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Experimental investigation of near-critical CO_2 tube-flow and Joule–Thompson throttling for carbon capture and sequestration

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A B S T R A C T

Flow of CO_2 in the vicinity of its critical point was studied experimentally in two different flow configurations. First, a 60 cm long stainless steel pipe with 2.1 mm inner diameter was used to study near-critical CO_2 pipe flow. In terms of raw flow data, the results indicated high sensitivity of pressure drop to mass flow rate as well as to inlet conditions; i.e. pressure and temperature. Remarkably though, when friction factor and Reynolds number were defined in terms of the inlet conditions, it was established that the classical Moody chart described the flow with satisfactory accuracy. This was rationalized using shadowgraphs that visualized the process of transition from a supercritical state to a two-phase subcritical state. During the transition the two phases were separated due to density mismatch and an interface was established that traveled in the direction of the flow. This interface separated two regions of essentially single-phase flow, which explained the effective validity of the classical Moody chart. Second, Joule–Thomson throttling was studied using a 0.36-mm-diameter orifice. For conditions relevant to carbon capture and sequestration, the fluid underwent Joule–Thompson cooling of approximately 0.5 °C/bar. The temperature difference during the cooling increased with increasing inlet enthalpy. Discrepancies with previous computed and experimentally measured values of Joule–Thompson throttling were discussed in detail.

1. Introduction

Geological media and specifically depleted hydrocarbon reservoirs and saline aquifers are the top candidates as storage sites for carbon sequestration [1,2]. Since most oil and gas reservoirs are not close to its primary sources, CO_2 needs to be transported in pipelines from the source to the storage site [1]. The transition from atmospheric pressure and high temperature of a flue gas stream to the low temperatures and high pressures of transport and storage can potentially pass near the critical point of CO_2 at 73.8 bar and 31 °C. Also, depending on reservoir pressure and temperature, which are determined by the geological characteristics of the site, CO_2 can be stored as supercritical fluid, liquid, or compressed gas [1]. CO_2 flow in the vicinity of its critical point is thus of particular interest because of the abrupt changes in thermophysical and transport properties in this region. Even small fluctuations in pressure and temperature can affect the fluid properties, and hence the flow behavior.

Studying of two-phase CO_2 flow has gained attention in the past two decades due to the increased popularity of CO_2 as a refrigerant [3,4]. Heat transfer and flow of supercritical CO_2 in pipes and channels have been studied in transcritical refrigeration cycle applications where heat rejection takes place at a supercritical state [5,6]. Similar studies have also been performed in the context of nuclear reactor cooling systems [7–9]. In these studies, the main focus was the determination of the heat transfer coefficient. However, an investigation of the underlying flow fundamentals is still missing.

In terms of flow visualization, the only relevant previous works were conducted by Pettersen [10] and Yun and Kim [11]. Pettersen studied two-phase flow patterns of CO_2 during vaporization in a horizontal glass tube at 0 °C and 20 °C (corresponding saturation pressure: 3.5 MPa and 5.7 MPa). Yun and Kim studied the flow boiling of CO_2 in a horizontal narrow rectangular channel at 4.0 MPa (corresponding saturation temperature: 5.3 °C). These pressures and temperatures are relevant to the evaporation process in air-conditioning systems. In both studies, high-speed visualization was employed to study the distribution of the two phases in the flow. Distinct flow regimes were identified and flow pattern maps were created based on quality (vapor mass fraction) and mass flux. The thermodynamic state of the fluid in these studies was relatively far from the critical point and thus may not represent the behavior of the flow of a "near-critical" fluid.

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Nomenclature

D	pipe inner diameter (m)
$f = \frac{\Delta p}{(L/D)(\rho U^2/2)}$	Moody friction factor (dimensionless)
h	enthalpy (kJ/kg)
L	pipe length (m)
$\dot{m}$	mass flow rate (g/s)
P	pressure (bar)
T	temperature (°C)
U	pipe volumetric average velocity (m/s)
$Re = \frac{\rho UD}{\eta}$	Reynolds number (dimensionless)
ΔP	pressure drop across the test section (kPa)

Greek symbols

ε	pipe roughness (mm)
η	dynamic viscosity (kg/ms)
μ_{JT}	Joule–Thomson coefficient (°C/bar)
ρ	density (kg/m^3)

Subscripts

crit	critical (i.e. at the critical point)
f	friction
in	inlet
JT	Joule–Thomson
out	outlet

Flow and heat transfer in supercritical and near-critical fluids have been studied analytically and computationally [12–14]. One key obstacle is that the critical point is a singular point where surface tension and effective mass diffusivity go to zero, and isobaric heat capacity and isentropic compressibility become infinite. As a result, the integral conservation equations may not necessarily be convertible to a differential form. The result is that the validity of the Navier–Stokes equations becomes questionable as the critical point is approached. Thus, any model for near-critical regime must be examined to ensure there are no inconsistencies [15].

