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In-tube convective heat transfer characteristics of CO_2 mixtures in a pipeline

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In the Carbon Capture, Transportation & Storage (CCS) process, CO_2 is captured with impurities such as N_2, CH_4 and Ar and is transported under a supercritical state. In this study, the characteristics of in-tube convective heat transfer of CO_2 mixtures such as $CO_2 + N_2$, $CO_2 + CH_4$ and CO_2 + Ar were experimentally investigated under the land transportation conditions of the CCS process. The test tube was made of a cooper tube buried in a PVC (Polyvinyl Chloride) pipe which was compactly filled with sand, which simulated the land CO_2 transportation. Mass flux was changed by 200, 400 and 600 kg m^{-2} s^{-1}, and operational pressures were 80, 90, and 100 bar. Operational temperatures ranged from 25 to 55 °C. The heat transfer coefficient of the CO_2 mixtures dominantly followed the trends of pure CO_2; however, they were decided by the type and quantity of the impurity. When the CO_2 mole fraction was changed from 1.00 to 0.95, the maximum heat transfer coefficient at the pseudo-critical temperature of $CO_2 + N_2$ and $CO_2 + CH_4$ decreased by 4389 $W{\cdot}m^{-2}$ K^{-1} and 2770 $W{\cdot}m^{-2}$ K^{-1}, respectively. As the mass flux increased, the heat transfer coefficient increased in all of the CO_2 mixtures.

1. Introduction

Even during the development of renewable energies, fossil fuel is still a dominant energy source. Increasing emissions of carbon dioxide due to the usage of fossil fuel has led to global warming concerns. Accordingly, the mean sea level has increased by 0.19 m from 1901 to 2010 and is higher than the increase in the mean sea level for past 2000 years before the 19th century [1]. The natural ecosystem is being destroyed by intensified environmental problems such as drought, desertification and collapse of glaciers due to global warming.

To solve the problem of global warming, many countries are developing endeavors that focus on decreasing carbon dioxide emission. Carbon Capture, Transportation & Storage (CCS) is one of the promising methods to reduce carbon dioxide emission. The CCS process involves the capturing of CO_2 from the CO_2 emission source, transportation via pipelines or ships, and storage process. In the CCS process, CO_2 is transported in pipelines for several tens or hundreds of kilometers under a supercritical condition. The heat transfer from and to the surrounding soil or seawater inevitably takes place during this transportation. It results in a significant change in the temperature and pressure of CO_2 along the pipeline. The thermo-physical properties of CO_2 under a supercritical condition dramatically change with variations of temperature and pressure such as in Fig. 1 [2]. In the process of capturing CO_2, some impurities such as N_2, CH_4, Ar and H_2S are present and the concentration of the impurities is different depending on the capturing methods. These impurities significantly affect the thermo-physical properties of CO_2 mixtures as shown in Fig. 1 [2]. This drastic change in the thermo-physical properties of CO_2 under a supercritical condition with the presence of impurities can cause a transportation failure, cracking of pipes, and significant variation of compressor power consumption. Therefore, it is essential for the designing pipelines in the CCS process to investigate the heat transfer characteristics of CO_2 with the presence of impurities under supercritical conditions.

Dang and Hihara [3] experimentally studied the influence of pressure, heat flux, and mass flow rate on convective heat transfer and pressure drop for supercritical pure CO_2 in a horizontal tube. They proposed a prediction model with an accuracy of 20% based on experimental data. The pressure drop decreased when increasing the operational pressure. However, the pressure drop was independent of the operational pressure when the temperature of the CO_2 was less than the pseudo critical temperature. Son et al. [4] also measured the heat transfer coefficient and pressure drop of supercritical CO_2 in a double-tube heat exchanger that had a 7.75-mm inside diameter and compared them with several prediction models. Chen and Zhang [5] investigated heat transfer and various convection mechanisms of the near critical CO_2 flow in

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Nomenclature

Cp	specific heat capacity at the constant pressure, J·kg^{-1} K^{-1}
h	heat transfer coefficient, W·m^{-2} K^{-1}
i	index for measurement parameters
k	thermal conductivity, W·m^{-1} K^{-1}
L	length of tube, m
$\dot{m}$	mass flow rate, kg·s^{-1}
$\dot{Q}$	heat flux, W·m^{-2}
q	heat transfer rate, W
r	radius of tube, m
T	temperature, °C
U	uncertainty
X	measured value
Y	calculated value

