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DETERMINATION OF MAXIMUM SIZE OF UNREINFORCED ISOLATED OPENINGS IN PRESSURE VESSELS

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ABSTRACT

Vessel components are weakened when material is removed to provide openings for nozzles or access. High stress concentrations exist at the opening edge and decrease radially outward from the opening. To avoid failure in the opening area, compensation or reinforcement is required.

To reduce the number of nozzle compensation calculations, an algorithm has been developed to determine the maximum size of an unreinforced isolated opening in a cylindrical shell and in the domed part of a head as well as in a spherical shell of a pressure vessel. The basic principle here is that use is made of the excess thickness of the shell in which the opening is located and, as it were, forms a fictitious reinforcement ring around the opening. The so-called "pressure area" method has been used as the basis for this.

Keywords: Nozzle, Compensation, Size Unreinforced Opening, Cylindrical Shell, Head, Sphere. Pressure Area.

I. INTRODUCTION

Nozzles in pressure vessels form a region of instability and therefore a disturbance of the membrane state. In order to ensure pressure integrity, the so-called "pressure area" method has been developed, which has been used satisfactorily for many years, especially in Europe [1],[2].This method is the counterpart of the "area compensation or area replacement" method as described in ASME BPV Code Section VIII-Division 1[3], the principle of which is further elaborated in the appendix. The "pressure area" method recognizes the attenuation of stresses in the vicinity of the opening which is a function of $\sqrt{\text{radius x thickness}}$ .This can be used to determine the necessary reinforcement of a nozzle penetration in the vessel wall in such a way that the region of instability is fully compensated. In principle, the nozzle neck, reinforcement pad and excess vessel wall thickness contribute to the compensation of the nozzle opening. The next section of this article elaborates on the procedure for determining the maximum size of an unreinforced opening.

II. ELABORATION OF PROCEDURE

When applying the "pressure area" method, the following condition must be met regarding nozzle penetrations in pressure vessels:

$$P\,(A_P + 0.5\,A_{fs}) \leq f_s \,.\, A_{fs}$$

The above mentioned expression together with Figure 1 represents the pressure-area method. This is based on ensuring that the reactive force provided by the vessel material is greater than or equal to the load from the internal pressure. This is a simplified limit load type approach with the yield stress factored to the design level.

For the calculation of the pressure - and stress - loaded areas the formulas apply as shown in the table below:

Cylindrical shell	Spherical shells and dished ends
$A_p = 0.5\,D_i\,(L_s + 0.5\,d_i) + 0.5\,d_i \text{ x } e_s$	$A_p = 0.5 \text{ x } r_{is}^2 \frac{L_s + a}{0.5\,e_s + r_{is}} + a \text{ x } e_s$ Simplified approach, neglecting the area: $0.5\,d_i \text{ x } e_s$ $A_p = 0.5\,r_{is}\,(L_s + 0.5\,d_i)$
$A_{fs} = e_s \,.\, L_s$	$A_{fs} = e_s \,.\, L_s$
$L_s = [(D_i + e_s)\,e_s]^{0.5}$	$L_s = [(2r_{is} + e_s)\,e_s]^{0.5}$ $r_{ms} = (r_{is} + 0.5 \text{ x } e_s)$ $\delta = \frac{d_i}{2\,.\,r_{ms}}$ $a = r_{ms}\,.\,\arcsin\delta$

Equations for the determination of the maximum size of the unreinforced opening are shown in the table below:

Cylindrical shell
$$d_{i,max} = \frac{L_s}{(D_i + 2e_s)}\left[\frac{4\, f_s \cdot e_s}{P} - 2(D_i + 2e_s) + 2\, e_s\right]$$ or $$d_{i,max} = 2\,(D_i + e_s)\left(\frac{L_s}{D_i + 2\, e_s}\right)\left(\frac{1}{z} - 1\right)$$ with $$z = \frac{P\,(D_i + e_s)}{2\, f_s\, e_s}$$
Spherical shell and dished ends
$$d_{i,max} = 2\left[\frac{(f_s - 0.5\, P)\, e_s\ . L_s}{0.5\, P . r_{is}} - L_s\right]$$ For simplification, the area inside the hole being ($0.5\ d_i$ x e_s) has not included in the pressure area because it has negligible effects on the calculated results.

