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INFLUENCE OF LINE PRESSURE AND TEMPERATURE ON FRACTURE PROPAGATION BEHAVIOUR IN CO_2 PIPELINES

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Abstract

This paper presents the results of a series of fundamentally important studies using a validated CFD based fluid/structure fracture model for predicting ductile fractures in pressurized pipelines employed for transporting captured CO_2 from fossil fuel power plants. The range of parameters investigated include the variations in the line temperature (0 – 30 ^oC), operating pressure (100 and 180 barg) and the presence of the different types of impurities in the CO_2 stream based on the various capture technologies including pre-combustion, post-combustion and oxy-fuel. In the case of a X65 pipeline chosen as a case example, it is found that the pure CO_2 and the post-combustion transmission pipelines exhibit very similar and highly temperature dependent propensity to fracture propagation. An increase in the line temperature from 20 to 30 ^oC results in the transition from a relatively short crack to a long running propagating fracture. The situation becomes progressively worse in moving from the pre-combustion to the oxy-fuel stream where long running ductile fractures are observed at all the temperatures under consideration. Remarkably and counter intuitively, an increase in the line pressure decreases the pipeline's propensity to ductile fractures. All of the above findings are successfully explained by examining the CO_2 and its mixtures depressurization trajectories during fracture propagation relative to the corresponding phase equilibrium envelopes.

1. Introduction

In the battle against global warming, pressurized pipelines are widely recognized as the most practical and economical means of transporting the huge amounts of captured CO_2 from coal fired power plants for subsequent sequestration . Typically, such pipelines are expected to cover distances of several hundred kilometres at pressures above 100 bar.

Given that CO_2 is as an asphyxiant at high concentrations (Kruse and Tekiela, 1996), the safety of CO_2 pipelines in the unlikely event of pipeline rupture is of paramount importance and indeed central to the public acceptability of Carbon Capture and Sequestration (CCS) as a viable means of combating the impact of global warming.

Ironically (in line with its abbreviation), CCS and related legislation generally focus on the capture and sequestration of CO_2 and not on its transportation.

It is noteworthy that CO_2 pipelines have been in operation in the US for over 30 year for enhanced oil recovery (Seevam et al., 2008; Bilio et al., 2009). However, these are either confined to low populated areas, and/or operate

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below the proposed supercritical conditions (73.3 bar and 31.18 ^{o}C) that make CO_2 pipeline transportation economically viable. Additionally, due to their small number, it is not possible to draw a meaningful statistical representation of the risk.

Running fractures are by far the most catastrophic type of pipeline failure. These involve the rapid tearing of the pipeline, sometimes running for several hundred meters resulting in the release of massive amounts of inventory in a very short space of time. Given its importance, a large number of studies spanning more than 30 years (see for example Leis et al., 2010; Maxey, 1974) have been devoted to understanding the mechanism and overcoming such failures in the hydrocarbon industry.

In essence, such fractures can initiate from defects introduced into the pipe by outside forces such as mechanical damage, soil movement, corrosion, material defects or adverse operating conditions. When the stress acting on the defect overcomes the fracture toughness of the pipe the fracture will propagate, reaching a critical size based on the pipeline material properties and operating conditions. As such it is highly desirable to design pipelines such that when a defect reaches a critical size and fails, the result is a leak rather than a long running fracture.

The so called Battelle Two Curve (BTC) method (Maxey, 1974) was the first used to express the criterion for the propagation of a ductile fracture in terms of the relation between the fluid decompression wave velocity and the crack propagation velocity. If the fluid decompression wave velocity is larger than the crack velocity, the crack tip stress will decrease, eventually dropping below the arrest stress causing the crack to arrest. Conversely, if the decompression wave velocity remains smaller than the crack velocity, the crack tip pressure will remain constant resulting in indefinite propagation.

Compared to natural gas for example, CO_2 has an unusually high saturation pressure. Depending on the starting pressure and temperature, the above coupled with the uniquely 'prolonged' depressurization during the liquid/gas phase transition (Bilio et al., 2009) mean that at certain operating conditions, CO_2 pipelines may be more susceptible to fracture propagation as compared to hydrocarbon pipelines (Bilio et al., 2009; Mahgerefteh et al., 2010). As such accounting for any parameters that may modify the CO_2 depressurization trajectory is of paramount importance when modelling ductile fractures in CO_2 pipelines.

