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Research Article

The Pressure Area Method (PAM) for Nozzle Reinforcement in Pressure Vessels: Theory, Application, and Design Implications

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Abstract - *The Pressure Area Method (PAM) is a simplified yet code-recognized analytical technique employed to evaluate the structural adequacy of nozzle penetrations in pressure vessels. Based on a limit load concept, PAM equates the internal pressure force acting on the removed area of the vessel wall to the resisting force provided by the available reinforcement, including both the parent shell and any additional reinforcement such as pads. This study presents a comprehensive overview of the PAM framework, applicable to both cylindrical and spherical shells, and outlines the governing equations for configurations with and without reinforcing pads. A detailed nomenclature and explanation of code-dependent k-factors are provided to support implementation. A worked example involving a flush set-in nozzle with a reinforcing pad in a cylindrical shell is included to demonstrate the methodology's practical application. Results show that the nozzle intersection governs the Maximum Allowable Working Pressure (MAWP), highlighting the method's conservative yet effective design approach. While PAM does not explicitly account for stress concentrations or external load effects, it remains a robust, mechanics-based tool widely adopted in pressure vessel design standards. Its straightforward nature makes it highly suitable for spreadsheet-based implementation and early-stage design validation in both European and international contexts.*

Keywords - *Pressure Area Method (PAM), pressure vessels, nozzle reinforcement, structural integrity, Maximum Allowable Working Pressure (MAWP), cylindrical shell, spherical shell, limit load analysis, design codes, mechanical design.*

I. INTRODUCTION

The Pressure Area Method (PAM) is a simplified, code-recognized approach used to assess the structural adequacy of nozzle penetrations in pressure vessels. The method is based on a limit load concept, where the internal pressure acting on the area removed from the vessel wall (due to the nozzle opening) is balanced by the load-carrying capacity of the surrounding reinforcing material. The underlying principle is that the force from internal pressure on the pressure-loaded area is resisted by the available reinforcing area, scaled by the allowable stress. To ensure the structural integrity of pressure vessels, particularly at openings such as nozzles and manholes, a fundamental reinforcement criterion must be satisfied. This criterion ensures that the localized stresses induced by internal pressure do not exceed the allowable limits of the material. The requirement is expressed as:

$$p \,.\, [\, A_p + 0.5\,(\sum A_f)] \le \frac{\sigma_y}{1.5} \sum A_f$$

Where:

- p is the internal design pressure
- A_p is the projected area of the opening on a plane perpendicular to the direction of pressure, representing the pressure-loaded area.
- σ_y is the yield stress of the material at design temperature

- $\sum A_f$ represents the total area of available reinforcement around the opening, defined as the effective load-bearing cross-sectional area. It includes the effective portion of the shell, the effective area of the nozzle neck, and the effective area of any reinforcing pad.

This formulation treats the region around the opening as a limit state problem, using a safety factor (commonly 1.5) applied to the yield stress to ensure conservative design under expected operating conditions. PAM provides a useful and conservative design instrument to ensure the vessel is capable of withstanding the internal pressure without crushing in the area of nozzle penetrations. It is suited especially in the case of cylindrical and spherical shells under internal pressure, and it is extensively used in accepted design codes and standards. Nevertheless, PAM is limited in nature: it is silent on local stress concentrations, bending behavior or interaction between openings that are extremely close to each other. More detailed approaches like finite element analysis (FEA) can be required (at least in complex geometries or where a more accurate measure of structural integrity is needed) to obtain an accurate measure of structural integrity.

II. METHODOLOGY

The Pressure Area Method (PAM) applied in this study assumes that the pressure vessels are predominantly subjected to static loading, operating under conditions with minimal pressure fluctuations. This assumption reflects typical service environments where fatigue and dynamic effects are negligible, consistent with internationally recognized pressure vessel design codes that generally recommend PAM for static loading scenarios. Figures 1 and 2 illustrate the PAM concept, showing the relationship between the removed pressure-carrying area and the reinforcement required to maintain the vessel's structural integrity in the vicinity of the nozzle.