NOMENCLATURE	
P = design pressure (MPa)	e_s = net wall thickness of shell (mm)
D_i = inside diameter of cylindrical (mm)	L_s = load bearing width (mm)
r_{is} = inside radius of spherical part (mm)	A_p = pressure loaded area (mm^2)
d_i = inside diameter of opening (mm)	A_{fs} = Stress loaded area (mm^2)
$di_{,max}$ = max. size unreinforced opening (mm)	f_s = nominal design stress shell material (MPa)

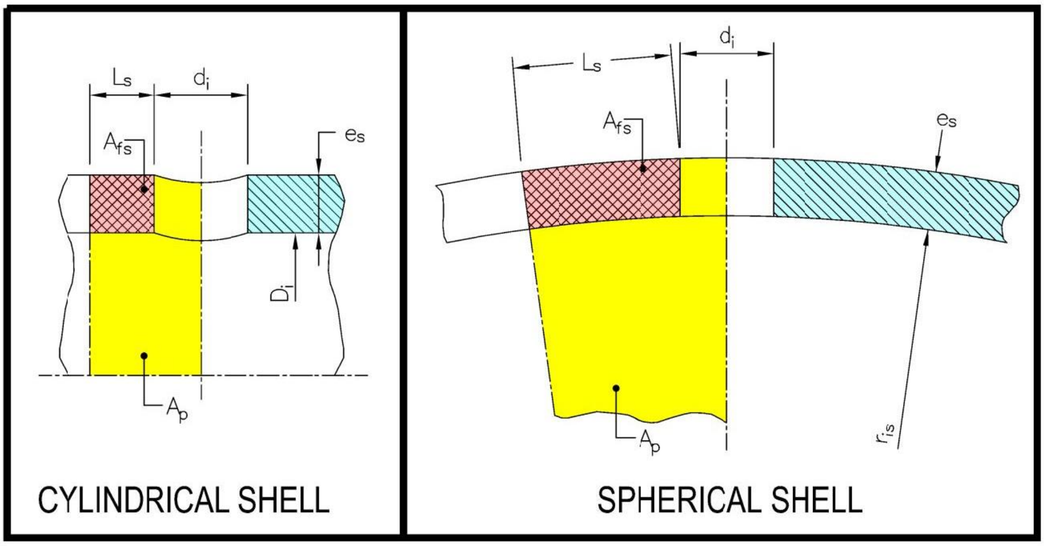

Figure 1: Illustration of unreinforced openings

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III. WORKED EXAMPLE

VESSEL DATA	
Design pressure 10 bar = 1 MPa	Inside radius domed part: 1200 mm
Design temperature: 65°C	Material of cylindrical shell ASTM A515 Grade 60
Outside diameter cylindrical shell: 1500 mm	Material "korbbogen" head ASTM A515 Grade 60
Net wall thickness cylindrical shell: 10 mm	Mechanical properties ASTM A 515 Grade 60 UTS = 415 MPa ;YS = 220 MPa ; Sy @ 65°C = 208 MPa
"Korbbogen" head acc. DIN 28013	
Thickness spherical part head:10 mm after forming	Nominal design stress:138.67 MPa

Calculation of maximum size of unreinforced isolated opening in cylindrical shell

Cylindrical shell

$$L_s = [(D_i + e_s)\, e_s]^{0.5}$$

$$L_s = [(1480 + 10)10]^{0.5} = 122.065 \text{ mm}$$

$$d_{i,max} = \frac{L_s}{(D_i + 2e_s)}\left[\frac{4\, f_s \cdot e_s}{P} - 2(D_i + 2e_s) + 2\, e_s\right]$$

$$d_{i,max} = \frac{122.065}{(1480 + 2\,x\,10)}\left[\frac{4\,x 138.67\,x\,10}{1} - 2(1480 + 2\,x 10) + 2\,x\,10\right]$$

$$d_{i,max} = 208.88 \text{ mm}$$

This means that nozzles in the cylindrical shell with a nominal diameter up to NPS 8" (NB 200) do not require additional reinforcement for internal pressure and thus the nozzle area compensation calculations can be omitted because it may be assumed that their internal diameters are smaller than the calculated $d_{i,max}$.

