Applied Energy 230 (2018) 816–835

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

A comprehensive study of the effect of chemical impurities on selection and sizing of centrifugal machines for supercritical carbon dioxide transport pipelines[☆]

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HIGHLIGHTS

- New model combining complex geometry and working processes of a centrifugal machine developed.
- Compressor performance depends on its size, mass flow rate, shaft speed and the properties of supercritical CO_2.
- Isentropic efficiency varies with the purity of the supercritical CO_2 and operating conditions of the compressor.
- Purity of the supercritical CO_2 plays a vital role in optimal sizing of compressors and booster pumps.
- Significant energy savings can be made through optimal sizing of compressors and booster pumps.

ARTICLE INFO

Keywords:
CCS
Compressor performance map
Energy requirement
Booster pump
Impurities
CO_2 transport pipeline
Quasi-dimensional model
Compressor
Supercritical phase
Critical point
Equation of state
Laws of conservation

ABSTRACT

Compressors and booster pumps constitute the “heart” of the supercritical carbon dioxide transport pipeline network because they consume most of the required energy input. In other words, most of the operating expenditure for the transport pipeline goes to the running of compressors and pumps. The long-term economic feasibility of running such pipeline networks is achievable only if operating costs linked to the energy consumption of both machines can be kept as low as possible. Energy consumption can be kept as low as possible by sizing compressors and booster pumps optimally to ensure that power losses in both machines are minimized.

In this study, a quasi-dimensional model based on the laws of conservation was developed, validated with available experimental data and then used for a detailed investigation of the effect of various impurities on the performance of a centrifugal machine handling supercritical carbon dioxide of varying purity. Results of the study show that discharge pressure, power requirement and efficiency of a centrifugal machine are strongly dependent on certain key parameters; namely, the size and speed of its impeller rotor as well as the composition of the impure CO_2 stream. More importantly, this study also demonstrates that the quasi-dimensional model can be used as a tool for appropriate selection and sizing of centrifugal compressors and booster pumps installed on a supercritical carbon dioxide transport pipeline.

1. Introduction

1.1. The basics of CO_2 pipeline transportation

In pipelines, CO_2 can be transported in gaseous, liquid, dense or supercritical states. CO_2 is in dense phase (also called “dense-liquid phase”) when its pressure is above the critical point while its temperature remains below the critical point. Supercritical CO_2 occurs when both temperature and pressure are above critical point (73.76 bar; 30.97 deg.C) [1–3]. CO_2 stream in dense or supercritical state have high density close to that of liquid CO_2 and low viscosity close to that of gaseous CO_2. This means that a larger amount of CO_2 per unit time can be transported in supercritical state than in gaseous or liquid state with a low pipelinefrictional pressure drop per unit mass. Therefore, from an economic standpoint, CO_2 is best transported in long distance pipelines when in dense or supercritical phase [1–4].

[☆] The short version of the paper was presented at ICAE2017, Aug 21–24, Cardiff, UK. This paper is a substantial extension of the short version of the conference paper.

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https://doi.org/10.1016/j.apenergy.2018.08.074
Received 5 January 2018; Received in revised form 11 June 2018; Accepted 15 August 2018

Nomenclature

A	area [m^2]
b	impeller width
d, D	diameter [m]
dF	change in force [N]
f	Fanning's friction factor [–]
Gap	width of clearance between Impeller and compressor housing [m]
h	specific enthalpy at static conditions [J/kg]
H	height [m]
K	loss coefficient [–]
L	characteristic length [m]
$\dot{m}$	mass flow rate [kg/s]
n_B	number of impeller blades [–]
N	rotor shaft speed [rpm]
P	static pressure [bar]
r	radius [m]
Re	Reynolds number [–]
s	specific entropy [J/kg K]
S_F	slip factor [–]
T	static temperature [K]
$\hat{u}$	specific internal energy at static conditions [J/kg]
U	impeller blade tip speed [m/s]
V	velocity [m/s]
W	specific work [J/kg]
Z	compressibility factor [–]

