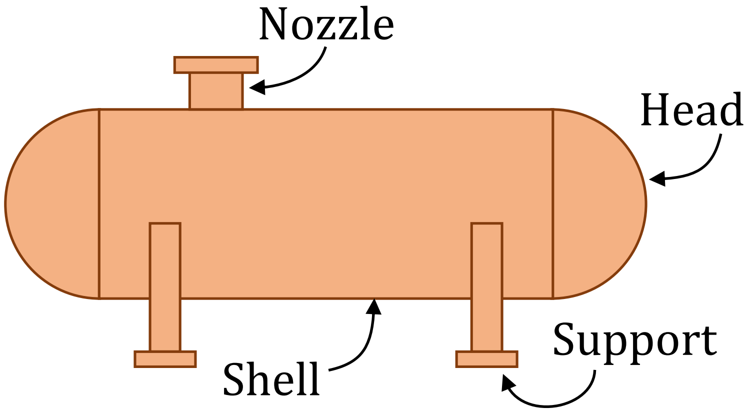
Pressure Vessels – Heads

Jose V Parambil

Components of a Pressure Vessel

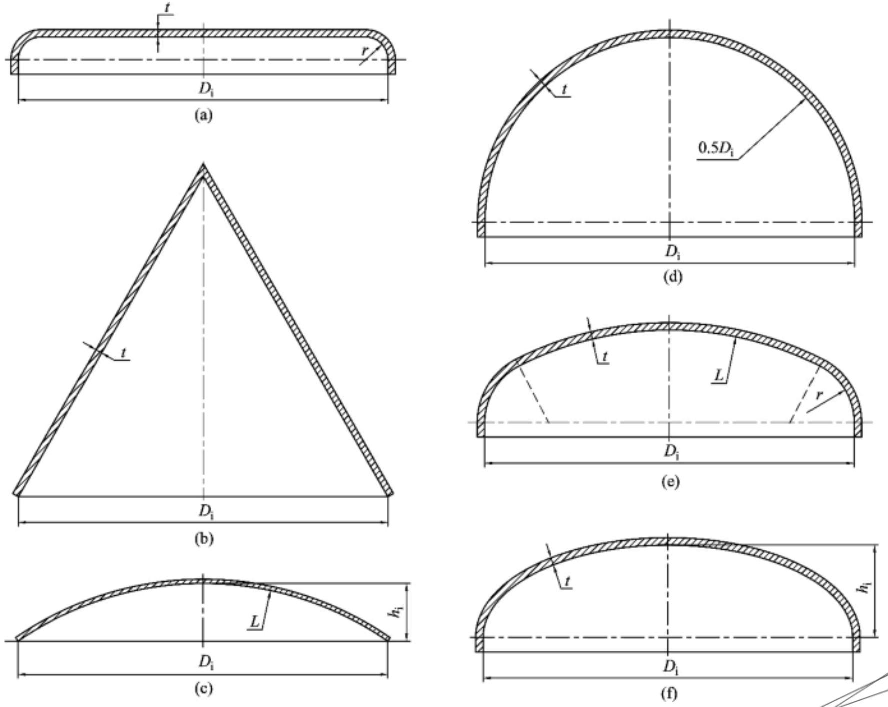


- Shell
  - Consists of plates welded together about an axis.
  - Cylindrical, conical, spherical.
- Head
  - Covers the ends of the vessel.
- Nozzle
  - Cylindrical components for connecting other components to the shell.
- Supports
  - Takes the weight off the pressure vessel; provide rigidity.

Heads and Closures

- Types:
  - Flat head
  - Standard dished or Torispherical head
  - Ellipsoidal head
  - Hemispherical head
  - Conical or toriconical head

Head shape variants: **a** flanged flat, **b** conical, **c** shallow spherical, **d** hemispherical, **e** torispherical, **f** ellipsoidal



(Zheng, J., Li, K. (2021). Introduction. In: New Theory and Design of Ellipsoidal Heads for Pressure Vessels. Springer, Singapore. https://doi.org/10.1007/978-981-16-0467-6_1)

Flat Heads

- Generally used for:
  - Manholes in low pressure vessels.
  - Blind/close flanged openings.
  - Small diameter vessels operating at low pressure.