Alternative solution:

$$d_{i,max} = 2\,(D_i + e_s)\left(\frac{L_s}{D_i + 2\,e_s}\right)\left(\frac{1}{z} - 1\right) \text{ with: } z = \frac{P\,(D_i + e_s)}{2\, f_s\, e_s} = \frac{1\,(1480 + 10)}{2\,x\,138.67\,x\,10} = 0.537246$$

$$d_{i,max} = 2\,(1480 + 10)\left(\frac{122.065}{1480 + 2\,x\,10}\right)\left(\frac{1}{0.537246} - 1\right) = 208.88 \text{ mm}$$

Check

$$A_p = 0.5\, D_i\,(L_s + 0.5\, d_i) + 0.5\, d_i\, x\, e_s = 0.5\,x\,1480\,(122.065 + 0.5\,x\,208.88) + 0.5\,x\,208.88\,x\,10$$

$$A_p = 169268.4 \text{ mm}^2$$

$$A_{fs} = e_s \,.\, L_s = 10 \,x\, 122.065 = 1220.65 \text{ mm}^2$$

$$P\,(A_P + 0.5\, A_{fs}) \leq f_s \,.\, A_{fs}$$

$$1\,(169268.4 + 0.5\,x\,1220.65) \leq 138.67 x\,1220.65$$

$$Ratio = \frac{P\,(A_P + 0.5\,A_{fs})}{f_s \,.\, A_{fs}} = \frac{169878.725}{169267.5355} = 1.0036 \Rightarrow \text{ rounded off : } 1.0$$

Condition has been satisfied!

Calculation of maximum size of unreinforced isolated opening in domed end

Domed end (korbbogen head)

$$L_s = [\,(2\, r_{is} + e_s)\, e_s\,]^{0.5}$$

$$L_s = [\,(2\,x 1200 + 10\,)10]^{0.5} = 155.24 \text{ mm}$$

For simplicity an approximate solution is chosen where the pressure area 0.5 d_i . e_s has been ignored.

$$d_{i,max} = 2\left[\frac{(f_s - 0.5\,P)\, e_s\,.\, L_s}{0.5\, P .\, r_{is}} - L_s\right]$$

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$$d_{i,max} = 2\,[\frac{(138.67 - 0.5\,x\,\ 1)10\,x\,155.24.}{0.5\,x\,1x\,1200} - 155.24\,] = 404.5\text{ mm}$$

Check (simplified approach)

$$A_p = 0.5\,r_{is}\,(L_s + 0.5\,d_i\,) = 0.5 \text{ x } 1200\,(155.24 + 0.5 \text{ x } 404.5) = 214494\text{ mm}^2$$

$$A_{fs} = e_s\ .\ L_s = [\,10 \text{ x } 155.24 = 1552.4\text{ mm}^2$$

$$P\,(A_P\ +\ 0.5\,A_{fs}) \le f_s\ .\ A_{fs} \Rightarrow 1\,(214494 + 0.5 \text{ x } 1552.4) \le 138.67 \text{ x } 1552.5$$

Condition has been satisfied!

Check (exact method)

$$r_{ms} = (r_{is} +\ 0.5\,x\,e_s) = (1200 + 0.5 \text{ x } 10\,) = 1205\text{ mm}$$

$$\delta = \frac{d_i}{2\,.\,r_{ms}} = \frac{404.5}{2\,x1205} = 0.167842324\text{ rad}$$

$$a = r_{ms}\,.\,arcsin\,\delta = 1205 \text{ x } 0.168640533 = 203.\,2118\text{ mm}$$

$$A_p = 0.5\,x\,r_{is}^2\,\frac{L_s + a}{0.5\,e_s + r_{is}} + a\,x\,e_s = 0.5\,x\,1200^2\,\frac{155.24 + 203.2118}{0.5\,x\,10 + 1200} + 203.2118\,x\,10 = 216210.8125\text{ mm}^2$$