Greek symbols

β	impeller blade angle
Δ	finite difference [–]
μ	viscosity [mPa s]
ρ	fluid density [kg/m^3]
θ	wrap angle [deg]
ϕ	convergence angle [deg]
η	efficiency [–]
π	Pi constant [–]
ω	angular speed [rad/s]
τ	shear stress [Pa]

Subscripts

1	compressor inlet (Suction); leading edge of impeller
2	compressor outlet (Discharge); trailing edge of impeller
a	actual value
ave	average value
con	converging duct
crit	critical value
curv	curved surface
disk	disk friction
euler	ideal value
gap	impeller tip leakage channel
HYD	hydraulic value
i	root of impeller eye
IMP	impeller
INPUT	actual input value
ISEN	isentropic value
leak	leakage
loss	loss
m	meridional direction
o	tip of impeller eye
rad	radial coordinate
rel	relative value
sum	sum of values
t	tangential coordinate

Moreover, cavitation which can damage compressors and pumps is impossible when CO_2 stream is in dense or supercritical state [5].

A typical CO_2 transport pipeline network consists of pipes, valves, compressors and booster pumps. Compressors are used to pressurize CO_2 beyond its critical point and booster pumps are required to ensure that the operating pressure inside the transport pipeline does not drop below the critical pressure of CO_2.

Anthropogenic CO_2 which the pipelines are intended to transport tends to contain chemical impurities such as CH_4, H_2, H_2O, H_2S, N_2, CO, O_2 and Ar. These impurities, even in trace amounts, can substantially alter the normal thermodynamic properties of CO_2 such as phase behaviour, compressibility, density, enthalpy, pressure, temperature and viscosity, thereby significantly affecting the general performance of the pipeline network [6–12]. As shown in Figs. 1(a) and 1(b), certain types of impurities can reduce the overall fluid density while increasing the critical point of CO_2 resulting in a high energy requirement for the compressors and pumps [7–12].

Impurities can also enlarge the two-phase region in the CO_2 phase envelope depicted in Fig. 1(a), increasing the risk of single-phase supercritical fluid transforming into a gas-liquid two-phase fluid if there is a slight pressure drop in the pipeline. Since compressors and pumps are part of the pipeline network, the formation of two-phase flow can lead to cavitation which may potentially damage both machines. To avoid this particular risk, the pipeline operating pressure will have to be very high, far beyond the critical pressure of the impure CO_2 stream. Higher pressures lead to higher energy requirement for the compressor and pumps, resulting in even greater operating costs for the pipeline network [12,13].

1.2. Previous studies

Installed compressors and booster pumps consume most of the energy required to operate an entire supercritical CO_2 pipeline network. To convert gaseous CO_2 into supercritical or dense phase and maintain it, compressors and booster pumps will need to generate extremely high pressures within the pipeline–far above the critical pressure of the CO_2 stream. This is necessary to reduce the risk of single-phase supercritical fluid transforming into a gas-liquid two-phase fluid if there is a slight pressure drop in the pipeline [8,9,12,14]. Two-phase fluid is undesirable because it can lead to cavitation and slugging, which can damage

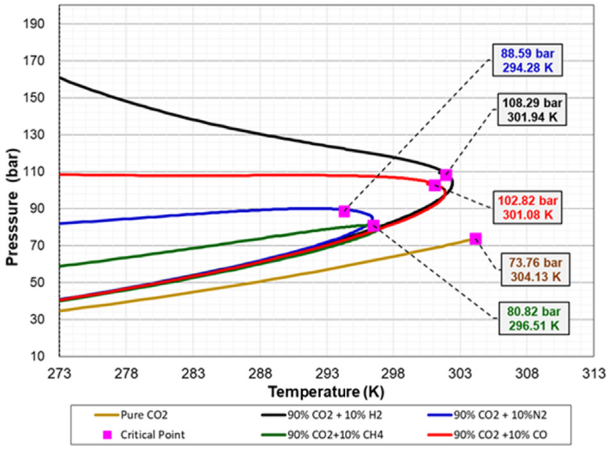

Fig. 1(a). Effect of impurities on the phase envelope.