Subscripts

1	inner
2	outside
f	fluid
i	inlet
m	mixture
o	outlet
s	tube surface

the microchannel. New instabilities occurred due to the thermal-mechanical expansion characteristics in an open system; while the piston effect was dominant in a closed system. They also discussed possible applications and further development of the microchannel for convective flow and micro-mixing. Li et al. [6] widely reviewed the existing experimental data and theoretical models for the transport properties of CO_2 mixtures such as CO_2 + O_2, CO_2 + N_2 and CO_2 + SO_2. Mazzoccoli et al. [7] compared the experimental data with the predicted data from the Equations of State (EOS) for the CO_2-rich binary mixtures. They also simulated the pipeline transportation for CO_2-rich binary mixtures in the CCS conditions. Liu et al. [8] conducted a numerical analysis to investigate the buoyancy effect on the heat transfer of CO_2 at supercritical pressures by using the FLUENT. Wetenhall et al. [9] studied the main factors for affecting heat transfer of CO_2 along the pipeline. They showed that the inlet temperature and flow rate significantly influenced the heat transfer of CO_2. Prah and Yun [10] presented a study on the heat transfer and pressure drop of a CO_2 hydrate mixture in land-based pipelines. The in-tube heat transfer and pressure drop of the CO_2 hydrate was significantly affected by the formation and dissociation of the CO_2 hydrate mixture, which was dependent on the temperature difference between the

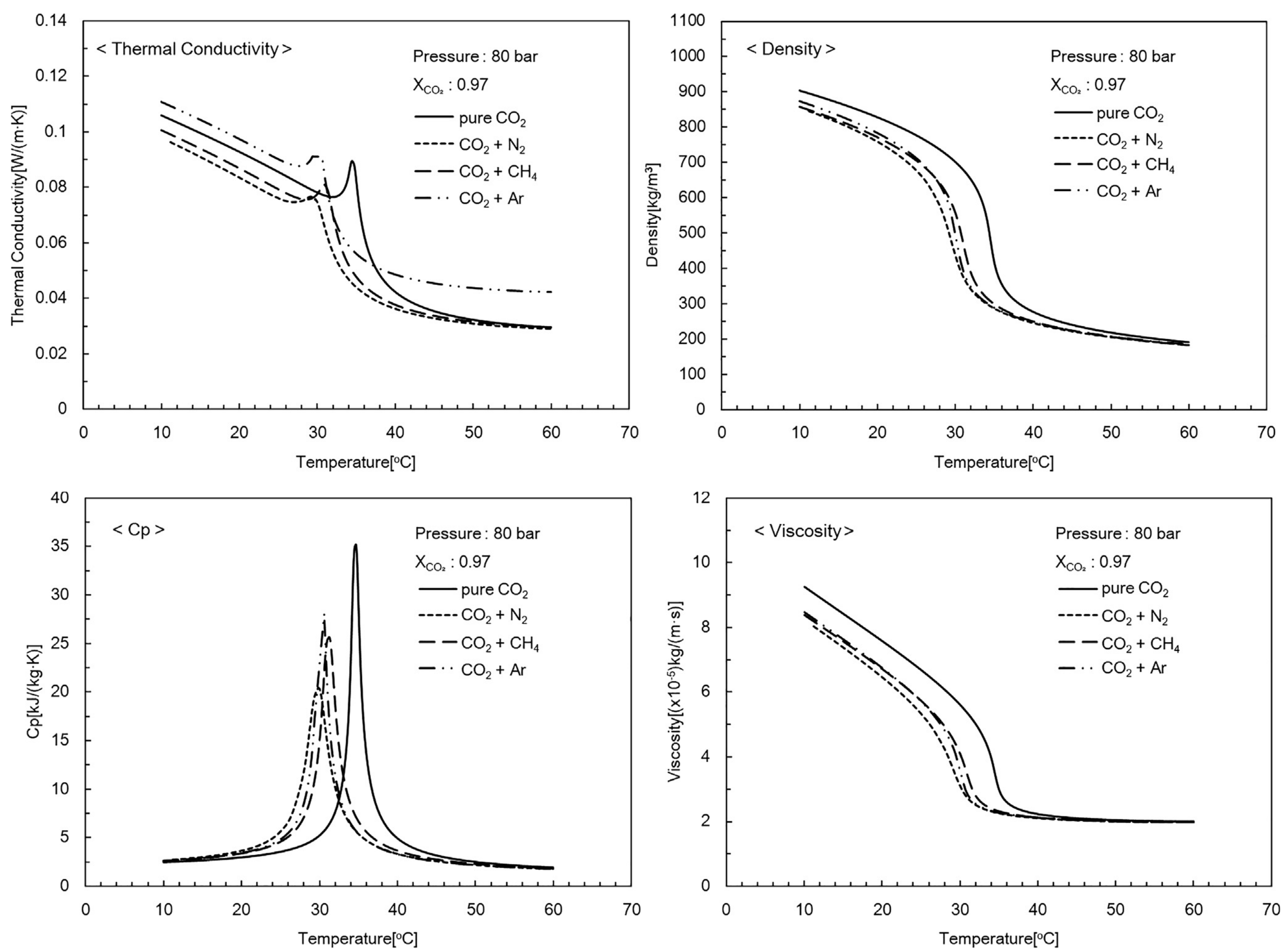

Fig. 1. Properties of pure CO_2, CO_2 + N_2, CO_2 + CH_4 and CO_2 + Ar [2].