ANGEL Torispheric Head Design, using (2010 ASME PV Code Section VIII, div. 2, part 4 rules)
CF flange window version NW100 **DRAFT** D. Shuman, LBNL, Apr 15, 2011

These design rules require selecting trial dimensions and iterating to find acceptable stresses. Shown here are final dimensions from repeated iterations.

Torispheric head with multiple ports for sapphire windows in NW100 CF flanges. First step determine the following:

I.D.

$D_i := 1.14\text{m}$

Crown radius (largest size possible without using part 5, design by analysis)

constraints

$L_{cr} := 1.14\text{m}$ $\qquad 0.7 \le \frac{L_{cr}}{D_i} \le 1.0 = 1$ (true when conditional = 1)

Knuckle radius, here chosen to maximize crown, smallest size that gives sufficient pressure capacity after increasing head thickness for reinforcement of nozzles. Use 0.17m otherwise

$r_{kn} := .07\text{m}$ $\qquad \frac{r_{kn}}{D_i} \ge 0.06 = 1$

(c) Step 3 calculate:

thickness, this is an iterated value after going through part 4.5.10.1 (openings) further down in the document

$t_{ts} := 13\text{mm}$ $\qquad 20 \le \frac{L_{cr}}{t_{ts}} \le 2000 = 1$

initial thickness (no nozzle reinforcement) value: 4.9mm for r_{kn}=0.17m; 7mm for r_{kn}=.07m)

$\beta_{th} := \operatorname{acos}\left(\frac{0.5D_i - r_{kn}}{L_{cr} - r_{kn}}\right)$ $\qquad \beta_{th} = 1.085\,\text{rad}$

$\phi_{th} := \frac{\sqrt{L_{cr} \cdot t_{ts}}}{r_{kn}}$ $\qquad \phi_{th} = 1.739\,\text{rad}$

$R_{th} := \frac{0.5D_i - r_{kn}}{\cos(\beta_{th} - \phi_{th})} + r_{kn}$ <--disabled calculation, because conditional-> $\phi_{th} < \beta_{th} = 0$ is false

$R_{th} := 0.5D_i$ <--enabled calculation, because conditional-> $\phi_{th} \ge \beta_{th} = 1$ is true

$R_{th} = 0.57\,\text{m}$

(d) Step 4 compute:

$C_{1ts} := 9.31\left(\frac{r_{kn}}{D_i}\right) - 0.086$ $\qquad$ for $\frac{r_{kn}}{D_i} \le 0.08 = 1$

$C_{1ts} := 0.692\left(\frac{r_{kn}}{D_i}\right) + 0.605$ $\qquad C_{1ts} = 0.486$ $\qquad$ for $\frac{r_{kn}}{D_i} \ge 0.08 = 0$

$$C_{2ts} := 1.25 \qquad \text{for} \quad \frac{r_{kn}}{D_i} \le 0.08 = 1$$

$$C_{2ts} := 1.46 - 2.6\left(\frac{r_{kn}}{D_i}\right) \qquad C_{2ts} = 1.25 \qquad \text{for} \quad \frac{r_{kn}}{D_i} > 0.08 = 0$$

(e) Step 5, internal pressure expected to cause elastic buckling at knuckle

$$P_{eth} := \frac{C_{1ts} \cdot E \cdot t_{ts}^{2}}{C_{2ts} \cdot R_{th} \cdot \left(0.5R_{th} - r_{kn}\right)} \qquad P_{eth} = 547\,\text{bar}$$

(f) Step 6, internal pressure expected to result in maximum stress (S_y) at knuckle

$$C_{3ts} := S_{y\_Ti\_g3} \qquad S_{y\_Ti\_g3} := 55000\text{psi} \quad \text{time independent}$$

$$P_y := \frac{C_{3ts} \cdot t_{ts}}{C_{2ts} \cdot R_{th} \cdot \left(0.5\frac{R_{th}}{r_{kn}} - 1\right)} \qquad P_y = 22\,\text{bar}$$

