A Method for Predicting Centerline Target Pressure of a Two-Phase Jet Load Under BWR LOCA

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Abstract

Certain structures and components in a nuclear power plant have to be designed for the two-phase jet loading resulting from the hypothetical rupture of hot-water carrying piping. It is demonstrated that the most important parameter influencing the impingement force is the target centerline pressure. Based on large and small scale two-phase blowdown tests an empirical expression is obtained for the target centerline pressure. For design purposes a two-step pressure distribution is introduced to replace the characteristic pressure profile of a perpendicularly impinging jet. This simplified two-step model is compared with the experimental data.

1. Introduction

Postulating a break in hot-water carrying piping in a nuclear power plant results in discharge of high energetic fluid into surrounding and impinging on components and structures. Ability to predict impinging pressure profiles is important for safe design of nuclear reactor systems. Simple but conservative models, ANS (1), have been used to determine the jet impingement loads. Based on such models the width and distribution of a pressure profile on the impacted wall is determined. Tomasko (2), Tompson (3) and Mohammadian et al (4) have determined the impingement jet pressure profile with computer programs and compared their analytical results with available experimental data. In the last 10 years many blowdown-experiments such as Kastner et al (5,6), Wind (7), Centi et al (8), Kitade et al (9), Yano et al (10) and Isozaki et al (11) have been carried out which enable us to obtain a better understanding of the physical phenomenon of two phase jets.

In the design practice a simple pressure profile is used, such as conical, two-step or cylinderical distribution. For all pressure profiles chosen, the important parameter is the target centerline pressure, which is depen-

dent on the discharge conditions and the target distance.
The objective of this paper is:

- to present and evaluate the available blowdown experimental data on jet impingement and
- to obtain a correlation for the target centerline pressure as a function of the target distance and flow loss between vessel and break location.

2. Thrust and impingement force

Figure 1 shows a schematic diagram of a ruptured pipe and an expanding jet impinging on a wall. For homogeneous discharge the resulting thrust force may be calculated from

$$F_T = (P_B - P_\infty + \rho V^2)\ A. \qquad (1)$$

with P_o as the pressure in the vessel and P_B, ρ, V the pressure, density and velocity at the discharge point respectively, and A is the break area.

This force is dependent on the fluid condition in the vessel and the loss coefficient along the discharge line. For blowdown of saturated water, P_B can be replaced with the critical pressure P_c. The thrust force may also be calculated by

$$F_T = S\ (P_o - P_\infty)\ A \qquad (2)$$

with S the thrust factor, which is dependent on P_o and flow loss, P_∞ is the ambient pressure. Equation (2) can be used for non-homogeneous flow with the proper thrust factor. Alternatively, the jet impingement force can be estimated from the pressure distribution on the target. With P (r) as the pressure on the impacted wall, the jet impingement force F_j is given by

$$F_j = \int_0^R P(r)\ 2\pi\ r\,dr \qquad (3)$$

Figure 2 shows three profiles all with the same centerline pressure $P_{r=o}$ and identical values for the volume integral under the curve. If the blowdown jet is perpendicularly discharged against the target plate and fully deflected, the impingement force can be taken equal to the thrust force. This is not true for all cases as shown by Centi et al (8) and Yano et al (10). They measured both forces and found, that for large impingement distance L/d = 10, the impingement force is about 10 % smaller than the thrust force.
By assuming $F_T = F_j$, the computed impingement load includes some conservatism for large impingement distances. With this assumption and also with a specified pressure distribution (conical, cylindrical or two-step) the jet impingement area can be computed once the target centerline pressure is known. In general, the target pressure written in non-dimensional form

is a function of

$$\eta = f (\varphi , \zeta , L/d) \qquad (4)$$

with $\eta = (P_{r=o} - P_\infty) / (P_o - P_\infty)$ the non-dimensional centerline pressure, $\varphi = (P_s - P_\infty) / (P_o - P_\infty)$ prescribing the degree of subcooling in the vessel (P_s = saturation pressure), ζ the loss coefficient between vessel and discharge point and L/d the ratio of the target distance to discharge diameter. For hot water at saturated condition φ is equal 1 and thereforce

$$\eta = f (\zeta , L/d) \qquad (5)$$

3. Target centerline pressure

To date there is no relation, theoretical or empirical, to prescribe the target centerline pressure in terms of flow resistance and target distance ratio. In order to find an approximate method for computing the target pressure, the available blowdown experiments are considered.
The thermodynamic conditions and the geometrical data of four different two-phase blowdown tests are shown in Table I. Kastner et al (5) performed a series of two-phase blowdown tests at Kraftwerk Union in Erlangen, Germany in 1975. As listed in Table I, the pressure in vessel varied between 50 to 100 bar with the water at saturation temperature and a vapor quality of nearly zero. The tests were performed with small diameter nozzles of 10 to 65 mm. These experiments were continued with the series, reported by Kastner et al (6). Large scale blowdown tests with the vessel at saturated condition were performed at HDR, Wind and Tenhumberg (7). The last experiments shown in Table I were performed in Japan by Yano et al (10).
The measured centerline pressure from the above mentioned experiments were entered in Figure 3 in non-dimensional form. There is some scatter in the measured values for tests with the small discharge diameters at L/d = 1 and 3. Still these measurements can be approximated with a straight line on a logarithmic scale yielding the relation

$$\eta = 0.65 \, (L/d)^{-2.21} \quad \text{for } L/d \geq 0.82 \qquad (6)$$

Eq. (6) does not include the flow loss coefficient between the vessel and discharge point and gives a fair approximation for KWU experiments with negligibly small ζ -values, whereas it overestimates the measurements performed with large scale discharge pipe, HDR (7) and Yano (10). In these tests the flow loss coefficient was approximately $\zeta = 1$.
One method of accounting for the effects of flow losses in the target centerline pressure is to introduce in Eq. (6) a factor which gives the relative decrease of thrust force due to flow losses:

$$\eta = 0.65 \quad \varepsilon \, (L/d)^{-2.21} \qquad (7)$$

with

$$\varepsilon = S_\zeta / S_{\zeta=0}$$

In the above equation S is the thrust factor with ζ as index.
Figure 4 shows a comparison between the empirical expression (7) and the measurements with $\zeta = 1$. Based on the only two measurements at L/d = 2 and 5 Yano et al (10) suggested a similar correlation for the centerline pressure which is also plotted in Figure 4.

