. The compressed gas will be transported to underground structure located 140 km away from the capture plant.

Three different capture technologies, namely: Post-combustion, Pre-combustion, and Oxyfuel were considered for the purpose of the hydraulic analysis of the CO_2 transmission system.

The Post-combustion and Pre-combustion processes were modelled by binary combinations of CO_2 with nitrogen and hydrogen, respectively, while Oxyfuel technology was represented by a four component mixture of CO_2, nitrogen, oxygen, and argon.

The mass flow rate in the capture plant varies between the values of 40 and 100 kg/s (Fig. 1). Delivery pressure, equal to 10 bar above the critical pressure of the respective CO_2 mixture, was set as the boundary condition at the end of the pipeline (delivery node). For oxyfuel mixture the delivery pressure 20 bar above the critical pressure was necessary to avoid two-phase flow conditions in the pipeline (Fig. 2).

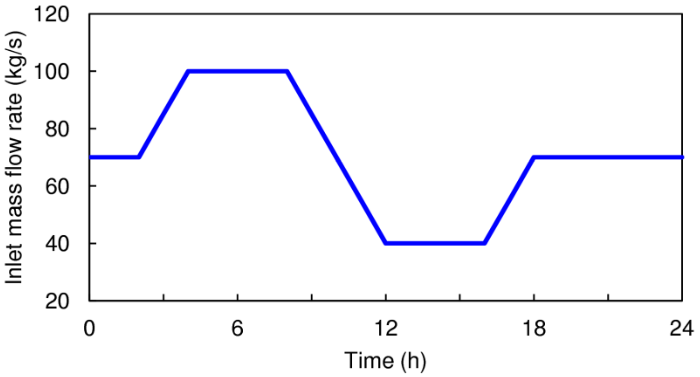

Fig. 1

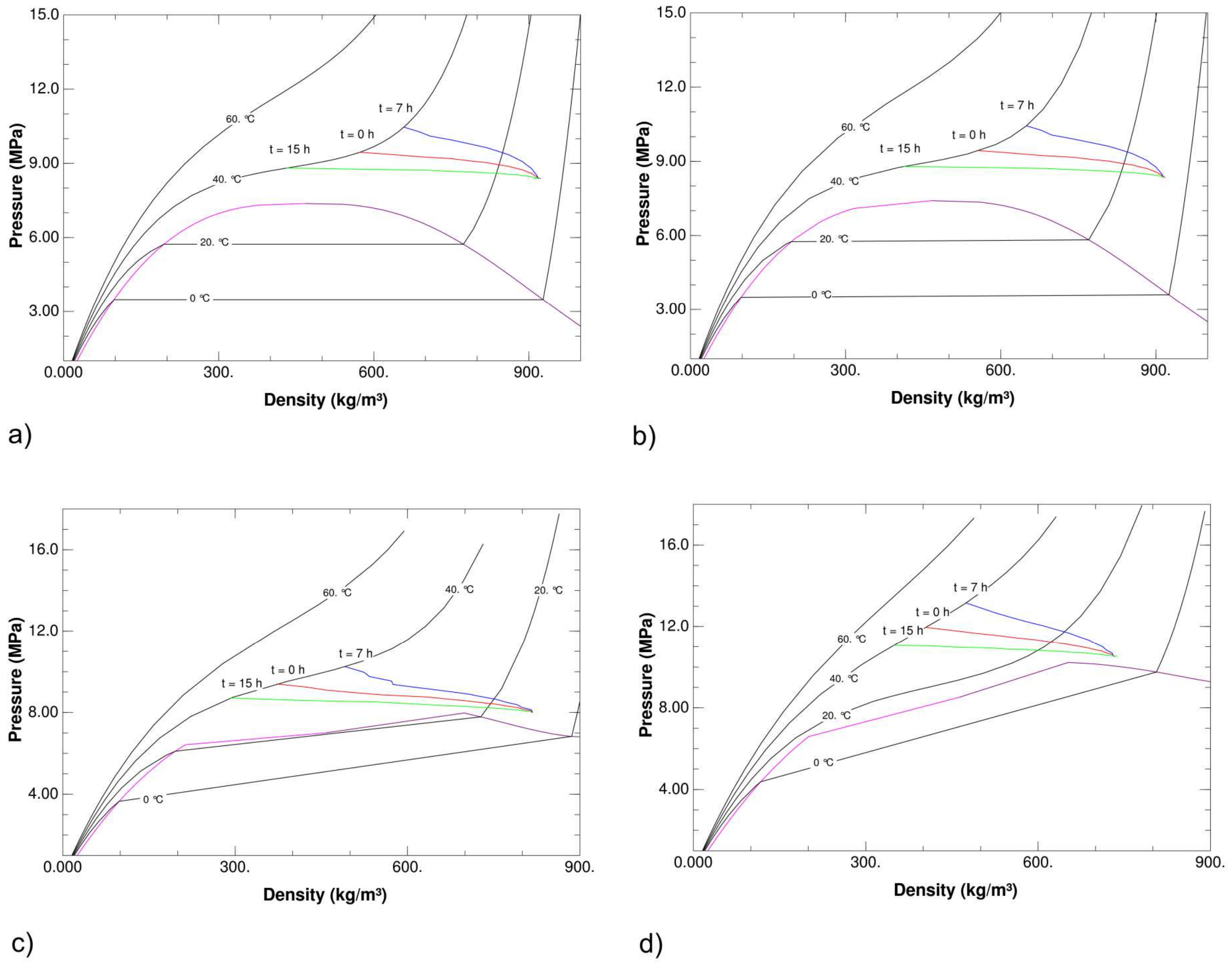
15.0
12.0
9.00
6.00
3.00
Pressure (MPa)
0.000
300.
600.
900.
Density (kg/m³)
60. ℃
40. ℃
20. ℃
0 ℃
t = 7 h
t = 0 h
t = 15 h
a)
b)
16.0
12.0
8.00
4.00
c)
d)