Our purpose in this paper is to provide seminal results for the challenging and intriguing field of near-critical CO_2 flows that are relevant to Carbon Capture and Sequestration (CCS). CO_2 transport systems, like any other fluid transport system, consist of pipes and valves. At a fundamental level, these two flows share the common feature that they constitute irreversible phenomena with the irreversibility being more intense in Joule–Thompson throttling than pipe flow. The pressure drop due to friction in pipe and due to throttling in valve can result in transition from a supercritical to a subcritical state. In the valves the relatively large pressure drop can bring about a substantial temperature change due to the Joule–Thomson throttling phenomena. Thus, we have chosen tube flow and Joule–Thompson throttling as our flow configurations. Contrary to previous studies, heat transfer has been decoupled by studying flow in an insulated pipe and our effort was focused on flow very close to the critical point (74–80 bar, 20–40 °C) and the transition from a supercritical to a subcritical state. In particular, near-critical CO_2 pipe flow has been investigated. Detailed measurements of pressure losses in pipes were performed together with measurements of the Joule–Thomson coefficient. A shadowgraph technique was used to visualize the transition from a supercritical to a subcritical state and rationalize the flow data.

2. Experimental setup

The experimental setup is shown schematically in Fig. 1. A 1-lt Parker piston accumulator was used to compress CO_2 to the desired pressure using high-pressure nitrogen. Three different test sections were used in this setup. The first one was a stainless steel pipe, 60 cm (2 ft) long with 6.35 mm (0.25 in) outer diameter and 2.13 mm (0.084 in) inner diameter. The pipe was used to study flow of CO_2 near its critical point, which has significance in CO_2 transport in pipelines to the storage sites. The second test section was a stainless steel orifice with 0.36 mm (0.014 in) diameter (O'Keefe Controls Co., Trumbull, CT). It was used to study Joule–Thomson throttling process and the cooling effect caused by sudden expansion of high-pressure CO_2. The third test section which was an optically accessible high-pressure chamber (Jerguson, Strongsville, OH) incorporated two tempered borosilicate glass windows on opposite sides of the chamber and a rectangular flow cross-section approximately 16 mm × 35 mm. The inlet and outlet were located at the top and the bottom of the chamber, respectively. The chamber was approximately 12.7 cm (5 in) long with a visible range of 9.5 cm (3¾ in), rated at 138.0 bar (2000 psi) for operation at 38 °C. This test section was used for visualization purposes.

Pressure and temperature at the inlet and outlet of the test section were measured using pressure transducers and T-type thermocouples respectively. The pressure transducers (Setra 209) measured the gage pressure up to 206.8 bar (3000 psi) with ±0.25% full-scale accuracy (±0.5 bar). Pressure drop in the pipe was measured using a differential pressure transducer (Rosemount 3051C) with 0-1000 in-H_2O (0–250 kPa) range and 0.15% accuracy. Ungrounded T-type thermocouples in 0.062 in (1.6 mm) diameter sheath were used for temperature measurements. Cold junction compensation (CJC) was accomplished using the DAQ Assistant virtual instrument for T-type thermocouples. For the Joule–Thomson experiment, pressure drop across the orifice was obtained by

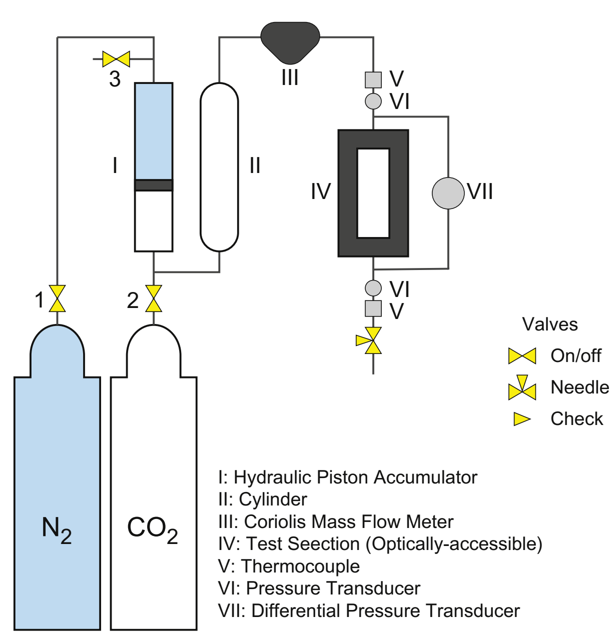

Fig. 1. Experimental setup.