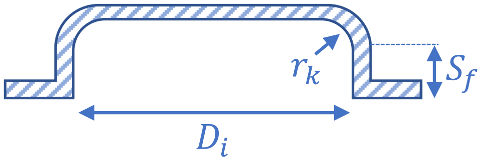
- Not suitable for large vessels, high pressure, high temperature, and large openings.

- High discontinuity of stress at the junction of head and shell.

- Simplest and cheapest to fabricate; highest material cost.

Flanged-only heads

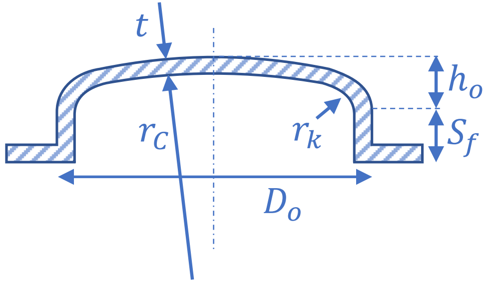
- Flat heads with a gradual change in the shape at the corner.
  - Reduces local stress.
- Economical to fabricate and lower thickness than flat head.
- Suitable for storing liquids with low vapour pressure (fuels)



(https://www.sanitaryvalvefittings.com/pressure-manways/)

Flanged Dished Heads

- Consists of Knuckle radius (r_k) and Crown radius (r_c).
  - $\frac{r_k}{r_c} > 0.06$ to avoid buckling.
  - $r_k \geq 3 \times t$
  - As per IS, $0.1 \times D_i < r_k < D_o$

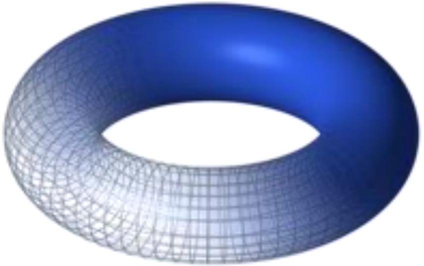


- When $r_c > D_o$, called as Flanged and Shallow Dished Head.
- When $r_c \leq D_o$, called as Flanged and Standard Dished Head.

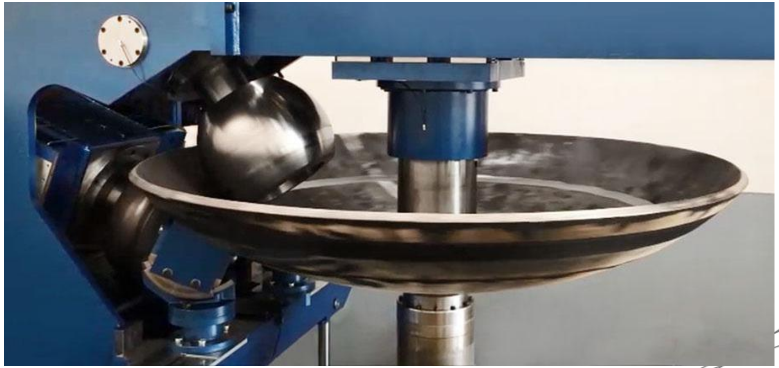
- Local stresses at the inside corners are reduced.

Flanged Dished Heads

- Used for vertical process vessel with low pressure or horizontal cylindrical storage tanks for volatile fluids (naptha, gasoline).
  - Pressure rating higher than flanged-only heads and flat heads.
  - 0.1-1.5 MN/m^2.



Torus shape



(https://en.wikipedia.org/wiki/Toroid; https://www.thefabricator.com/thefabricator/article/bending/dished-end-manufacturing-for-beginners)

Elliptical Dished Heads

- Preferred for high pressure vessels (> 1.5 MN/m^2).
- Formed on dies with diametrical cross-section of an ellipse.
- Mostly retain 2:1 ratio of major to minor axis.
- More uniformly distributed stress than torispherical heads due to smoother change in radius.
- Strength similar to cylindrical shell of same diameter and thickness.

Hemispherical Heads

- Strongest design for a given thickness.
  - Only half thickness is needed w.r.t. ellipsoidal dished head or cylindrical shell for same diameter and pressure
- Most expensive to manufacture; but least material cost.
  - Small sizes prepared by spinning or forming.
  - Large sizes may require welding pressed plate sections or forging.