$$A_{fs} = e_s\ .\ L_s = 10 \text{ x } 155.24 = 1552.4\text{ mm}^2$$

$$P\,(A_P\ +\ 0.5\,A_{fs}) \le f_s\ .\ A_{fs} \Rightarrow 1\,(216210.\,8125 + 0.5 \text{ x } 1552.4) > 138.67\,x\,1552.4$$

$$Ratio = \frac{P\,(A_P\ + 0.5\,A_{fs})}{f_s\ .\ A_{fs}} = \frac{216987.0125}{215271.308} = 1.00797 \Rightarrow \text{rounded off: } 1.0$$

Note that $d_{i,max}$ is only valid if the bearing width (L_s) falls completely within the spherical part of the head. This means that nozzles in the spherical part of the domed end with a nominal diameter up to NPS 16" (NB 400) do not require additional reinforcement for internal pressure and thus the nozzle area compensation calculations can be omitted , because it may be assumed that their internal diameters are smaller than the calculated $d_{i,max}$.

APPENDIX

The idea of the area replacement for nozzle is obscure. The design engineer can replace the area cut away by the cross-section of the hole. Then relocate this area around the hole close to the cut out. The area "replaced" is in addition to any thickness required to meet the basic pressure strength of either shell or nozzle. Notice it is an area replacement rather than a volume replacement. The idea is clearly seen by reference to Figure 2. The disposition of the replaced area is important. Although the stress field is increased local to the opening it "dies out" in a relatively short distance so that to be effective the replaced material needs to be close to the edge of the opening. The area replacement method has largely fallen into abeyance since it has been superseded by more sophisticated approaches, but it is still used in ASME VIII - Div.1.

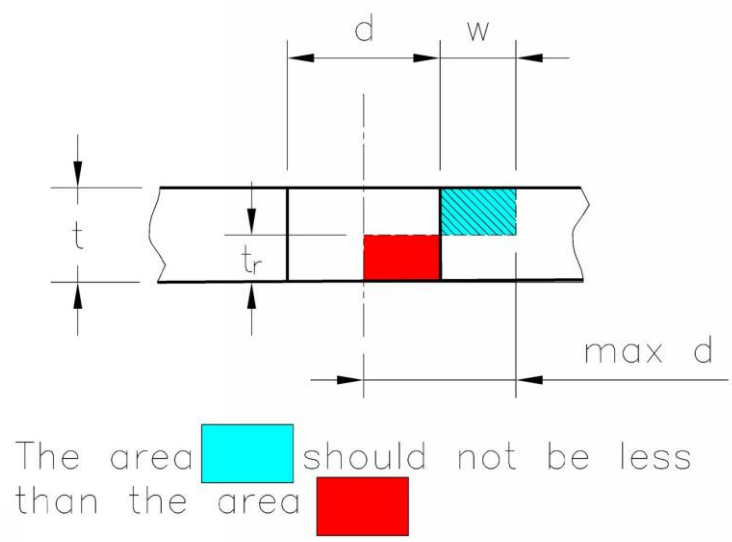

Figure 2: Illustration of "area replacement" of unreinforced opening

The condition that must be met is therefore: $(t - t_r)W \geq (0.5\ d\ .\ t_r)$ with t_r is the thickness calculated by the equation for pressure loading only.

IV. CONCLUSION

The design engineer can benefit from the procedure described in Part II, as it can significantly reduce the number of nozzle compensation calculations to be performed. In addition, it increases the insight into the influence of the size of nozzles on the wall thicknesses of pressure vessels and the criticality of the opening compensation wise.

V. REFERENCES

[1] PD 5500: 2021 + A2: 2022; "Specification for unfired pressure vessels"; (UK)
[2] EN 13445 - Part 3 "Design" : 2021 - "Unfired pressure vessels"; (EU)
[3] ASME BPV - Section VIII - Division 1 (2021) "Rules for construction of pressure vessels" ; (USA)