Fig. 2

The effect of CO_2 mixture composition on the flow is very distinct (Figure 3). Disturbing the flow rate at the beginning of the pipeline – we have unsteady state. Depending on the gas composition the flow rates gradually approach their steady state values. The mass flow rates of the Oxyfuel and Pre-combustion streams slowly reach steady state condition, the mass flow rate of the Post-combustion mixture shows much faster approach to its steady state value (result of relatively low impurity concentration).

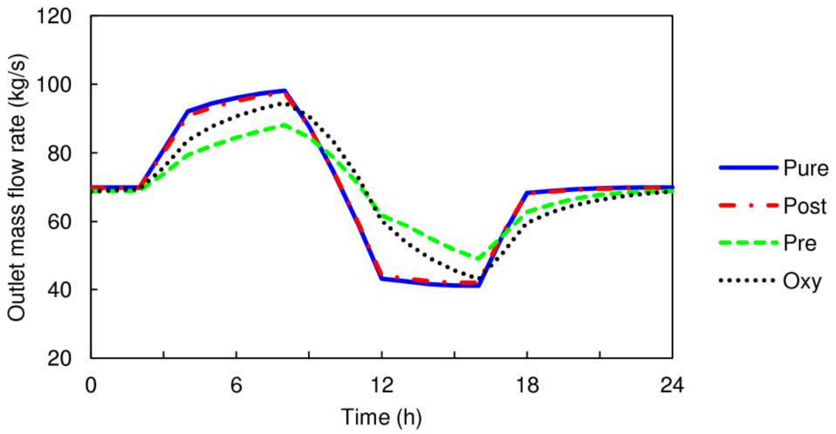
120
100
80
60
40
20
Outlet mass flow rate (kg/s)
0
6
12
18
24
Time (h)
Pure
Post
Pre
Oxy

Fig. 3

The compressor station discharge pressure necessary to maintain dense phase in the pipeline under transient conditions is a function of quality of the stream of mixture (fig.4). In case of Oxyfuel stream the discharge pressure must be considerably higher than for the remaining streams. This occurs because of higher critical pressure and larger pressure variations of the Oxyfuel mixture, compared to other CO_2 mixtures (Fig. 2).