One such important factor which is receiving increasing attention (see for example de Visser et al.,2008; Heggum et al., 2005) is the impact of impurities. Recent studies using various equations of state have shown that even small amounts of the likely impurities in the CO_2 stream will increase the saturation pressure significantly (see for example Oosterkamp and Ramsen, 2008, Li and Yan, 2006).

The type of these impurities will depend on the fuel, capture method (i.e pre-combustion, post-combustion or oxy-fuel) and the post-capture processing (ICF International, 2010). The percentage composition of the transported stream on the other hand, although being overwhelmingly CO_2, will have to comply with the prevailing legislative emission limits (de Visser et al., 2008; ICF International, 2010).

Crucially, given that the decompression and the fracture velocity curves are not coupled means that the Battelle Two Curve method is primarily indicative as to whether or not a fracture will propagate for a given pipe toughness. Important information such as the variation of the crack length with crack propagation velocity and, ultimately the crack arrest length cannot be produced using this approach.

In this paper we report the results of a series of studies using a fully coupled Fluid/Structure Fracture Model to investigate the impact of line pressure, line temperature and the various impurities on the fracture propagation and arrest behaviour in dense phase CO_2 pipelines. The compositions of the impurities assumed are those based on the various capture technologies, including pre-combustion, post-combustion and oxy-fuel as suggested by ICF International (2010). In each case, the variation of fracture velocity versus fracture length is reported for an hypothetical CO_2 pipeline with a realistic fracture toughness.

2. Theory

The full background theory and validation of the Fluid/Structure Fracture Model (FSFM) employed in this study is presented in separate publications (Mahgerefteh et al., 2010, 2011). A brief account of the main features is given here.

In essence the model involves the coupling of the well-established Drop Weight Tear Test energy fracture model (Makino et al., 2001a) with our extensively validated real fluid CFD model, PipeTech (Mahgerefteh et al., 2007; Mahgerefteh et al., 2006; Wong and Mahgerefteh, 1999; Oke et al., 2003). The coupled fracture model, FSFM accounts for all of the important fluid/structure interaction processes governing the fracture propagation and arrest process. These include expansion wave propagation, real fluid behaviour, multi-phase pipe/wall friction and heat transfer as well as the rapidly diminishing dynamic loading effects as the crack tip opens.

FSFM's predictions have been successfully validated (Mahgerefteh et al., 2010) against the full-scale fracture tests conducted by the High-Strength Line Pipe Committee (Inoue et al., 2003), ECSC X100 (Takeuchi et al., 2006) and Alliance (Johnson et al., 2000).

Based on the homogeneous flow assumption, shown to generally be valid in the case of rupture of long pipelines (Chen et al., 1993), in the case of unsteady, one-dimensional flow the mass, momentum and energy conservation equations are respectively are given by (Mahgerefteh et al., 2006; Mahgerefteh and Atti, 2006):

$$\frac{d\rho}{dt} + \rho\frac{\partial u}{\partial x} = 0 \qquad \textbf{(1)}$$

$$\rho\frac{\partial u}{\partial x} + \rho u\frac{\partial u}{\partial x} + \frac{\partial P}{\partial x} = \alpha \qquad \textbf{(2)}$$

$$\rho\frac{dh}{dt} - \frac{dP}{dt} - \left(q_h - u\beta_y\right) = 0 \qquad \textbf{(3)}$$

Where ρ, u, P and h are the density, velocity, pressure and specific enthalpy of the homogeneous fluid as function of time, t, and space, x. q_h is the heat transferred through the pipe wall to the fluid and β_y is the friction force term given by:

$$\beta_y = -2\frac{f_w}{D}\rho u\left|u\right| \qquad \textbf{(4)}$$

where, f_w is the Fanning friction factor and D the pipeline diameter.

Also,

$$\alpha = -\left(2\frac{f_w}{D}\rho u\left|u\right| + \rho g \sin\theta\right) \qquad \textbf{(5)}$$

θ is the angle of inclination of the pipeline to the horizontal.

