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Design based on ductile–brittle transition temperature for API 5L X65 steel used for dense CO_2 transport

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A B S T R A C T

Safe and reliable transport of dense carbon dioxide by pipes needs a careful choice of the constitutive pipe materials to prevent brittle crack propagation after ductile or brittle failure initiation. So the material must remain ductile at this temperature; its ductile–brittle transition temperature has to be lower than −80 °C minus a margin. This temperature is not a material characteristic but depends on specimen geometry, loading rate and loading mode, i.e. on constraints. Constraints can be estimated by different parameters: stress triaxiality, Q factor or *T*-stress. Constraints in a pipe under pressure are close to those given by a tensile specimen.

1. Introduction

Carbon dioxide is an odorless, colorless gas which forms naturally in the atmosphere at room temperature, with concentrations of approximately 0.037%. According to temperature and pressure, CO_2 is present in 3 distinct states. CO_2 is in a supercritical phase with temperatures higher than 31.1 °C and pressures higher than 7.38 MPa (values of the critical point). For conditions of temperature and pressure lower than these values, CO_2 will be in a gas, liquid or solid state.

Beyond its critical point, carbon dioxide enters a phase called supercritical. The liquid–gas equilibrium curve is cut at the level of the critical point, ensuring for the supercritical phase a continuum of the physicochemical properties without phase transformation. CO_2 is then a dense phase such as a liquid but exhibiting transport properties (viscosity, diffusion) close to those of a gas. Supercritical carbon dioxide is used as a green solvent, the extracts being free from solvent trace. In this form, it is useful, in particular:

- For extraction of chemical or biological compounds.
- For purification of chemical compounds.
- For transport and storage for geological sequestration of carbon dioxide.

Dense CO_2 transport is mainly performed by pipeline. Only in the United States the existing national CO_2 pipeline infrastructure dedicated primarily to deliver CO_2 for enhanced oil recovery (EOR) comprises 3900 miles, and an extended national CO_2 pipeline system is forecasted with the implementation of carbon dioxide capture and storage (CCS)-derived

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Nomenclature

T_{K27}	transition temperature for Charpy V test
T_{K50}	transition temperature at half the jump between brittle and ductile plateau
T_{K100}	fracture toughness transition temperature
T_s	service temperature
T_t	transition temperature
RT_i	reference temperature
MAT	Minimum Allowable Temperature
CET	Critical Exposure Temperature
T_{struct}	structure or component transition temperature
R_e	yield stress
R_m	ultimate strength
$A\%$	elongation at failure
K_{CV}	Charpy energy
K_{Jc}	fracture toughness
HV	hardness
R_e^{μ}	yield stress threshold
$Re^{\mu,d}$	yield stress threshold in dynamic
R_m^{μ}	ultimate strength threshold
$Rm^{\mu,d}$	ultimate strength threshold in dynamic
W	width
B	thickness
a	notch depth
L	constraint factor
P_{GY}	load at general yielding
P_{max}	maximum load
U_c	energy for fracture initiation
K_{min}	fracture toughness threshold
L_{mc}	crack length
T	*T*-stress
σ_{xx}	stress in the direction xx
σ_{yy}	stress in the direction yy
K_I	stress intensity factor
$f_{ij}(\theta)$	angular function
δ_{ij}	symbol of Kronecker's determinant
A_3	transferability parameter
X_{ef}	effective distance
σ_{ef}	effective stress
$X(r)$	relative stress gradient
$\sigma_{yy}(r)$	crack opening stress
$\Phi(r)$	weight function
T_{ef}	effective *T*-stress

emission reductions. The entire system could be comprised between 11,000 and 23,000 additional miles dedicated CO_2 pipeline before 2050 and dependent upon the hypothetical climate stabilization policies adopted [1].

As shown on Fig. 1, transport of CO_2 in dense state presents a high potential for auto-refrigeration due to depressurisation, either during operations or due to equipment failure (e.g., a safety relief valve sticks open).

The concept of brittle–ductile transition temperature was discovered during the Second World War, because of the rupture of Liberty ships at sea. The ductile–brittle transition temperature (DBTT), nil ductility temperature (NDT), or nil ductility transition temperature (NDTT) of a metal represents the point at which the fracture energy passes below a pre-determined value [3].

Design against brittle fracture considers that the material exhibits at service temperature, a sufficient ductility to prevent cleavage initiation and sudden fracture with an important elastic energy release. Concretely, this means that service temperature T_s is higher than transition temperature T_t:

$$T_s \geq T_t \tag{1}$$

Service temperature is conventionally defined by codes or laws according to the country where the structure or the component is built or installed. For examples, in France, a law published in July 1974 indicates that service temperature in France is −20 °C.