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Measurements of the flow of supercritical carbon dioxide through short orifices

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ABSTRACT

This paper describes the methods used to measure flow rate of supercritical and two-phase CO_2 through short orifices. Orifices with diameters of 1 millimeter and orifice length-to-diameter ratios of 3.2 and 5 were tested. Flow rates through these orifices were measured over a broad range of inlet conditions in the supercritical region with orifice inlet pressures ranging from 5 MPa to 11 MPa and inlet densities ranging from 86.5 kg/m^3 to 630 kg/m^3. The data were compared to the isentropic real gas model for expansion of a fluid through a nozzle in order to observe the behavior of the discharge coefficient. For a given orifice inlet condition, the single-phase discharge coefficient was found to be between 0.81 and 0.87 and was independent of the pressure ratio. The discharge coefficient increased as the pressure ratio decreased when two-phase CO_2 was present with orifice inlet pressures of 7.7 MPa and 9 MPa. The critical mass flow rate and critical pressure ratio were determined for each test. The raw data from this investigation are available on the internet.

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1. Introduction

The Supercritical Carbon Dioxide (S-CO_2) Brayton gas turbine cycle has been studied as an efficient and cost-effective option for providing power for several decades. However, until recently (within the last decade or so), a number of issues have prevented its full-scale implementation. For example, the low temperatures (below 500 °C) of the heat sources used for the majority of large-scale power production are more suitable for traditional steam cycles than for the S-CO_2 Brayton cycle in terms of thermal efficiencies. In addition, the optimization and establishment of the Rankine power cycle over the past century has limited the development of alternative power cycles such as the Brayton gas turbine cycle. Also, the unique properties and behavior of the working fluid, S-CO_2, have caused difficulties in the design and analysis of plant components such as heat exchangers, turbomachinery, valves, and seals. In recent years, however, the push to design high temperature heat sources such as the Generation IV nuclear reactors [1] and concentrating solar power plants, in addition to significant research on the properties and behavior of S-CO_2 ([2–6]), have generated renewed interest in the S-CO_2 Brayton cycle as a means for providing power. As a result of imminent carbon taxes and carbon

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Nomenclature

P	pressure
ρ	density
h	specific enthalpy
s	specific entropy
A	cross sectional area
v	velocity
u	uncertainty
$\dot{m}$	mass flow rate
C_c	contraction coefficient
C_D	discharge coefficient
PR	pressure ratio

Subscripts

o	upstream stagnation
d	downstream
critical	critical condition
measured	measured quantity
actual	actual quantity
isentropic	isentropic model quantity

emissions regulations, the S-CO_2 Brayton cycle is also under consideration for use in fossil fuel power production as well as in waste heat recovery applications, due to the increasing cost of energy production. The objective of this study is to provide data associated with the flow of supercritical and two-phase carbon dioxide (CO_2) that will be useful for the practical implementation of the S-CO_2 Brayton cycle.

The real gas behavior of CO_2 near the critical point and the presence of both single-phase and two-phase CO_2 create challenges in analytical and numerical modeling of the flow of S-CO_2 through restrictions, such as valves, turbomachinery seals, and pipe ruptures. Further, the high pressures and the sensitivities of the properties of CO_2 to changes in temperature near the critical point complicate the design and operation of turbomachinery and safety systems that depend on the determination of the flow of S-CO_2 through various restriction geometries.

Restrictions found in valves, turbo machinery seals, and pipe ruptures can be modeled as simple orifices as a first approximation. The objective of this study is to provide experimental measurements of the mass flow rate of S-CO_2 through short, sharp-edged orifices. These initial data are useful in creating new models, verifying existing models, and aiding in design calculations as they quantify the form losses associated with short, sharp-edged orifices. As discussed further below, the form losses associated with the orifices are pressure losses that occur at the orifice entrance. The data are provided as an electronic supplement to the author's thesis [7], which can be found on the University of Wisconsin-Madison Solar Energy Laboratory's webpage: http://www.sel.me.wisc.edu.

