Property impacts on performance of CO2 pipeline transport

Yuting Tan\textsuperscript{a,\*}, Worrada Nookuea\textsuperscript{b}, Hailong Li\textsuperscript{b}, Eva Thorin\textsuperscript{b}, Li Zhao\textsuperscript{c}, Jinyue Yan\textsuperscript{a,b,\*}

\textsuperscript{a}Department of Chemical Engineering, Royal Institute of Technology, SE 100 44 Stockholm, Sweden
\textsuperscript{b}School of Sustainable Development of Society and Technology, Malardalen University, SE 721 23 Västrås, Sweden
\textsuperscript{c}Key Laboratory of Efficient Utilization of Low and Medium Grade Energy, MOE, Tianjin University, 300072 Tianjin, PR China

Abstract

Carbon Capture and Storage (CCS) is one of the most potential technologies to mitigate climate change. Using pipelines to transport CO\textsubscript{2} from emission sources to storage sites is one of common and mature technologies. The design and operation of pipeline transport process requires careful considerations of thermo-physical properties. This paper studied the impact of properties, including density, viscosity, thermal conductivity and heat capacity, on the performance of CO\textsubscript{2} pipeline transport. The pressure loss and temperature drop in steady state were calculated by using homogenous friction model and Sukhof temperature drop theory, respectively. The results of sensitivity study show that over-estimating density and viscosity increases the pressure loss while under-estimating of density and viscosity decreases it. Over-estimating density and heat capacity leads to lower temperature drop while under-estimating of density and heat capacity result in higher temperature drop. This study suggests that the accuracy of property models for example, more accurate density model, should be developed for the CO\textsubscript{2} transport design.

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Keywords: Thermal-physical property; Sensitivity study; Pipeline transport; CCS

1. Introduction

Carbon Capture and Storage (CCS) accounts for a potential reduction of 20\% to 28\% of greenhouse gases (GHG) emissions in achieving 2°C climate change target by 2050 [1]. In order to transport CO\textsubscript{2} from capture plants to storage sites, different means including pipeline, ship or tanker trucks can be used mainly depending on the distance [2]. Pipelines today operate as a mature technology and have the ability to transport a large amount of CO\textsubscript{2} over a long distance.

Design of CO\textsubscript{2} pipeline combines technical, cost and environment impact assessments, and considers a wide range of variables and parameters [3]. Among the parameters, pressure and temperature profiles are

* Corresponding author. Tel.: +46-(0)8-790-6223
E-mail address: tany@kth.se, jinyue@kth.se
significant to keep CO$_2$ transported in dense phase. In addition, pressure loss and temperature drop play key roles in determining the initial investment and operating cost. For example, pressure loss in pipeline is relevant to pump selection and pumping energy consumption.

Calculating the pressure and temperature drop requires thermo-physical properties, including density, viscosity, heat capacity, thermal conductivity etc. [4]. Under- or over-estimated properties may result in a high investment cost or the failure of operation. Many works have been done concerning the evaluation of property models [4-6]. However, fewer efforts have been focused on the impact of properties on pipeline design and operation. Different properties have different impacts on the process; and the accuracy of modeling various properties are also various. Therefore, prior to the development of new models, it is of great importance to identify the key properties and the bottle neck in property calculations, which has not been yet conducted to our knowledge. This work aims to evaluate the impact of different properties on pressure loss and temperature drop. Sensitivity study is also carried out to identify the key impacts of the thermophysical properties on the pipeline transport.

### Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_p$</td>
<td>Heat capacity (kJ/kg·K)</td>
</tr>
<tr>
<td>$D_p$</td>
<td>Outer diameter of pipe (m)</td>
</tr>
<tr>
<td>$D_t$</td>
<td>Inner diameter of tube (m)</td>
</tr>
<tr>
<td>$f$</td>
<td>Friction factor</td>
</tr>
<tr>
<td>$G$</td>
<td>Mass flow rate (kg/s)</td>
</tr>
<tr>
<td>$h$</td>
<td>Depth of pipe underground (m)</td>
</tr>
<tr>
<td>$K$</td>
<td>Total transfer coefficient (W/m$^2$·K)</td>
</tr>
<tr>
<td>$L$</td>
<td>Length of pipeline (km)</td>
</tr>
<tr>
<td>$\Delta P$</td>
<td>Pressure loss (Pa/m)</td>
</tr>
<tr>
<td>$\text{Re}_f$</td>
<td>Reynolds number</td>
</tr>
<tr>
<td>$\text{Pr}_f$</td>
<td>Prandtl number at fluid temperature</td>
</tr>
<tr>
<td>$\text{Pr}_t$</td>
<td>Prandtl number at tube temperature</td>
</tr>
<tr>
<td>$T_L$</td>
<td>Temperature at distance L (K)</td>
</tr>
<tr>
<td>$T_s$</td>
<td>Temperature of soil (K)</td>
</tr>
<tr>
<td>$T_0$</td>
<td>Temperature at distance 0 (K)</td>
</tr>
<tr>
<td>$u$</td>
<td>Velocity of fluid (m/s)</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Density (kg/m$^3$)</td>
</tr>
<tr>
<td>$\alpha_1$</td>
<td>Heat transfer coefficient of fluid (W/m$^2$·K)</td>
</tr>
<tr>
<td>$\alpha_2$</td>
<td>Heat transfer coefficient pipe to soil (W/m$^2$·K)</td>
</tr>
<tr>
<td>$\lambda_i$</td>
<td>Thermal conductivity of insulation (W/m·K)</td>
</tr>
<tr>
<td>$\lambda_f$</td>
<td>Thermal conductivity of fluid (W/m·K)</td>
</tr>
</tbody>
</table>

