Study on leak rate in LBB analysis of welded pipe

Chunrun Li$^{1,2}$, Yanwei Shen$^{1,2}$, Yazhang He$^{1,2}$, Tianli Zhang$^{1,2}$, Jian Liu$^{1,2}$, Liang Chang$^1$

$^1$CNPC Engineering Technology Research Co. Ltd, No. 40 Jintang Road Tanggu Tianjin, 300451, P. R., China

$^2$Key Laboratory of Offshore Engineering of CNPC, No. 40 Jintang Road Tanggu Tianjin 300451, P.R., China

E-mail address: shenyw@cnpc.com.cn (Yanwei Shen)

Abstract. The leak-before-break (LBB) technology has been widely used in the design of welded pressure vessels and pipelines, and it is based on the theory that the penetration of fluid through cracks, which exist in the walls of the pipe and vessel, can be detected before the they reach a state of instability. In this paper, leak rates in different opening direction are calculated and analysed by finite element analysis software Fluent in the case of single phase fluid. It is concluded that there is no linear relationship between the leak rate and the CTOD value or the crack length, and that the influence of the CTOD increase on the leak rate is greater than that of the crack length.

1. Introduction

With the influence of external loads and other factors, surface cracks in a pipeline can develop into a stable through-wall crack, where the penetration of the wall thickness occurs. And when the leak rate reaches a certain threshold value, it can be detected by the monitoring system; but at this stage, the axial crack length is still too short to cause instable extension and fracture. If there is enough time between the detection of leakage and the pipeline destruction to take efficient measures, such as pressure relief and repair, catastrophic accidents due to the rapid overall damage can be avoided. Sharples etc. put forward the general guidelines for evaluation of LBB, as shown in Figure 1.

![Figure 1. General guidelines for evaluation of LBB.](image-url)
and social benefits. At present, some latest and most influential standards have put forward the evaluation methods of LBB, like the UK's BS - 7910 [1] "Acceptance Methods of Defects in Metal Structure" and the European Union’s SINTAP [2] " the Assessment Methods of Structural Integrity ".

One of the most important conditions of LBB evaluation is that the leakage rate is high enough to be detected before the length of the crack in the pipe is grown to the critical length of destructive fracture (that is, the crack size is still less than the critical crack length). Therefore, the calculation of the relationship between crack leak rate and its geometry is very important in LBB analysis. In this paper, a large finite element calculation software Fluent [3] is used to calculate the relationship between the crack geometry and the leak rate.

2. Crack growth mechanism in pipeline
When the surface crack has extended into a through-wall crack, two different kinds of crack growth mechanism may happen [4] according to the direction and forms of the applied stress: one is the circumferential propagation, increasing the length of the crack; another kind of propagation increases the CTOD of cracks due to tensile stress and bending moment, as is shown in Figure 2. Both growth mechanisms can increase the crack-opening-area and thus affect the leak rate.

3. Calculation of leak rate
The calculation of leak rate of pipeline cracks is based on fluid mechanics. The outflow of fluid under pressure is mainly determined by the internal pressure, flow velocity, temperature and water resistance. Different methods are adopted according to different conditions to calculate the leakage. Calculation of leakage rate through the cracks is a complex problem, involving the crack geometry, the path length, the effects of friction, thermal dynamics and so on. As one of the most difficult part of LBB analysis, it is related to a lot of uncertain conditions and it is necessary to simplify the calculation process [5-7]. In this study, the flow state is simplified as follows:

1) The leaking fluid is assumed to be single-phased, one-dimensional and adiabatic;
2) Heat exchange between the fluid and the environment is ignored;
3) The fluid is assumed to be incompressible;
4) The vaporization of the liquid is ignored.

The leak rate is usually calculated by a simplified fluid model. The crack is generally modeled as an elliptic section, so the leak rate depends on the shape of the crack surface and the CTOD. In order to study the influence of crack propagation direction on the leak rate, the fluid leak rate is calculated by the finite element program Fluent, which can be used for computing fluid dynamics and simulating fluid problems in various states.
The main parameters of the pipeline model for calculation are as follows:

1. Main size of pipeline: \( R = 317.55 \text{mm}, t = 12.7 \text{mm} \);
2. Crack geometry features: circumferential and penetrated orientation, uniform-sectioned flow path, elliptic crack open area;
3. Liquid state in the pipeline: \( P = 1000 \text{kPa}, T_0 = 60 \text{°C}, v = 2 \text{m/s}, \rho = 9.98 \times 10^3 \text{kg/m}^3 \), incompressible (external pressure 100kPa);