(g) Step 7

$$G_{th} := \frac{P_{eth}}{P_y} \qquad G_{th} = 24.594$$

$$P_{ck} := \left(\frac{0.77508 \cdot G_{th} - 0.20354 \cdot G_{th}^{2} + 0.019274 \cdot G_{th}^{3}}{1 + 0.19014G_{th} - 0.089534G_{th}^{2} + 0.0093965G_{th}^{3}}\right) \cdot P_y \qquad P_{ck} = 44\,\text{bar}$$

(h) Step 8

$$P_{ak} := \frac{P_{ck}}{1.5} \qquad P_{ak} = 29.645\,\text{bar}$$

(i) Step 9

$$P_{ac} := \frac{2S_{max\_Ti\_g3\_div2} \cdot 1}{\frac{L_{cr}}{t_{ts}} + 0.5} \qquad P_{ac} = 42.6\,\text{bar}$$

(j) Step 10

$P_a := \min(P_{ak}, P_{ac})$ $\qquad P_a = 29.6\,\text{bar}$ $\qquad$ OK, min thickness is 4.9mm (no openings rkn=.17m)

4.5.10.1 Radial Nozzle in formed head

We need to accommodate 76mm dia PMT's, having 64mm photo

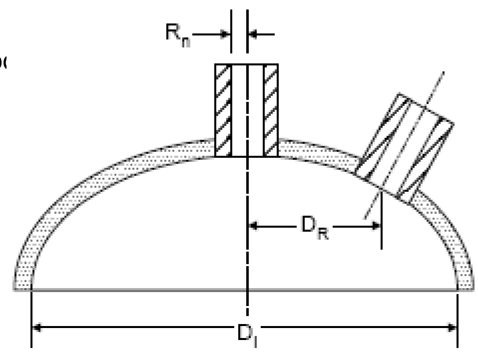


Fig 4.5.9

$R_n := 3.5\text{cm}$

We have no nozzle (flange does not count for reinforcement under div 1 and perhaps div 2

$t_n := 0.01\text{mm}$ (we need a non zero value for further calculations)

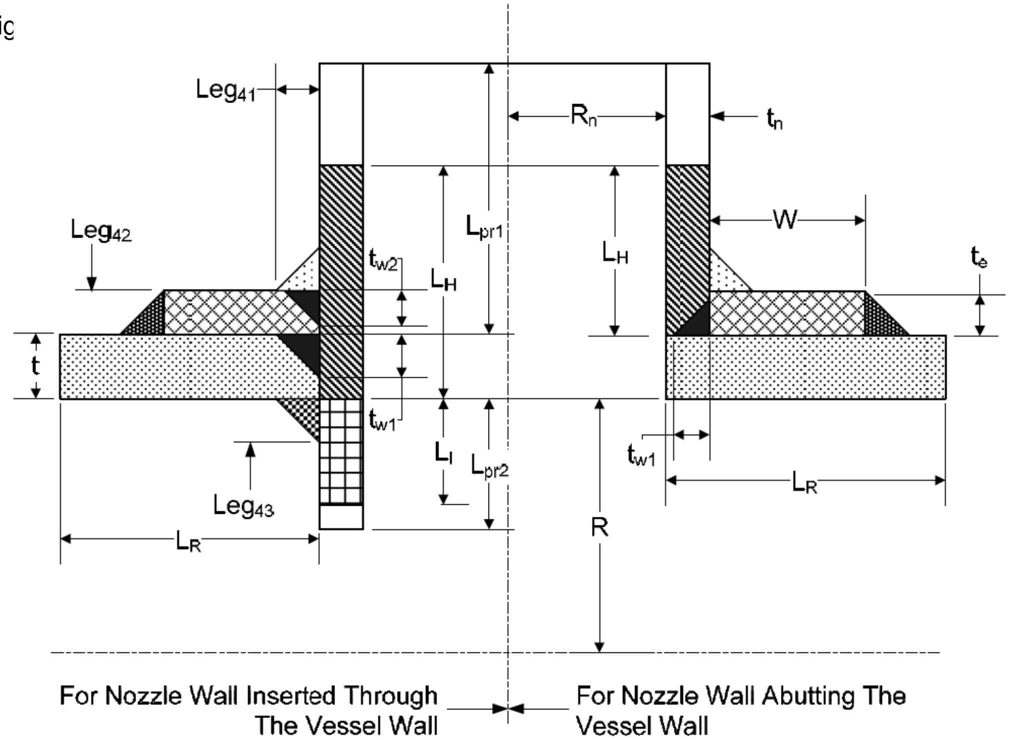
Considering nozzle as separate from head, to obtain a trial thickness