4. Comparison between a two-step-pressure profile and measurements

Figure 5 and 6 demonstrate two pressure profiles measured by Wind (7) for L/d = 2 and 3. As mentioned earlier, simple pressure profiles are used in the analyses of containment structures. Pressure profiles in Figures 5 and 6 can be replaced by the conical ones. For structural analysis an even simpler pressure distribution is desired, such as a two-step pressure profile.

The outer and inner diameter of a two-step pressure profile can be determined by assuming that this profile produces the same maximum shear stresses in the impacted structure as a conical profile with the same centerline pressure and the same pressure integral. Figure 5 and 6 compare measurents with the approximate method.
A cylinderical pressure distribution is the simplest one and may be applied for large target distance ratio. It produces very conservative shear stresses in wall structures where L/d is small.

Conclusion

- The pressure profiles resulting from two-phase jet impingement on structures were studied. It was shown that the target centerline pressure is the most important parameter in describing any pressure profile.
- Based on small and large scale two-phase blowdown tests performed in Germany and Japan, a simple equation was derived for perdiction of the centerline target pressure as a function of the ratio of target distance to discharge diameter L/d and the flow loss coefficient along the discharge pipe.
- It was demonstrated that a pressure profile convinient for structural analysis in the form of a two-step pressure distribution provides an adequate representation as shown by comparison with experimental data.

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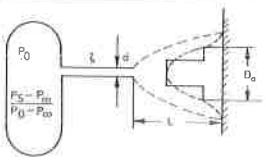
Table I
Two-phase blowdown tests

	P_0 bar	$\frac{P_s-P_\infty}{P_0-P_\infty}$	ζ	d mm	L/d -
Kastner et al (5) KWU-RS93	50-100	1	0.34	10-65	0.25-10
Kastner et al (6) KWU-RLL3	40-74	1	0.19	40	1 and 3
Wind&Tenhumberg (7) HDR-V21.1-3	106	1	1.0	450	2 and 3
Yano et al(10) JAERI (Japan)	68	1	1.0	150	2 and 5



P_0 vessel pressure
P_s saturation pressure
P_∞ ambient pressure
ζ flow loss coefficient
d discharge diameter
L target distance

Figure 1 Schematic view of a pipe break and resulting jet impingement

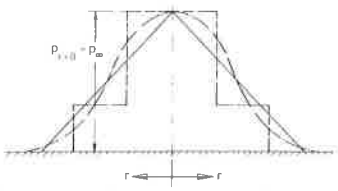


Figure 2 Pressure profiles of a perpendicularly impinging jet

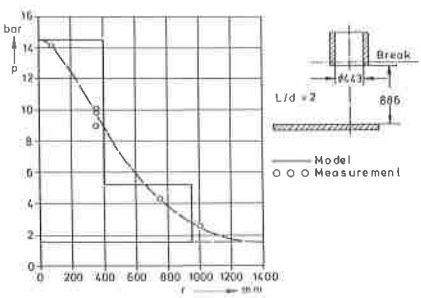


Figure 5 Comparison of pressure profile between two-phase jet experiment HDR-V21.1 and two-step model

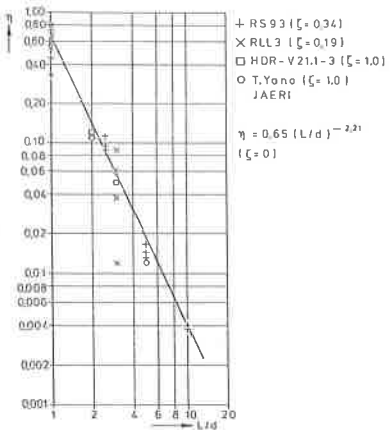


Figure 3 Measured target centerline pressure

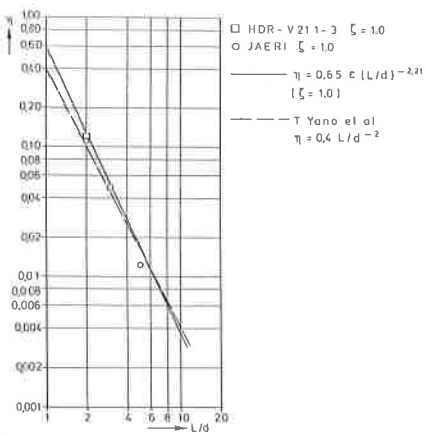


Figure 4 Prediction of target centerline pressure for discharge with ζ = 1

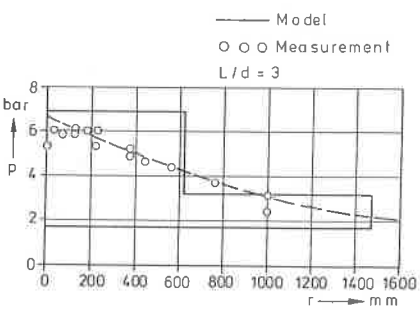


Figure 6 Comparison of pressure profile between two-phase jet experiment HDR-V21.3 and two-step model