(https://www.glmhead.com/hemispherical-dished-ends-product/)

Conical Heads and Reducers

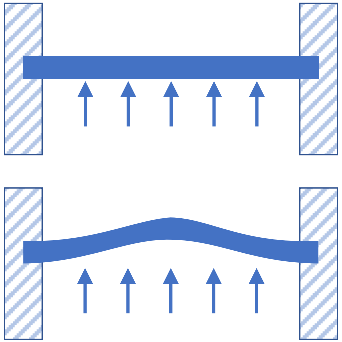
- Generally used as bottom of process equipment that are under pressure.
  - Evaporators, spray driers, crystallizers, settling tanks, silos.
- Can act as reducer for smooth transition between two vessels of different diameter.
- Require knuckle radius to reduce stress concentration especially when apex angle is above 60°.

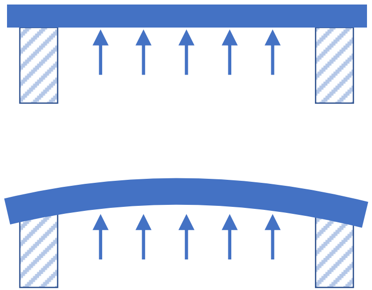
(https://www.gianesiedilio.it/conical-bottom-head-vessels)

Design of Flat Heads (1)

- Based on deflection of a uniformly loaded circular plate.

- 2 conditions:
  - Clamped edges (not free to rotate, strong joint)
  - Simply supported or unstayed circular heads (weak joint)





Design of Flat Heads (2)

- Clamped Edges
  - Maximum deflection at the center; maximum stress at clamped edges (bending moment)

$$\sigma_{max} = \frac{3}{16}\frac{pD_{eff}^2}{t^2}$$

$D_{eff} \rightarrow$ effective diameter

- Simply supported edges
  - Maximum stress at the center of the plate (bending moment)

$$\sigma_{max} = \frac{3(3+\nu)}{32}\frac{pD_{eff}^2}{t^2}$$

Design of Flat Heads (3)

General expression for thickness of flat heads: $t = C D_{eff} \sqrt{\frac{p}{f}}$

C → shape factor; constant based on edge support.

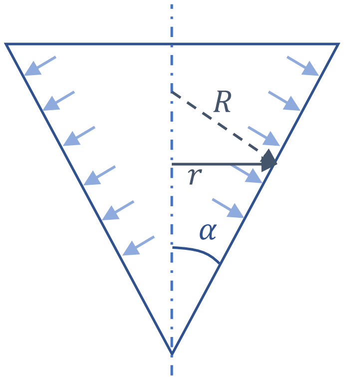
Condition	C value	D_{eff}
Flanged flat heads butt welded to the vessel	0.45	D_i
Plates welded to the inside of the vessel	≥ 0.55	D_i
Plates welded to the end of the shell	0.7	D_i
Plates welded to the end of the shell with additional fillet weld on the inside	≥ 0.55	D_i
Covers riveted or bolted with a full face gasket to shells or flanges	0.42	D (diameter of bolt circle)

Design of Conical Heads (1)

- Gradual reduction in the diameter.
  - Generally joined with the shell with a knuckle radius.

- Stress analysis comparable with a cylinder where diameter changes continuously.
  - Radius of curvature (for pressure calculation) is different from the radius of hoop/cone at specific point.

- Cone of radius 'r' will experience the same stress effect as experience by an equivalent cylinder of radius $\left[\frac{r}{\cos(\alpha)}\right]$.



$$Cos(\alpha) = \frac{r}{R}$$

Design of Conical Heads (2)

For thick shell cylinder (IS: 2825-1969), $$t = \frac{PD_i}{2fJ - P} = \frac{PD_o}{2fJ + P}$$

Hence, for conical head, $$t = \frac{PD_k}{2fJ - P}\frac{1}{\cos(\alpha)}$$

Where D_k is the inner dia. of cone at any position.

The above equation is applicable for cone thickness in region away from the knuckle junction.

Regions in a conical head:

a) Region near the knuckle.
b) Region away from the knuckle.