2. Theoretical background

2.1. Pressure losses

The total pressure drop for a fluid flowing through an orifice is the sum of the minor pressure losses and the major pressure losses, as represented by Equation (1). The minor pressure losses, also known as form losses, result from contraction and expansion of the fluid flowing through the orifice as it encounters the sudden restriction in flow area at the orifice entrance. The major pressure losses result from friction, acceleration of the fluid through the orifice, and gravitational force on the fluid along the length of the orifice.

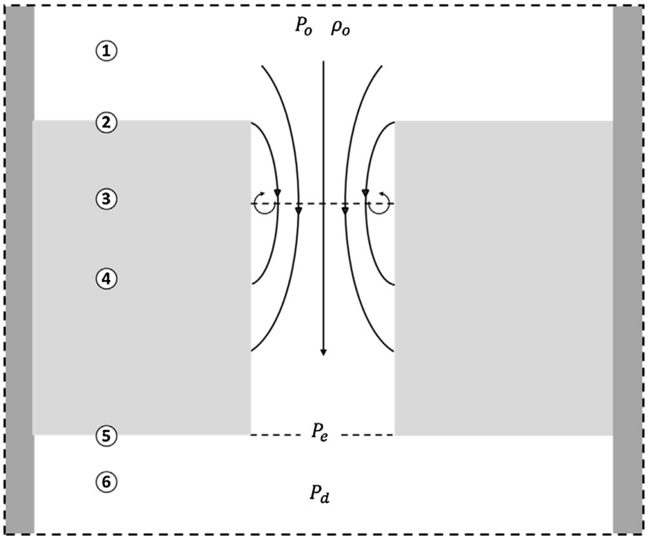

Fig. 1. Flow of fluid through a sharp edged orifice.

$$\Delta P = \sum \Delta P_{minor} + \sum \Delta P_{minor} = \sum \Delta P_{form} + \sum \Delta P_{friction} + \sum \Delta P_{acceleration} + \sum \Delta P_{gravity} \qquad (1)$$

Each of the flow applications of interest (i.e., pipe ruptures, valves, turbomachinery seals) is characterized by CO_2 encountering a drastic reduction in flow area as it flows through the restriction. The ratio of the flow area of the restriction (regardless of the restriction geometry) to the area upstream from the restriction is very small, which results in significant form losses and therefore these geometries can often be modeled as orifices as a first approximation. An understanding of the form losses associated with simple geometries such as orifices is required before moving on to more complex geometries due to the unique property variations of S-CO_2. This study provides data that are useful for modeling form losses associated with the flow of supercritical and two-phase CO_2 through well-defined orifice geometries.

Fig. 1 illustrates a fluid (CO_2 in this case) flowing through a sharp-edged orifice. Upon entering the orifice at point (2), the CO_2 contracts to a flow area that is smaller than that of the orifice since the streamlines of the CO_2 cannot change direction abruptly. The point at which the flow area reaches a minimum is known as the vena contracta, represented by point (3) in Fig. 1. After reaching the vena contracta, the CO_2 expands until it reattaches to the wall of the orifice, represented by point (4) in Fig. 1. The form loss of the CO_2 is equivalent to the pressure loss associated with the contraction and the expansion of the CO_2 from the orifice entrance, point (2), to the point of reattachment to the orifice wall, point (4). At the point of reattachment the pressure drop resulting from the form loss has occurred and the friction and acceleration pressure losses become dominant.

3. Critical flow

The maximum mass flow rate that can be achieved by a fluid flowing through a converging nozzle or orifice is referred to as the critical mass flow rate. Critical flow occurs when the bulk velocity of the fluid reaches the local speed of sound [8]. Fig. 2 shows the mass flow rate (in arbitrary units) as a function of pressure ratio; the pressure ratio is defined as the ratio of the downstream stagnation pressure to the upstream stagnation pressure. Any decrease

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