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Property impacts on performance of CO_2 pipeline transport

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Abstract

Carbon Capture and Storage (CCS) is one of the most potential technologies to mitigate climate change. Using pipelines to transport CO_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_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_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_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 CO2 over a long distance.

Design of CO_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

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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 thermophyical properties on the pipeline transport.

Nomenclature

C_p	Heat capacity (kJ/kg·K)	Pr_t	Prandtl number at tube temperature
D_p	Outer diameter of pipe (m)	T_L	Temperature at distance L (K)
D_t	Inner diameter of tube (m)	T_s	Temperature of soil (K)
f	Friction factor	T_0	Temperature at distance 0 (K)
G	Mass flow rate (kg/s)	u	Velocity of fluid (m/s)
h	Depth of pipe underground (m)	ρ	Density (kg/m^3)
K	Total transfer coefficient ($W/m^2 \cdot K$)	α_1	Heat transfer coefficient of fluid ($W/m^2 \cdot K$)
L	Length of pipeline (km)	α_2	Heat transfer coefficient pipe to soil ($W/m^2 \cdot K$)
ΔP	Pressure loss (Pa/m)	λ_i	Thermal conductivity of insulation (W/m·K)
Re_f	Reynolds number	λ_f	Thermal conductivity of fluid (W/m·K)
Pr_f	Prandtl number at fluid temperature		

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:

$$\Delta P = \frac{1}{2}\left(\frac{L}{D_t}\right) f \rho u^2 \tag{1}$$

Where L is length of pipeline, D_t is inner diameter of tube, f is fanning friction factor, u is velocity of fluid, ρ 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.

$$f = 1.613[\ln(0.234\left(\frac{\varepsilon}{D_t}\right)^{1.1007} - \frac{60.525}{{Re_f}^{1.1105}} + \frac{56.291}{{Re_f}^{1.0712}})]^{-2}\left(\frac{\mu_t}{\mu_b}\right)^{0.49(\frac{\rho_f}{\rho_{pc}})^{1.31}} \quad (2)$$

Where Re_f represents Reynolds number, ε is roughness of the pipe, μ_t and μ_b are viscosity at inner wall temperature and at fluid bulk temperature respectively, ρ_f and ρ_{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]

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

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]:

$$T_L = T_0 + (T_s - T_0)e^{-\frac{K\pi D_p}{GC_p}L} \quad (3)$$

$$K\frac{1}{2}(D_t + D_p) = \left[\frac{1}{\alpha_1 D_t} + \frac{1}{\alpha_2 D_p} + \frac{\ln(\frac{D_p}{D_t})}{2\lambda_i}\right]^{-1} \quad (4)$$

$$\alpha_1 = 0.021\frac{\lambda_f}{D_t}{Re_f}^{0.8}{Pr_f}^{0.44}\left(\frac{Pr_f}{Pr_t}\right)^{0.25} \quad (5)$$

$$\alpha_2 = \frac{2\lambda_s}{\frac{1}{2}(D_t+D_p)ln\left[\frac{2h}{\frac{1}{2}(D_t+D_p)} + \sqrt{\left(\frac{2h}{\frac{1}{2}(D_t+D_p)}\right)^2 - 1}\right]} \quad (6)$$

Where T_L and T0 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. α_1 and α_2 are heat transfer coefficient of fluid and pipe to soil respectively. λ_i and λ_f are thermal conductivity of isolation and fluid respectively. Re_f is Reynolds number, Pr_t 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 CO_2 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 t 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 d 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.

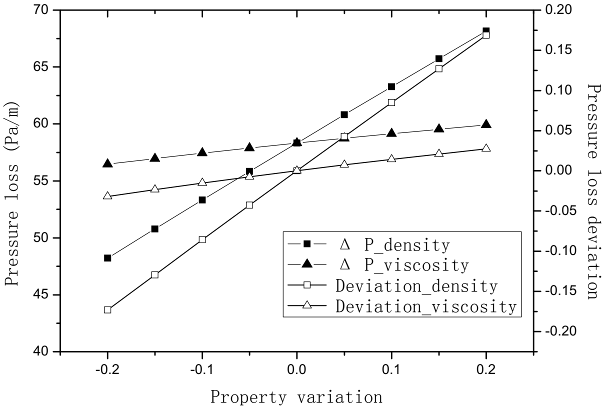

Fig. 1. Sensitivity study of property impacts on pressure loss

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 ($R_{i\&s}$), 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 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.

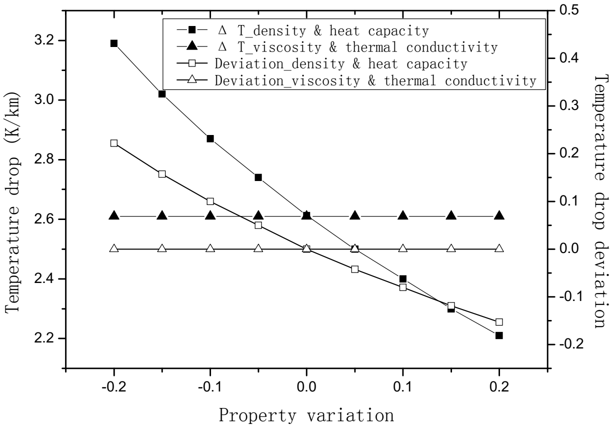

Fig. 2. Sensitivity study of property effects on temperature drop

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 CO_2 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.

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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.