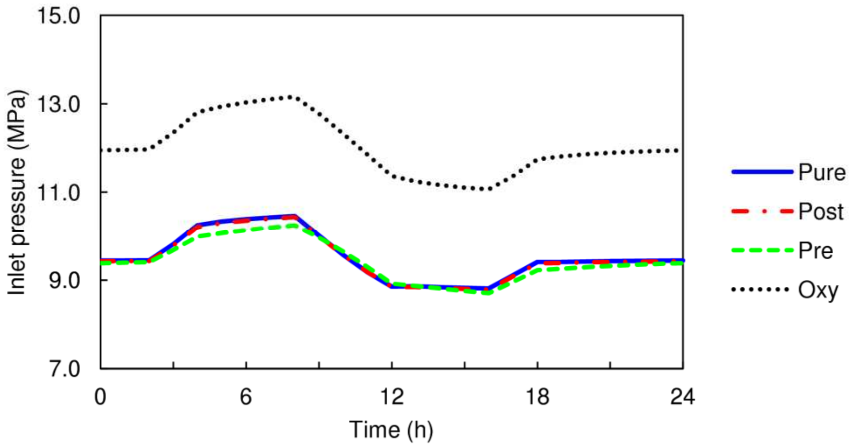
15.0
13.0
11.0
9.0
7.0
Inlet pressure (MPa)
0
6
12
18
24
Time (h)
Pure
Post
Pre
Oxy

Fig. 4

The selection of Oxyfuel capture technology will generate higher operational costs.
The fluctuation amplitude of Pre-combustion and Post-combustion CO_2 mixtures remains approximately constant, comparable to that of CO_2 fluid. The impurity combination in the Oxyfuel mixture, however, causes the difference in pressure drop to become slightly higher.

The comparison of compression power for different CO_2 mixture compositions under transient conditions is illustrated in Fig. 5. The total energy demand (compressor work input) for the 24h simulation period in case of Oxyfuel stream was 588 MWh, compared to 524 MWh in case of the CO_2 stream. For Pre-combustion and Post-combustion streams, the figures were 541 and 524 MWh, respectively.

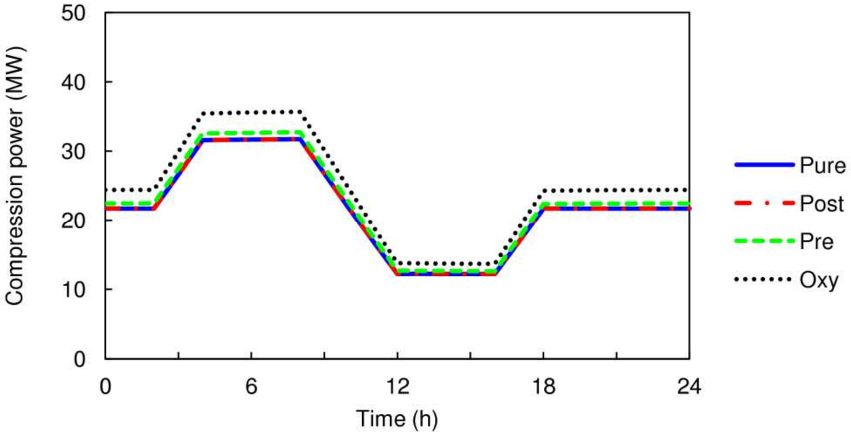
50
40
30
20
10
0
Compression power (MW)
0
6
12
18
24
Time (h)
Pure
Post
Pre
Oxy

Fig. 5

Conclusions

The results of the transient simulation of the CO_2 pipelines indicate that the CO_2 mixtures from different capture technologies show different dynamic behaviour during pipeline transport. Oxyfuel technology presents considerable different pressure-temperature conditions, as well as fuel consumption, in comparison to Post-combustion and Pre-combustion processes.

Conclusions

The results show that the type and quantity of impurities have a significant influence on the hydraulics of the pipeline transportation system under transient conditions. They also indicate that the transportation costs vary and are dependent on the capture technology used.

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Dynamic simulation of pipelines containing dense phase/supercritical CO_2–rich mixtures for carbon capture and storage

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