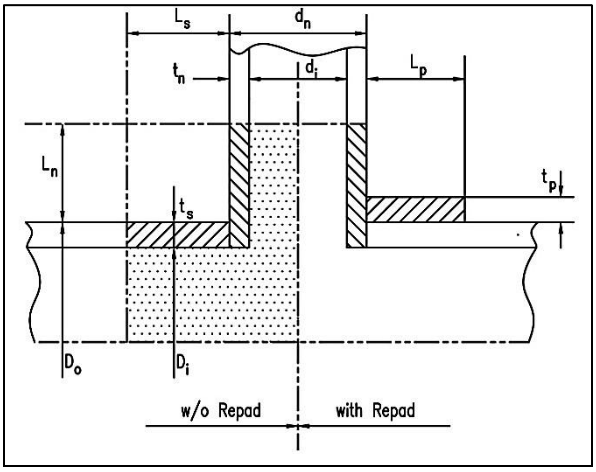

Figure 1. Nozzle Configuration on Cylindrical Shell

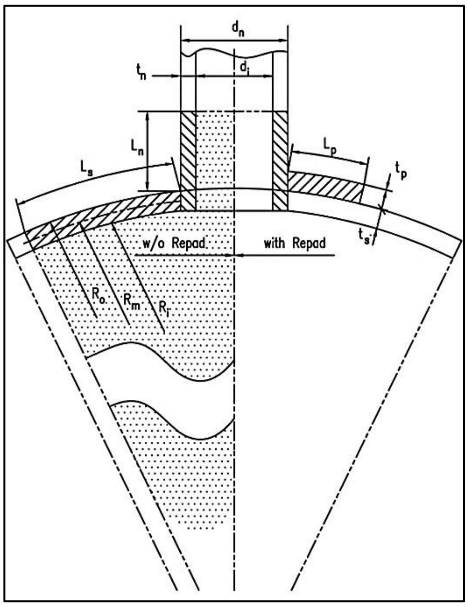

Figure 2. Nozzle Configuration on Spherical shell

Table 1. Overview of Formulas

FLUSH ISOLATED SET-IN NOZZLE WITHOUT REINFORCING PAD IN CYLINDRICAL SHELL	FLUSH ISOLATED SET-IN NOZZLE WITH REINFORCING PAD IN CYLINDRICAL SHELL
$L_n = k_n \sqrt{(d_n - t_n)t_n}$	
$L_s = k_s \sqrt{(D_o - t_s)t_s}$	
$A_p = \frac{D_i}{2}(L_s + \frac{d_n}{2}) + \frac{d_i}{2}(L_n + t_s)$	

$A_f = t_s \,.\, L_s + (L_n + t_s)\, t_n$	$A_f = t_s \,.\, L_s + (L_n + t_s)\, t_n + k_p\,(L_p \,.\, t_p)$
$MAWP_{intersection} = \dfrac{f}{(\frac{A_p}{A_f} + 0.5)}$	
$MAWP_{\text{undisturbed shell}} = f \,.\, l_n\,(\frac{D_o}{D_i})$	
FLUSH ISOLATED SET-IN NOZZLE WITHOUT REINFORCING PAD IN SPHERICAL SHELL	**FLUSH ISOLATED SET-IN NOZZLE WITH REINFORCING PAD IN SPHERICAL SHELL**
$L_n = k_n\,\sqrt{(d_n - t_n)t_n}$	
$L_s = k_s\,\sqrt{[(2R_i + t_s)t_s}$	
$R_m = (R_i + 0.5\, t_s)$	
$\delta = \dfrac{d_n}{2R_m}$	
$a = R_m \,.\, \arcsin \delta$	
$A_p = 0.5\, R_i^2\, \frac{L_s + a}{0.5t_s + R_i} + 0.5\, d_i\,(L_n + t_s)$	
$A_f t_s \,.\, L_s + (L_n + t_s)\, t_n$	$A_f = t_s \,.\, L_s + (L_n + t_s)\, t_n + k_p\,(L_p \,.\, t_p)$
$MAWP_{intersection} = \dfrac{f}{(\frac{A_p}{A_f} + 0.5)}$	
$MAWP_{\text{undisturbed shell}} = 2f \,.\, l_n\,(\frac{D_o}{D_i})$	