Equations (1-3) form a system of quasi-linear partial differential equations that must be solved numerically. In this study, the Method of Characteristics (MOC) (Zucrow and Hoffman, 1975) is used as the numerical solution method, as opposed to other numerical techniques such as finite element (Bisgaard and Sørensen, 1987; Lang, 1991) and finite difference methods (Bendiksen et al., 1991; Chen et al., 1995a,b) as both have difficulty in handling the choking condition at the rupture plane.

Pipeline resistance to fracture is obtained based on the full-scale pipe bust tests conducted by the High-Strength Line Pipe Committee (HLP) (Makino et al., 2001b). In these investigations the BTC approach is used in conjunction with the Drop Weight Tear Test (DWTT) energy, as this coupling is shown to provide an accurate indication of the pipeline resistance to fracture. The crack propagation velocity, v_c and crack arrest pressure, P_a are respectively given by (Makino et al., 2001b):

$$v_c = 0.67\frac{\sigma_{flow}}{\sqrt{\frac{D_p}{A_P}}}\left(\frac{P_t}{P_a} - 1\right)^{0.393} \qquad \textbf{(6)}$$

$$P_a = 0.382\frac{t_w}{D}\sigma_{flow}\cos^{-1} e^{\left(\frac{-3.81\times10^{7}\frac{D_p}{A_p}}{\sqrt{Dt}\,\sigma_{flow}^{2}}\right)} \qquad \textbf{(7)}$$

Where σ_{flow}, D_p and A_p are respectively the flow stress (the mean value of the tensile and yield stresses), pre-cracked DWTT energy and ligament area of a pre-cracked DWTT specimen. On the other hand P_t and t_w are the crack tip pressure and pipe wall thickness respectively. The crack tip pressure P_t is taken to be the choked pressure at the pipeline release plane.

The coupling of the fracture and the fluid decompression models involves a feedback algorithm in which the effective pipeline length is continuously updated based on the crack extension calculated from the crack velocity using equations (6) and (7). The crack tip pressure as the pipeline depressurizes is determined from the numerical solution of the conservation equations (1-3) taking account of heat transfer and frictional effects. The Modified Peng-Robinson Equation of State (Wu and Chen, 1997) (MPPR EoS) is used for the prediction of the pertinent fluid phase equilibrium data for CO_2 and its mixtures. This equation has been shown (Mahgerefteh et al., 2008) to produce generally good agreement with the well-established but computationally demanding GERG-2004 Equation of State (Kunz et al., 2007).

3. Results and Discussion

The following presents the simulation results obtained based on the application of the fracture model described above to an hypothetical pipeline containing various dense phase mixtures of CO_2 in the temperature and pressures ranges of 0 - 30 ^{o}C and 100 and 180 barg respectively.

The pipeline characteristics and the prevailing conditions are given in table 1. The adopted pipeline grade of X65, the line pressures and the overall dimensions are those considered to be the most likely (Cosham and Eiber, 2008) to be employed for CO_2 pipelines as part of the CCS chain. In order to maintain practical computational run times, the pipeline length is limited to 500 m. This assumption will have no influence on the findings. The un-insulated pipeline is assumed to be exposed to still air corresponding to a heat transfer coefficient of 5 W/(m^2 K). The ambient temperature is assumed to be the same as the line temperature.

Table 2 shows the various CO_2 stream compositions employed in the fracture simulations according to post-combustion, pre-combustion and oxy-fuel capture technologies as proposed by ICF International (2010).

Table 2. Pipeline characteristics and prevailing conditions utilised for fracture propagation simultations.

Parameter	**Value**
Internal diameter (m)	0.5905
Wall thickness (mm)	9.45
Line pressure (barg)	100
Ambient pressure (bara)	1.01
Ambient temperature (^{o}C)	20
Feed temperature (^{o}C)	0,10,20,30
Pipe length (m)	500
Tensile stress (MPa)	531
Yield stress (MPa)	448
Pipe wall roughness (mm)	0.05
Heat transfer coefficient (W/m^{2}K)	5
Wind speed (m/s)	0
Pipe grade	X65
Fracture toughness (J)	50

Table 1. CO_2 stream compositions based on the various capture technologies (ICF International, 2010).