(4) The leak rates of specimens in different propagation forms are calculated as follows:
   a. The length of the through-wall crack was constant \( (2\theta = 60 \text{°}, \text{circumferential}) \), and crack open along the axial (the change of CTOD) extends from 0.05 mm to 0.6 mm.
   b. The CTOD of the through-wall crack remains unchanged \( (2a = 0.2 \text{mm}) \), and crack extends from 30° to 60° along the circumferential direction.

4. Modelling and grid division based on Fluent
The model of velocity related only involves the inner wall and crack body of the pipeline, so the external wall of the pipeline can be omitted, and the 3D model of the inner wall and the crack body can be built directly. The grid model is hexahedral, and its schematic diagram after partition is shown in Figure 4, where \( 2\theta \) is 30° and \( 2a \) is 0.2 mm.

After grid division, the minimum volume of the finite element model is \( 1.1576 \times 10^{-0.001} \text{m}^3 \), and the maximum is \( 1.7144 \times 10^{0.003} \text{m}^3 \), with a total of 73,216 units. \( k-\epsilon \) turbulence model is built in this paper, and then it is imported into the Fluent main program for iteration calculation.
5. Result and analysis
By calculating CTOD and crack length, curves of leak rate can be obtained.

![Graph showing CTOD vs. Leak rate](image)

Figure 5. COTD vs. Leak rate

As shown in Figure 5, the leak rate increases with the rising CTOD value, but the relationship of CTOD and the leak rate is not linear. The leak rate does not increase significantly when the CTOD value increases from 0.05mm to 0.1mm; then the leak rate starts to enhance steadily from 0.1 to 0.4mm; when the CTOD extends to 0.4 mm, the leak rate increases sharply.

![Graph showing Circumferential opening length of crack vs. Leak rate](image)

Figure 6. Circumferential opening length of crack vs. Leak rate

The relationship of crack open angle and the leak rate is shown is Figure 6. It illustrates that when the open angle of crack extends from 30 ° to 60 °, the leak rate shows only a slight increase, except for the turning point in the back part of the line. The relationship between the crack length and leak rate can be seen in Figure 7.
From the calculation results of different aspects, the effect of CTOD on the leak rate is much greater than that of the crack open angle. When CTOD changes from 0.1mm to 0.6mm, the leak rate increases from 0.0115 kg/s to 0.73241 kg/s; whereas, while crack open Angle extends from 30 ° to 60 °, leak rate increases only 0.02432 kg/s; therefore, CTOD is the main factor affecting the leak rate.

6. Conclusions
1. In this paper, the finite element program Fluent is used to calculate the leak rate of the fluid in the pipeline, and it indicates that the Fluent program is fitted to the calculation leak rate.
2. Calculation results show neither CTOD nor crack length has a liner relationship with the leak rate, and that the increase of CTOD has a far more important influence on the leak rate than that of crack length.

References
[1] BS 7910:1999. Guide on methods for assessing the accept ability of flaws in metallic structures. British Standards Publishing Limited (BSPL); 1999.
[2] SINTAP: structural integrity assessment procedures for European industry, ProjectBE95-1426. Finalprocedure, Britishsteelreport,Rotherham; 1999.
[3] FLUENT 6.2. Code Manual. Fluent Inc; 2004.
[4] Bjorn Brickstad, Iradj Sattari-Far. Crack shape developments for LBB applications. Engineering Fracture Mechanics 67 (2000) 625-46.
[5] Arturas Klimasauskas, Sigitas Rimkevicius, Linas Nedzinskas. Complex leak before break analysis demonstrated on RBMK-1500 austenitic piping. International Journal of Pressure Vessels and Piping 80 (2003) 655–63.
[6] Yukio Takahashi. Evaluation of leak-before-break assessment methodology for pipes with a circumferential through-wall crack. Part III: estimation of crack opening area. International Journal of Pressure Vessels and Piping 79 (2002) 525–36.
[7] D.L.Rudland, G Wilkowski, P Scott. Effects of crack morphology parameters on leak-rate calculations in LBB evaluations. International Journal of Pressure Vessels and Piping 79(2002)99-102.