A detailed examination of the expression for the maximum allowable working pressure (MAWP) at a nozzle-shell intersection in a pressure vessel,

$$MAWP_{intersection} = \frac{f}{(\frac{A_p}{A_f} + 0.5)}$$

where f is the design stress, A_p is the projected pressure area, and A_f is the available reinforcement area, reveals a fundamental inverse relationship between the ratio $\frac{A_p}{A_f}$and the pressure capacity of the intersection. As the ratio$\frac{A_p}{A_f}$ decreases, the MAWP increases, indicating an improved ability of the joint to sustain internal pressure. This relationship highlights the importance of maximizing the reinforcement area relative to the projected pressure area in the design of pressure vessels. The reinforcement area compensates for material removed due to the nozzle opening and strengthens the region around the intersection. Enhancing A_f can be achieved through geometric modifications such as increasing nozzle neck thickness, incorporating reinforcing pads, or using integral reinforcement or through the selection of higher-strength materials. Conversely, a high $\frac{A_p}{A_f}$ ratio implies that a large pressure-exposed area is supported by relatively little reinforcement, thereby reducing the MAWP and potentially compromising the structural integrity of the vessel under design or operating conditions. Therefore, optimizing the reinforcement-to-projection area ratio is essential for ensuring the safety, efficiency, and reliability of pressure vessels.

The efficiency factors associated with the shell (k_s), nozzle neck (k_n) and reinforcing pad (k_p) vary depending on the applicable design code. Their typical ranges are summarized below:

Table 2. Summary of Efficiency Factors (k-Factors)

k-Factors Associated with Shell, Nozzle Neck En Reinforcing Pad	
k_s	0.75 and 1.0
k_n	1.0 and 1.25
k_p	0.75 and 1.0

As specified in reference [8,9], the efficiency factor ks is determined based on the dimensionless geometric parameter δ, defined as:

$$\delta = \frac{d_i}{\sqrt{(D_o - t_s)\,t_s}}$$

where:

- d_i_ is the internal diameter of the nozzle,
- D_o is the outside diameter of the shell, and
- t_s is the shell thickness.

The efficiency factor k_s varies as a function of δ , according to the following piecewise relationship:

- For $\delta \leq 4$; $k_s = 1.0$
- For $4 < \delta < 16$; $k_s = \frac{13}{12} - \frac{\delta}{48}$
- For $\delta \geq 16$; $k_s = 0.75$

To ensure continuity and smoothness in design calculations, linear interpolation is permitted for values of δ between 4 and 16.

Table 3. Nomenclature

Symbol	**Description**	**Unit**
D_o	Outside diameter shell	mm
D_i	Inside diameter shell	mm
R_i	Inside radius sphere	mm
R_m	Mean radius sphere	mm
t_s	Shell thickness	mm
t_n	Nozzle neck thickness	mm
d_n	Outside nozzle diameter	mm
d_i	Inside nozzle diameter	mm
L_p	Width of reinforcing pad	mm
t_p	Thickness of reinforcing pad	mm
L_n	Effective length of nozzle neck	mm
L_s	Effective length of shell	mm
k_s	Shell factor	-
k_n	Nozzle factor	-
k_p	Repad factor	-
A_p	Pressure loaded area	mm^2
A_f	Load - carrying cross- sectional area	mm^2
$MAWP_{intersection}$	Maximum Allowable Working	MPa

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	Pressure for nozzle intersection	
$MAWP_{undisturbed\ shell}$	Maximum Allowable Working Pressure for undisturbed shell	MPa
f	Design stress per applicable design code or standard	MPa

A. Application Limits

$\frac{d_i}{D_i} \leq 0.8$ for radial nozzles on cylindrical shells respectively $\frac{d_i}{D_i} \leq 0.6$ for radial nozzles on spherical shells