Species	**Post-combustion**	**Pre-combustion**	**Oxy-fuel**
CO_2	99.82	95.6	88.4
Ar	0	0	3.7
CO	0	0.4	0
N_2	0.17	0.6	2.8
H_2S	0	3.4	0
Cl	0	0	0.14
H_2	0	0	0
O_2	0.01	0	3.6
SO_2	0	0	1.36
H_2O	0	0	0
NO_2	0	0	0

3.1 Impact of Line Temperature and Impurities

Detailed analysis of the impact of line temperature in the range 0 to 30 °C for the various CO_2 stream concentrations was presented in our previous publication (Mahgerefteh et al., 2011). Table 3 shows a summary of the results in terms of the variation of ratio of crack to pipeline length for the various capture technologies. A crack ratio of unity corresponds to a fracture running through the entire length of the pipeline.

The following important observations may be made based on the data in table 3:

- For pure CO_2, in the temperature range 0 – 20 °C, an increase in the line temperature results in a modest increase in the crack arrest length and fracture velocity. The maximum crack length is limited to a distance of 11 m. However, remarkably only a 10 °C rise in the line temperature to 30 °C results in a fast running fracture travelling through the entire length of the 500 m pipeline.
- For post-combustion CO_2, the fracture behavior is substantially the same as that for pure CO_2 with the expectation of the crack length running over a marginally longer distance between 0 – 20 °C before coming to rest. Once again the rise in the line temperature to 30 °C results in fracture propagating through the entire pipeline length.
- In the case of the pre-combustion CO_2 stream, the transition to a long running fracture commences at a lower temperature of 20 °C as compared to the pure and post-combustion CO_2 streams.
- The oxy-fuel composition demonstrates the worst case scenario. Here long running fractures are obtained at all the temperatures tested.

Table 3. Ratio of crack to pipeline length for the various capture technologies for different line temperatures at 100 barg.

Capture technology	**Temperature (°C)**	**Crack to pipeline length**
100% CO_2	0	0.011
	10	0.018
	20	0.018
	30	1
Post-combustion	0	0.011
	10	0.013
	20	0.018
	30	1
Pre-combustion	0	0.013
	10	0.013
	20	0.015
	30	1
Oxy-fuel	0	0.024
	10	1
	20	1
	30	1

3.2 Impact of the Line Pressure

Figure 1 shows the variation of the crack velocity with crack length for the pre-combustion stream chosen as an example. The data are for a line pressure of 100 barg in the temperature range 0 – 30 °C presented at 10 °C intervals. Figure 2 on the other hand shows the corresponding data at the higher line pressure of 180 barg.

According to figure 1, it is clear that at the operating pressure of 100 barg, long running fractures may be expected whenever the line temperature exceeds 10 °C. Remarkably and counter intuitively, according to figure 2, when the line pressure increases to 180 barg, the pipeline becomes more resistance to fracture propagation. This time, the transition temperature resulting in a long running fracture increases to a higher temperature of 30 ^{o}C.

Figures 3 and 4 show the corresponding data presented above for the oxy-fuel CO_2 stream. Referring to figure 3, when the line pressure is 100 barg, it is clear that long running fractures may be expected at all the temperatures under consideration. This situation is not improved when the line pressure increases to 180 barg.

To explain the above behavior, figure 5 shows the fluid depressurization trajectories in terms of the variation of crack tip pressure with the discharging fluid crack tip temperature at the two starting line pressures of 180 barg (curve A) and 100 barg (curve B) for the pre-combustion mixture. The data are presented for a line temperature of 20 ^{o}C chosen as an example. The vapour/liquid saturation curve is plotted in the same figure for reference. The crack arrest pressure of 43.65 barg calculated from equations (6) and (7) is also shown for comparison. The corresponding data for the oxy-fuel mixture is given in figure 6. The broadening of the phase transition envelop in moving from the pre-combustion to the oxy-fuel compositions is due to the presence of increasing amounts of impurities in the CO_2 stream.

Returning to figure 5 for the pre-combustion mixture, the onset of fracture results in a rapid drop in the crack tip pressure from the liquid phase to the dew point curve followed by a slow depressurization. The accompanying significant drop in the fluid temperature is due to its near adiabatic expansion.

Based on the data presented, it is important to note that the pressure at which the two depressurization trajectories (curves A and B) intersect the dew curve decreases with increase in the starting line pressure. In the case of the 100 barg pipeline, the intersection pressure is ca. 46 barg. The corresponding value for the 180 barg pipeline is at the lower pressure of ca. 38 barg. Given that the crack arrest pressure is ca. 43 barg, it is to be expected that a long running fracture may not be expected in the case of the 180 barg pipeline at 20 ^{o}C. This is consistent with the data shown in figure 2; curve C.