Design of Conical Heads (3)

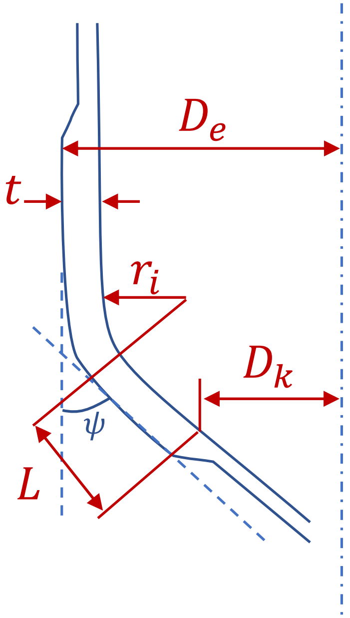
Thickness of the cylinder and conical section within distance L from the junction is determined by,

$$t = \frac{pD_eC}{2fJ}$$

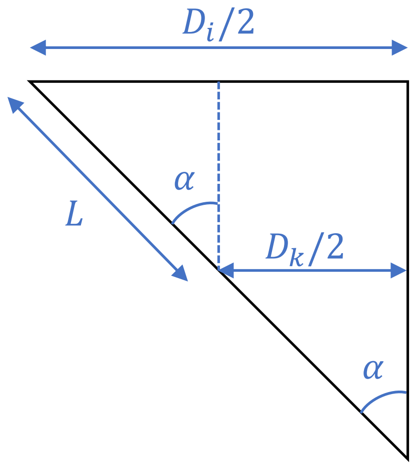
$$L < 0.5\sqrt{\frac{D_e t}{\cos(\psi)}}$$

$$D_e \approx D_o(shell)$$

$\psi \downarrow r_i/D_e \rightarrow$	**0.01**	**0.02**	**0.03**	**0.04**	**0.08**
10 °	0.70	0.65	0.60	0.60	0.55
20 °	1.00	0.90	0.85	0.80	0.65
30 °	1.35	1.20	1.10	1.00	0.85
45 °	2.05	1.85	1.65	1.50	1.20
60 °	3.20	2.82	2.55	2.35	1.75
75 °	6.80	5.85	5.35	4.75	3.50



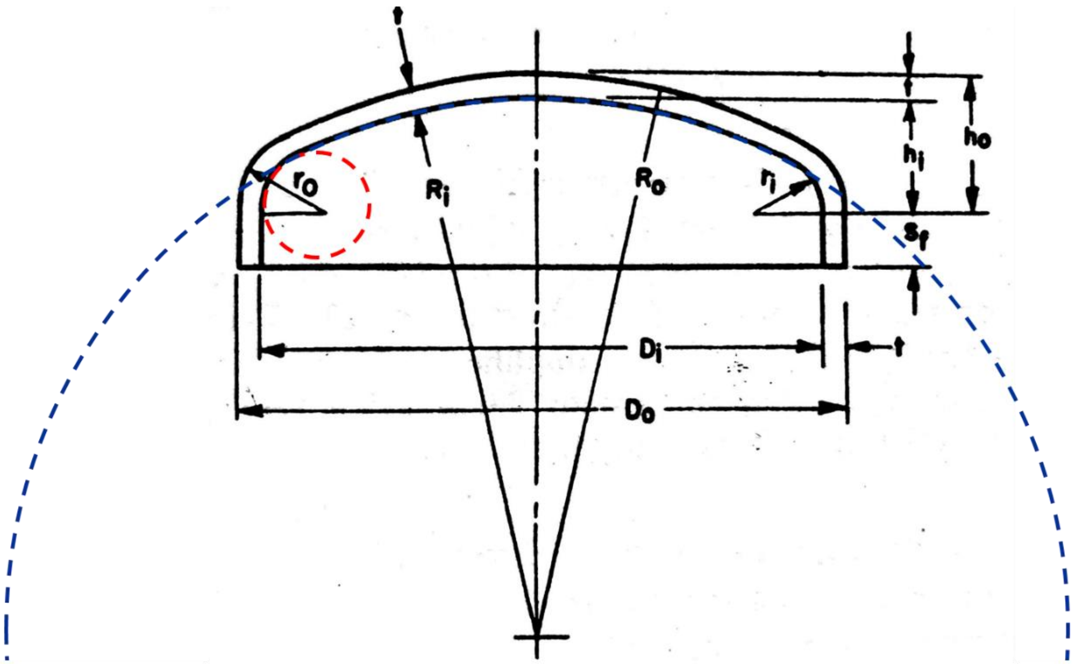
Design of Conical Heads (4)



Torispherical and Ellipsoidal Dished Heads (1)

- 3 distinctive parts:
  - Central dishing
  - Corner torus
  - End straight flange