$$t_{n\_int\_min} := \frac{MAWP_{pv} \cdot (R_n)}{S_{max\_Ti\_g3} \cdot E_w - 0.6 \cdot MAWP_{pv}} \qquad t_{n\_int\_min} = 0.429\,\text{mm}$$

However, the nozzle not only must withstand internal pressure, but must also help to carry head stresses across the openings made for them.

4.5.10.1 Procedure for Radial Nozzle in a Spherical or Formed head

Fig



a) Step 1

$R_{eff} := L_{cr}$ $\qquad R_{eff} = 1.14\,\text{m}$ (4.5.64)

b) Step 2- limit of reinforcement along vessel wall

sec VIII- div. 2 sec 4.3.9.2(d) states that drilled holes for nozzle attachment must be located outside reinforcement area. for NW100 flange (Rayotek #7). This will likely limit the reinforcement area, if not limited by other equations. sec VIII- div 1 rules (UG-40(e) state that flanges attached by studs do not count for reinforcement, even for that part located within the area of reinforcement. sec VII-div 2 rules do not explicitly state this (insofar as I have found), but is is clear, by implication, that this holds as well. Plus, I would not rely on the sapphire window to carry any pressure stresses; it is not a material allowed under the ASME PV rules sec II part D.

NW100 flange dimensions:

$BC := 13.02\text{cm} \qquad BH := 8.4\text{mm} \qquad OD := 15.24\text{cm}$

Limit of reinforcement along vessel wall:

$L_{R1a} := 0.5 \cdot BC - \left(R_n + 0.5BH\right) \qquad L_{R1a} = 2.59\,\text{cm}$

Though this is likely the minimmum, there are other limits to consider. We must first determine the various D_i that will be present (see fig 4.5.9 above). We can use "vectors" in mathCAD to perform parallel calculations. Three "rings" of flanges will fit if spaced at 8 degree spacing along radius of crown:

$d_s := L_{cr} \cdot 8\deg \qquad d_s = 15.917\,\text{cm}$ check --> $OD = 15.24\,\text{cm}$

Then

$$D_R := \begin{pmatrix} 0 \\ \sin(8deg) \\ \sin(16deg) \\ \sin(24deg) \end{pmatrix} \cdot L_{cr} \qquad D_R = \begin{pmatrix} 0 \\ 15.866 \\ 31.423 \\ 46.368 \end{pmatrix} cm$$

Possible limits of reinforcment:

$$L_{R1} := 0.5 \cdot D_i - \left(D_R + R_n + t_n\right) \qquad L_{R1} = \begin{pmatrix} 53.499 \\ 37.633 \\ 22.076 \\ 7.131 \end{pmatrix} cm \tag{4.5.67}$$

<---as we get toward knuckle, limits decrease

$$\sqrt{R_{eff} \cdot t_{ts}} = 12.174\,cm \qquad 2R_n = 7\,cm$$

$$L_{R2} := \min\left(\sqrt{R_{eff} \cdot t_{ts}}, 2R_n\right) \qquad L_{R2} = 7\,cm \tag{4.5.67}$$

Final Limit of reinforcement along vessel wall:

$$L_R := \min\left(L_{R1}, L_{R2}, L_{R1a}\right) \qquad L_R = 2.59\,cm \tag{4.5.68}$$

c) Step 3- limit of reinforcement along nozzle wall projecting outside vessel surface wall.