Exactly the same arguments apply when using figure 6 to explain the fracture propagation behavior observed in figures 3 and 4 for the oxy-fuel mixture. Here the two depressurization trajectories (figure 6: curves A and B) never fall below the fracture arrest pressure thus leading to long running fractures.

4. Conclusion

Pressurized pipelines are expected to play a key role as part of the CCS chain for combating the impact of global warming. Given the hazardous nature of CO_2 at high concentrations and heightened public concern regarding the introduction of such nascent technology, the risk of an accidental pipeline rupture must be minimised.

Central to above is the design of pipelines with the correct mechanical properties which can withstand the most catastrophic type of failure, long running ductile fractures. Although considerable understanding of ductile fractures already exists for hydrocarbon pipelines, this experience can not be wholly extended to CO_2 pipelines given the unique depressurization thermodynamic trajectory of CO_2.

In this paper, using a rigorous validated fully coupled fracture model, we reported the results of a series of simulations investigating the impact of the line temperature, pressure and the different types of likely impurities on ductile fracture propagation behaviour in CO_2 pipelines. The model, validated against real data, for the first time accounts for all the important fluid/structure interactions taking place during the fracture propagation process. These include real fluid behaviour, heat transfer, friction and the change in the dynamic loading as the crack tip opens.

Using a X65, 500 m pipeline as a case study, our investigations reveal the remarkable impact of the line temperature on the pipeline's propensity to fracture propagation. For example, in the case of the post-combustion pipeline, increasing the line temperature from 20 to 30 ^{o}C results in the transformation of a short crack into a fast running long fracture.

Of all the three classes of impurities corresponding to the various capture technologies examined, it was found that the oxy-fuel mixture represented the worse case scenario with long fractures occurring under all the conditions tested. Remarkably, the increase in the line pressure from 100 to 180 barg improved the pipeline's propensity to fracture propagation. All of the above findings were successfully explained by examining the CO_2 and its mixtures depressurization trajectories during fracture propagation relative to the corresponding phase envelopes.

'In essence a fracture propagates if the pressure at which the discharging fluid intersects the due point curve is higher than the crack tip arrest pressure'.

In conclusion, we point out that the results presented in this paper are based on the particular pipeline with the given fracture toughness chosen as the case study. The fracture model presented in this paper can serve as a powerful tool for pipeline design engineers to select the appropriate pipeline mechanical properties to resist running fractures for a range of mixtures and operating conditions.

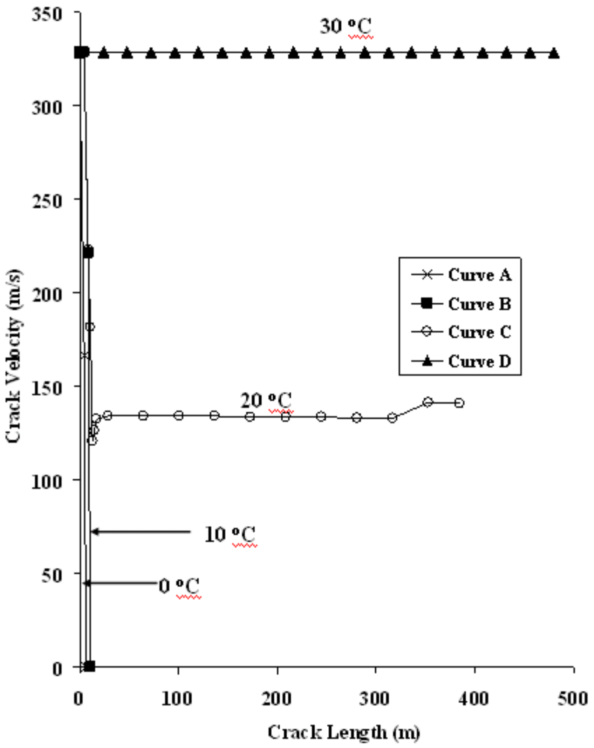

Figure 1. The impact of the line temperature on the variation of crack velocity with crack length for pre-combustion CO_2 pipeline at 100 barg.