### 2. Methodology and models

#### 2.1. Thermo-physical property

The thermo-physical properties studied in this paper include density, viscosity, thermal conductivity and heat capacity. The calculation of the properties is conducted by using REFPROP [7].

#### 2.2. Pressure loss

Gaseous CO$_2$ is typically compressed to a pressure above 8 MPa in order to avoid two-phase flow and increase the density of CO$_2$, thereby making it easier and less costly to transport. This paper uses single-phase homogenous friction model [8] to estimate the pressure loss:

$$\Delta P = \frac{1}{2} \left( \frac{L}{D_t} \right) f \rho u^2$$ (1)
Where $L$ is length of pipeline, $D_t$ is inner diameter of tube, $f$ is fanning friction factor, $u$ is velocity of fluid, $\rho$ is density. To calculate friction factor, a model proposed by Xiande Fang et al. [9] is used which can satisfy supercritical flow in rough pipes.

\[
f = 1.613 \left[ \ln \left( 0.234 \left( \frac{\varepsilon}{D_t} \right)^{1.1007} - \frac{60.525}{Re_f^{1.1105}} + \frac{56.291}{Re_f^{1.0772}} \right) \right]^{-2} \left( \frac{\mu_t}{\mu_b} \right)^{0.49} \left( \frac{\rho_f}{\rho_{pc}} \right)^{1.31}
\]

Where $Re_f$ represents Reynolds number, $\varepsilon$ is roughness of the pipe, $\mu_t$ and $\mu_b$ are viscosity at inner wall temperature and at fluid bulk temperature respectively, $\rho_t$ and $\rho_{pc}$ are density at film temperature and at pseudo-critical temperature respectively. Table 1 lists the key parameters in pressure loss calculation based on the case suggested by MIT [10].

Table 1. Parameters in pressure loss and temperature drop calculation [10, 11]

<table>
<thead>
<tr>
<th>Parameter in pressure loss</th>
<th>Value</th>
<th>Parameter in temperature drop</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure of fluid / (MPa)</td>
<td>15.20</td>
<td>Insulation thickness / (m)</td>
<td>0.10</td>
</tr>
<tr>
<td>Temperature of fluid / (K)</td>
<td>298</td>
<td>Thermal conductivity of soil / (W/m·K)</td>
<td>1.10</td>
</tr>
<tr>
<td>Diameter of tube/ (m)</td>
<td>0.50</td>
<td>Thermal conductivity of insulation / (W/m·K)</td>
<td>0.04</td>
</tr>
<tr>
<td>Mass flow rate / (kg/s)</td>
<td>303</td>
<td>Length of pipeline / (km)</td>
<td>100</td>
</tr>
</tbody>
</table>

2.3. Temperature drop

Sukhov temperature drop theory has been widely used in temperature profile calculation for crude oil pipeline transport, hence, it is employed in this paper to estimate the temperature drop of CO$_2$ pipeline. It is assumed that the viscous heating in the condition of $Re>10^4$ and $Pr<2500$ is negligible. The temperature drop can be estimated by the equations as follows [12]:

\[
T_L = T_0 + (T_s - T_0)e^{-\frac{K\pi(D_t + D_p)}{6G C_p L}}
\]

\[
K = \frac{1}{2} \left( D_t + D_p \right)
\]

\[
\alpha_1 = 0.021 \frac{Re_f^{0.8}}{Pr_f^{0.25}}
\]

\[
\alpha_2 = \frac{2 \lambda_s}{\frac{2(D_t + D_p)}{2(D_t + D_p)}}
\]

Where $T_L$ and $T_0$ is temperature at distance L and 0 respectively, $T_s$ is temperature of soil, $K$ is total transfer coefficient, $D_p$ is outer diameter of pipe, $G$ is mass flow rate, $C_p$ is heat capacity, $L$ is length of pipeline. $\alpha_1$ and $\alpha_2$ are heat transfer coefficient of fluid and pipe to soil respectively. $\lambda_i$ and $\lambda_f$ are thermal conductivity of isolation and fluid respectively. $Re_f$ is Reynolds number, $Pr_i$ and $Pr_f$ are Prandtl number at tube temperature and at fluid temperature, $h$ is depth of pipe underground.
Key parameters in temperature drop calculation are listed in table 1.