We have no pad reinforcement, and no nozzle so:

$$t_e := 0mm \qquad L_{pr1} := 0cm \qquad L_{pr2} := 0cm$$

$$L_H := \min\left[\left(t_{ts} + t_e + F_p \cdot \sqrt{R_n \cdot t_n}\right), L_{pr1} + t_{ts}\right] \tag{4.5.73}$$

where:

$$X_o := D_R + R_n + t_n \qquad X_o = \begin{pmatrix} 0.035 \\ 0.194 \\ 0.349 \\ 0.499 \end{pmatrix} m \tag{4.5.79}$$

$$C_p := e^{\frac{0.35D_i - X_o}{8t_{ts}}} \qquad C_p = \begin{pmatrix} 33.112 \\ 7.202 \\ 1.614 \\ 0.383 \end{pmatrix} \tag{4.5.78}$$

$$C_n := \min\left[\left(\frac{t_{ts} + t_e}{t_n}\right)^{0.35}, 1.0\right] \qquad C_n = 1 \tag{4.5.81}$$

$$F_p := \min\left(C_n, C_p\right) \qquad F_p = 0.383 \tag{4.5.80}$$

$$L_H := \min\left[\left(t_{ts} + t_e + F_p \cdot \sqrt{R_n \cdot t_n}\right), L_{pr1} + t_{ts}\right] \qquad L_H = 1.3\,cm \tag{4.5.73}$$

<--we have only the wall thickness

d) Step 4- limit of reinforcement along nozzle wall projecting inside vessel surface wall, if applicable

$$L_I := \min\left(F_p \cdot \sqrt{R_n \cdot t_n}, L_{pr2}\right) \qquad L_I = 0\,cm \tag{4.5.82}$$

e) Step 5- determine total available area near nozzle opening

(material strength ratios)--> $f_{rn} := 1$ $f_{rp} := 1$ (4.5.30) (4.5.31)

$$A_T := A_1 + f_{rn}(A_2 + A_3) + A_{41} + A_{42} + A_{43} + f_{rp} \cdot A_5 \quad (4.5.83)$$

$A_1 := t_{ts} \cdot L_R$ $A_1 = 3.367\,cm^2$ (4.5.84)

$A_2 := t_n \cdot L_H$ $A_2 = 1.3 \times 10^{-3}\,cm^2$ (4.5.86)

$A_3 := t_n \cdot L_I$ $A_3 = 0\,cm^2$ (4.5.83)

$L_{41} := 0cm$

$A_{41} := 0.5L_{41}{}^2$ $A_{41} = 0\,cm^2$ (4.5.88)

$L_{42} := 0cm$

$A_{42} := 0.5L_{42}{}^2$ $A_{42} = 0\,cm^2$ (4.5.89)

$L_{43} := 0cm$

$A_{43} := 0.5L_{43}{}^2$ $A_{43} = 0\,cm^2$ (4.5.90)

$t_e = 0\,cm$

$A_5 := 0cm^2$ (4.5.94)

$$A_T := A_1 + f_{rn} \cdot (A_2 + A_3) + A_{41} + A_{42} + A_{43} + f_{rp} \cdot A_5 \qquad A_T = 3.368\,cm^2 \quad (4.5.83)$$

f) Step 6 determine applicable forces

$$t_{eff} := t_{ts} \cdot \left(\frac{t_{ts} \cdot L_R + A_5 \cdot f_{rp}}{t_{ts} \cdot L_R} \right) \qquad t_{eff} = 13\,mm \quad (4.5.100)$$