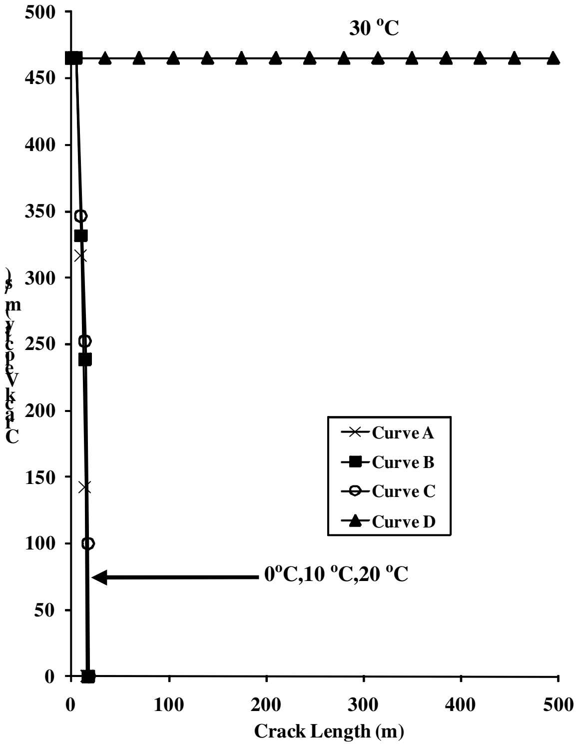

Figure 2. The impact of the line temperature on the variation of crack velocity with crack length for pre-combustion CO_2 pipeline at 180 barg.

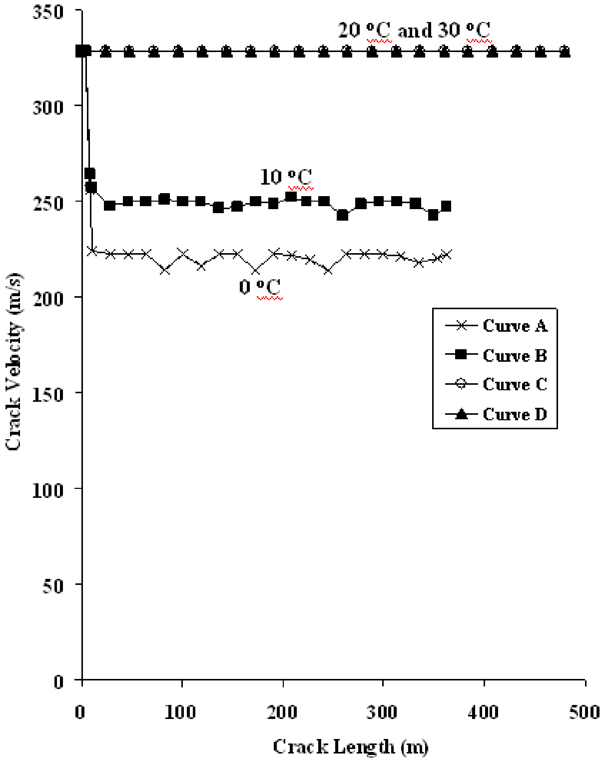

Figure 3. The impac of the line temperature on the variation of crack velocity with crack length for oxy-fuel combustion CO_2 pipeline at 100 barg.

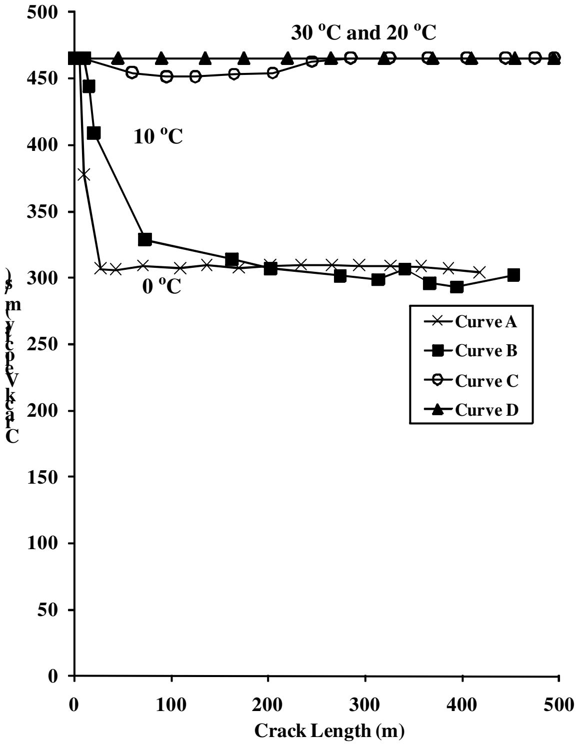

Figure 4. The impact of the line temperature on the variation of crack velocity with crack length for oxy-fuel combustion CO_2 pipeline at 180 barg.