3. Results and discussions

3.1. Property impacts on pressure loss

According to the model, pressure loss in CO₂ pipeline transport is only related to density and viscosity. Fig. 1 shows the change of pressure drop when properties vary in a range of ±20%. It is clear that overestimating density and viscosity increases the pressure loss while underestimating them decreases it. It is easy to understand that a higher viscosity will increase frictional force between fluid and pipe, resulting in the rise of pressure loss. Moreover, pressure loss increases because of the increased kinetic energy according to equation 1. In addition, pressure loss is more sensitive to density than to viscosity as shown in the figure. For example, overestimates of density and viscosity by 20% lead to 16.9% and 2.7% increment in pressure loss respectively, therefore it is more important to calculate density accurately, compared to viscosity.

For different properties, the property models give different accuracy. For predicting the density and viscosity, the maximum modelling deviations are 18.4% and 5% respectively [13-15], correspondingly, the maximum deviations lead to the variation of pressure loss of 15.7% and 0.73%. Therefore from the perspective of property modeling, developing more accurate density model should be prioritized.

![Fig. 1. Sensitivity study of property impacts on pressure loss](image)

3.2. Property impacts on temperature drop

Fig. 2 shows the property impacts on the temperature drop. According to the figure, effects of density and heat capacity on temperature drop are the same and more obvious, and the effects of viscosity and thermal conductivity are the same and rather small, thus can be negligible. Viscosity and thermal conductivity can affect the heat resistance of the fluid \( R_f \). Since \( R_f \) is so small compared to the heat resistance of insulation and soil \( R_{in} \), \( R_f \) can be ignored. Therefore, viscosity and thermal conductivity have little impact on temperature drop. On the contrary, according to equation 3, the temperature drop is directly related to mass flow rate and heat capacity. The over-estimate of density and heat capacity leads to lower temperature drop while under-estimate of properties results in higher temperature drop. A higher heat capacity means that more heat is needed to achieve the same change in temperature, and the
increment of density will increase the mass flow rate of the fluid. Therefore the temperature drop will be reduced according to equation 3. In addition, density and heat capacity have similar impacts on temperature drop. For example, over-estimate of density and heat capacity by 20% leads to 15.4% decrement in temperature drop. To calculate the temperature drop correctly, it is more important to calculate density and heat capacity accurately.

For predicting the density and heat capacity, the maximum modelling deviations are 18.4% and 5% respectively [15, 16], correspondingly, the maximum deviations lead to the variation of temperature drop of 20.1% and 2.8%. Therefore from the perspective of property modeling, developing more accurate density model should be prioritized.

![Fig. 2. Sensitivity study of property effects on temperature drop](image)

3.3. Effects between temperature drop and pressure loss

The property effects on pressure loss and temperature drop have been discussed individually. However, the effects are also coupled together at the same time. On one hand, the over- or under-estimate of density and heat capacity leads to the temperature profile change. Therefore the temperature-dependent properties, such as density and viscosity vary correspondingly, which further results in the variation in pressure loss. From the results obtained by Sukhov model, the total temperature drop is very small, and the variation of density and viscosity caused by temperature variation is small as well, hence the temperature effect on pressure loss can be ignored. On the other hand, the over- or under-estimate of density and viscosity lead to the pressure profile change, resulting in change of the pressure-dependent properties, such as density and heat capacity, consequently the temperature drop varies. From the results achieved from homogenous friction model, for example, when density and viscosity vary by 20% in pressure loss estimation, the pressure loss varies 16.9%, which cause the variation of density and heat capacity around 2%. Variation of density and viscosity caused by temperature variation is small as well, hence the temperature effect on pressure loss can be ignored.

4. Conclusion and future work

This paper studied the impacts of properties, including density, heat capacity, viscosity and thermal conductivity on pressure loss and temperature drop for CO₂ pipeline transport. Overestimate of density
and viscosity increases the pressure loss while underestimate of properties decreases it. Overestimate of density and heat capacity lead to lower temperature drop while underestimate of properties result in higher temperature drop. Model of density has larger the maximum deviation than the models of other properties, developing more accurate density model should be prioritized.

The current work chose homogenous friction model and Sukhov temperature drop theory to calculate the pressure loss and temperature drop, in the future work, more models could be compared to evaluate the difference of property effects. In addition, this study only focused on pipeline steady flow, the property effects on transient processes such as start-up and depressurization need to be investigated in the future.

Acknowledgements

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References


**Biography**

Yuting Tan now is a Ph.D. student in Royal Institute of Technology (KTH), with research interest in property impacts on Carbon Capture and Storage (CCS) processes as compression, transport and condensation.