$$R_{xn} := \frac{t_n}{\ln\left(\frac{R_n + t_n}{R_n}\right)} \quad R_{xn} = 3.5\,cm \qquad R_{xs} := \frac{t_{eff}}{\ln\left(\frac{R_{eff} + t_{eff}}{R_{eff}}\right)} \quad R_{xs} = 1.146\,m \quad (4.5.98)$$

$$f_N := P \cdot R_{xn} \cdot (L_H - t_{ts}) \qquad f_N = 0\,N \quad (4.5.95)$$

$$f_S := \frac{P \cdot R_{xs} \cdot (L_R + t_n)}{2} \qquad f_S = 2.318 \times 10^4\,N \quad (4.5.96)$$

$R_{nc} := R_n$ (radius along chord= R_n for radial nozzles)

$$f_T := \frac{P \cdot R_{xs} \cdot R_{nc}}{2} \qquad f_T = 3.132 \times 10^4\,N \quad (4.5.97)$$

g) Step 7 determine effective thickness for nozzles in spherical, ellipsoidal, or torispherical heads

$t_{eff} = 1.3\,cm$ same formula as above in step 6 (4.5.100)

h) Step 8 Determine avg. local primary membrane stress and general primary membrane stress at nozzle intersection

$$\sigma_{avg} := \frac{f_N + f_S + f_T}{A_T} \qquad \sigma_{avg} = 161.8\,MPa \quad (4.5.101)$$

$$\sigma_{circ} := \frac{P \cdot R_{xs}}{2t_{eff}} \qquad \sigma_{circ} = 68.8\,\text{MPa} \tag{4.5.102}$$

l) Step 9 Determine maximum local primary membrane stress

$$P_L := \max\left[\left(2\sigma_{avg} - \sigma_{circ}\right), \sigma_{circ}\right] \qquad P_L = 254.8\,\text{MPa} \tag{4.5.103}$$

$$S_{max\_Ti\_g3\_div2} = 190.3\,\text{MPa} \qquad E_w = 1$$

$$S_{allow} := 1.5 S_{max\_Ti\_g3\_div2} \cdot E_w \qquad S_{allow} = 285.4\,\text{MPa} \tag{4.5.43}$$

j) Step 10 Maximum local primary membrane stress must be less than the allowable stress

$$P_L \le S_{allow} = 1 \tag{4.5.104}$$

k) Determine max allowable working pressure of the nozzle

$$A_p := R_{xn} \cdot \left(L_H - t_{ts}\right) + \frac{R_{xs} \cdot \left(L_R + t_n + R_{nc}\right)}{2} \qquad A_p = 349.2\,\text{cm}^2 \tag{4.5.108}$$

$$P_{max1} := \frac{S_{allow}}{\left(\frac{2A_p}{A_T} - \frac{R_{xs}}{2t_{eff}}\right)} \qquad P_{max1} = 17.3\,\text{bar} \tag{4.5.105}$$

$$S := S_{max\_Ti\_g3\_div2} \qquad S = 190.3\,\text{MPa}$$

$$P_{max2} := 2 \cdot S \cdot \left(\frac{t_{ts}}{R_{xs}}\right) \qquad P_{max2} = 42.6\,\text{bar} \tag{4.5.106}$$

$$P_{max} := \min\left(P_{max1}, P_{max2}\right) \qquad P_{max} = 17.3\,\text{bar} \tag{4.5.107}$$

Conclusion: Sapphire or quartz windows in NW100 CF flanges may be used in a Ti ASME grade 3 torispheric head, 1.14cm ID, provided head thickness is increased from 7mm (no holes) to 13mm. Flange stud holes may be drilled no deeper than 10mm, giving just over 1 diameter of thread engagement. This should be sufficient for sealing purposes. Similar flanges can be used on outside of head, provided stud holes are staggered from inside holes. Head thickness of 13mm is required at the minimum thickness, after machining for flanges; it is not a stock material thickness, which may be 14mm or more.