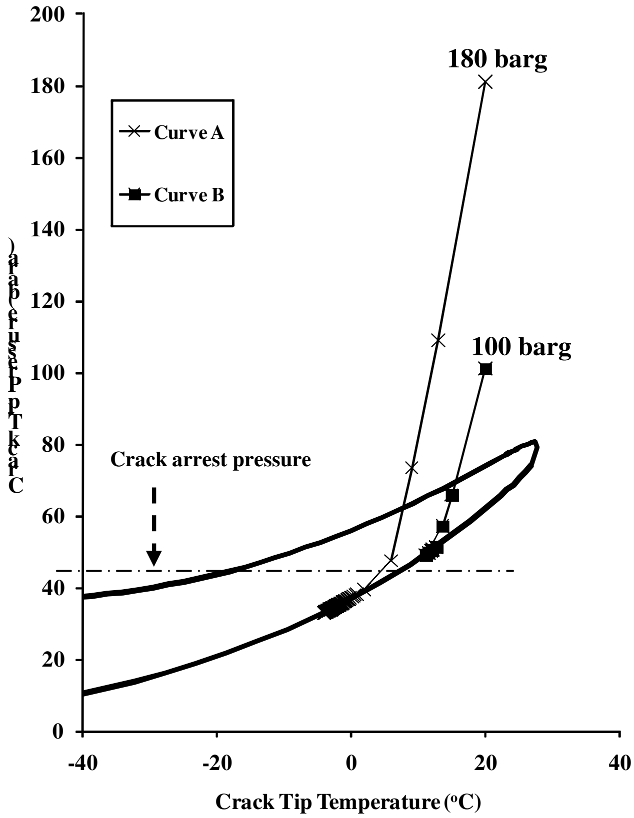

Figure 5. The variation of crack tip pressure with discahrging fluid temperature for the pre-combustion pipeline at different starting line pressures. Line temeparture: 20 °C.

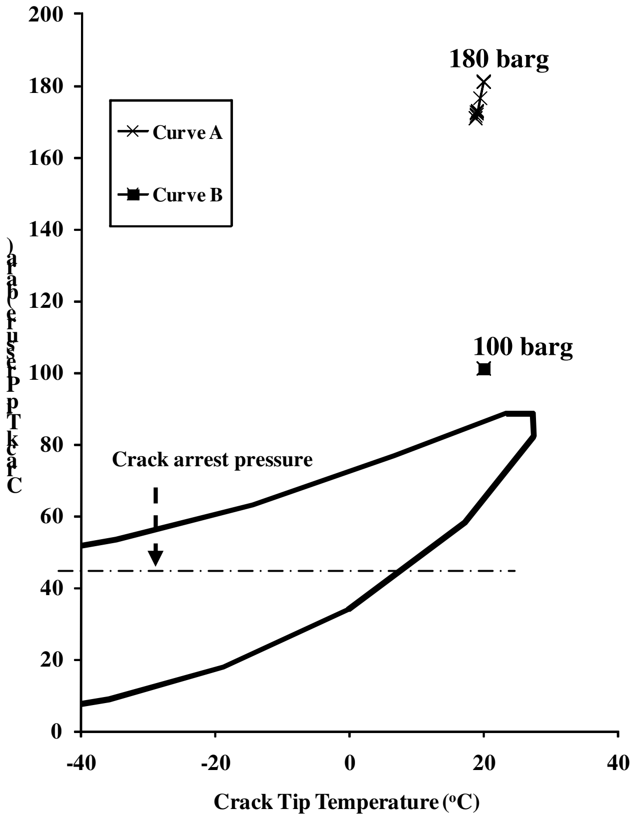

Figure 6. The variation of crack tip pressure with discharging fluid temperature for the oxy-fuel pipeline at different starting line pressures. Line temperature: 20 °C.

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