- 2 junctions of discontinuity
  - Knuckle and crown (dish)
  - Knuckle and straight flange



Torispherical and Ellipsoidal Dished Heads (2)

- Stress concentration is maximum in the torus section.
  - Thickness calculated based on shape factor (C): $t = \frac{pD_oC}{2fJ}$
- Value of C depends on h_E/D_o and t/D_o for head without any openings or with reinforced openings.
- h_E is the effective height of head without straight flange section and is defined as:

$$h_E = \min\left(h_o, \frac{D_o^2}{4R_o}, \sqrt{\frac{D_o r_o}{2}}\right)$$

$$h_o = R_0 - \sqrt{\left(R_o - \frac{D_o}{2}\right)\left(R_o + \frac{D_o}{2} - 2r_o\right)}$$

Torispherical and Ellipsoidal Dished Heads (3)

- Limiting value of h_E/D_o is 0.5 (hemispherical).
  - For a 2:1 ellipsoidal head, $h_E = h_o = 0.25D_o$.

	t/D_o				
h_E/D_o	0.002	0.005	0.01	0.02	0.04
0.15	4.55	2.66	2.15	1.95	1.75
0.20	2.30	1.70	1.45	1.37	1.32
0.25	1.38	1.14	1.00	1.00	1.00
0.30	0.92	0.77	0.77	0.77	0.77
0.40	0.59	0.59	0.59	0.59	0.59
0.50	0.55	0.55	0.55	0.55	0.55

[8] AD-MERKBLAETTER, Beuth-Vertrieb GMBH, Berlin.

Torispherical and Ellipsoidal Dished Heads (4)

- Value of C depends on h_E/D_o and $\frac{d}{\sqrt{tD_o}}$ for head <u>with unreinforced openings</u>.
  - *'d'* is diameter of the largest uncompensated opening in the head.

	$d/\sqrt{t\,D_o}$					
h_E/D_o	0.5	1.0	2.0	3.0	4.0	5.0
0.15	1.67	1.86	2.15	2.65	3.1C	3.60
0.20	1.28	1.45	1.85	2.30	2.75	3.25
0.25	1.00	1.15	1.60	2.05	2.50	2.95
0.30	0.83	1.00	1.45	1.88	2.28	2.70
0.50	0.60	0.80	1.10	1.50	1.85	2.15

Note : Values can be interpolated.

Torispherical and Ellipsoidal Dished Heads (5)

- For torus shapes created by forming: 6% in ‘t’
- Blank diameter
  - diameter of the plate from which the head can be formed

$$Blank\ diameter = D_o + \frac{D_o}{42} + \frac{2}{3} r_i + 2S_f \qquad (t \le 25\ mm)$$
$$= D_o + \frac{D_o}{42} + \frac{2}{3} r_i + 2S_f + t \qquad (t > 25\ mm)$$

- Volume contained within head:

$$V = 0.0847\ D_i^3 \quad (when\ r_i = 0.06\ D_i)$$
$$= 0.1313\ D_i^3 \quad (for\ 2{:}1\ ellipsoidal\ or\ deep\ dished\ head)$$

Numerical 4.1

A process vessel is to be designed for maximum operating pressure of 500 kN/m^2. The vessel has the nominal diameter of 1.2 m. The vessel is made of IS:2002-1962 Grade 2B steel having allowable design stress value of 118 MN/m^2 at working temperature. 2 mm is the recommended corrosion allowance for the expected life span of the vessel. This is a class 2 vessel as per Indian Standards, stipulating weld joint efficiency of 0.85.

Assuming that the material of construction is same for both head and shell, calculate the thickness of a flanged flat head butt welded to the vessel.

Numerical 4.2

For the pressure vessel mentioned in Numerical 4.1, calculate the thickness of the head if a conical head with half-apex angle of 30 ° is used.

Numerical 4.3

For the pressure vessel mentioned in Numerical 4.1, calculate the thickness of plate required to fabricate a standard dished head with no uncompensated opening. What should be the plate diameter if the head is to be made from a single sheet? Given, $R_i = D_o$, $r_o = 0.06D_o$, $S_f = 40$ mm.

Numerical 4.4

For the pressure vessel mentioned in Numerical 4.1, a 10 mm thick 2:1 ellipsoidal head with uncompensated opening is to be fabricated. What maximum diameter opening will be permissible?