$t_n \leq 2\ t_s$

$0.5\ t_s \leq\ t_p \leq 1.5\ t_s$

$L_p \geq 3\ t_p$

$t_s \leq D_i/10$

Material yield strength $(\sigma_y) \leq 440$ MPa

B. Pressure Stress at Nozzle Intersection (σ_p)

The pressure stress at the intersection between the nozzle and the shell, denoted as σ_p, is determined using the following formulas:

a. For a Nozzle on a Cylindrical Shell

$$\sigma_p = \frac{2.5}{z} \frac{p_d}{l_n\left(\frac{D_o}{D_i}\right)}$$

b. For a Nozzle on a Spherical Shell

$$\sigma_p = \frac{2.0}{z} \frac{p_d}{2 \,.\, l_n\left(\frac{D_o}{D_i}\right)}$$

where:

- σ_p is the pressure stress at the nozzle–shell junction (MPa),
- p_d is the design pressure (MPa),
- D_o and D_i are the outside and inside diameters of the shell, respectively (mm),
- l_n is the natural logarithm (–),
- z is a dimensionless factor accounting for geometry and reinforcement (-).

c. Auxiliary Value z

The factor z accounts for geometric and reinforcement influences and is defined as:

$$z = c\ \frac{D_o - t_s}{t_s} \frac{A_f}{2A_p + A_f}$$

Where: c = 1.0 for cylindrical shells and c = 0.5 for spherical shell.

C. Pressure Stress in the Nozzle Neck (σ_{pn})

The local pressure stress in the nozzle neck, σ_{pn}, is derived from the shell intersection stress σ_p and adjusted based on the relative wall thickness of the nozzle:

$$\sigma_{pn} = \sigma_p\sqrt{c_n}$$

where the correction factor c_n is given by:

$$c_n = \left(\frac{t_s}{t_n}\right)$$

and:

- t_n is the nozzle wall thickness (mm),
- t_s is the shell wall thickness (mm),
- c_n accounts for the difference in stiffness between the shell and the nozzle neck (-).

III. DISCUSSION

Reinforcement around openings shall restore the pressure-resisting capacity of the shell to that of the un-penetrated structure, through quantifiable, localized contributions of metal acting in the direction of the imposed pressure stresses. The methodology is conservative, mechanics-based, and intended for safe, modular application. Additional load effects, such as local forces, moments, and fatigue, shall be addressed by separate assessment. The main purpose is to limit membrane-type stresses in the vicinity of the nozzle-shell intersection due to internal pressure. Hence, the pressure-area reinforcement methodology serves to control the localized increase in membrane stress i.e., the stress concentration at the structural discontinuity introduced by a nozzle penetration, by ensuring that the pressure-carrying capacity of the shell is preserved within acceptable code-defined limits. A nozzle penetration introduces a geometric and structural discontinuity in an otherwise continuous pressure boundary. This disrupts the uniform distribution of internal pressure-induced membrane stresses in the shell. While the pressure-area reinforcement methodology is grounded in solid mechanics, its true value lies in its long-standing success in practical engineering and fabrication. This methodology has proven itself in the world of pressure vessels for many years, particularly in European countries, but is also increasingly being used abroad.

IV. WORKED EXAMPLE

The worked example will be limited to an isolated flush set-in type nozzle equipped with a reinforcing pad with the following data:

Outside diameter cylindrical shell : 1600 mm; Thickness cylindrical shell: 12 mm; Outside nozzle diameter: 273 mm; Nozzle neck thickness: 13.2 mm (net); Design stress: 150 MPa (for all components); Corrosion allowance: nil; Nozzle stand-out: 250 mm; Shell length: 5000 mm. Width of reinforcing pad:72 mm and pad thickness: 12 mm. Furthermore, it is assumed that the materials used for the shell, nozzle, and reinforcing pad have the same design stress and that the filled welds do not contribute to nozzle reinforcement. Applicable k-values respectively: $k_s = 1.0$; $k_n = 1.25$ and $k_p = 0.75$.

A. Calculation of the MAWPs

$L_n = 1.25\sqrt{(273 - 13.2)13.2} = 73.2$ mm

$L_s = 1.0\sqrt{(1600 - 12)12} = 138$ mm

$A_p = \frac{1576}{2}\,(138 + \frac{273}{2}) + \frac{246.6}{2}(73.2 + 12) = 226811.16\ \text{mm}^2$

$A_f = 12\,.\,138 + (73.2 + 12)13.2 + 0.75\,(72 \times 12) = 3428.64\ \text{mm}^2$

$\text{MAWP}_{\text{ intersection}} = \frac{150}{(\frac{226811.16}{3428.64} + 0.5)} = 2.25$ MPa

$\text{MAWP}_{\text{ undisturbed shell}} = 150\,.\,l_n\,(\frac{1600}{1576}) = 2.267$ MPa

$z = c\,\frac{D_o - t_s}{t_s}\,\frac{A_f}{2A_p + A_f} = 1.0\,\frac{1600 - 12}{12}\,\frac{3428.64}{2 \times 226811.16 + 3428.64} = 0.99272$

In case p_d is $\text{MAWP}_{\text{ intersection}}$ then follows: $\sigma_p = \frac{2.5}{z}\,\frac{p_d}{l_n\left(\frac{D_o}{D_i}\right)} = \frac{2.5}{0.99272}\,\frac{2.25}{l_n\left(\frac{1600}{1576}\right)} = 374.91$ MPa

$\sigma_{pn} = \sigma_p\sqrt{c_n}$; with $c_n = \frac{t_s}{t_n} = \frac{12}{13.2} = 0.9091$ follows: $\sigma_{pn} = 374.91\,\sqrt{0.9091} = 357.463$ MPa

The above calculation of the pressure stress (σ_p) is a conservative approximation according to [4].

In this configuration, nozzle penetration governs the overall maximum allowable working pressure (MAWP). However, the MAWP must not be less than the design pressure under any circumstances. The nozzle geometry was further evaluated using the FE-Pipe software package [10], which applies finite element analysis (FEA) techniques for pressure vessel and piping design. The analysis determined a MAWP of 2.83 MPa at the nozzle intersection representing an increase of 25% over the value calculated using the traditional pressure-area method. Several control calculations performed using FEA on various nozzle configurations have produced consistent results, demonstrating the reliability of the method. While the method is inherently conservative, this typically does not pose disadvantages or limitations except in rare cases. According to reference [6], and in alignment with paragraph UG-37 of ASME BPVC Section VIII, Division 1[7], the Pressure Area Method yields less conservative results compared to the Area Replacement Method.

V. CONCLUSIONS

The Pressure Area Method (PAM) provides a simplified, code-recognized, and conservatively robust approach for evaluating nozzle reinforcement in pressure vessels. Rooted in limit load theory, PAM equates the internal pressure acting on the removed shell area to the resistance provided by the surrounding reinforcement such as the shell, nozzle neck, and any reinforcing pad in accordance with major design codes, including EN 13445-3, PD 5500, AD 2000, and Rules for Pressure Vessels [1–4]. This study confirms PAM's practicality for standard nozzle configurations in both cylindrical and spherical shells. The worked example involving a flush set-in nozzle with a reinforcing pad demonstrates that the nozzle-shell intersection typically governs the vessel's Maximum Allowable Working Pressure (MAWP). The close alignment between the MAWP calculated via PAM (2.25 MPa) and the result obtained from finite element analysis (2.83 MPa) supports the method's reliability while highlighting its conservative nature consistent with the findings of Kuehn and Wulf [5] and Stikvoort [9]. Despite its limitations such as not accounting for local stress concentrations, external loads, or interaction effects between adjacent nozzles PAM's straightforward implementation makes it highly suitable for early-stage design, spreadsheet-based assessments, and compliance verification in both European and international contexts. In more complex scenarios, finite element methods (e.g., FE-Pipe) may be used to supplement PAM and provide a more detailed evaluation of structural behaviour.

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