Ex-2 Kettle Type Reboiler

It is required to design a kettle-type reboiler to vaporize 5000 kg/h of n-butane at 5.84 bar. The minimum temperature of feed will be 0°C. Steam is available at 1.7 bar(g).

Physical properties of n-butane at 5.84 bar:

Boiling point = 56.1°C
Latent heat = 326 kJ/kg
Mean specific heat of liquid = 2.51 kJ/kg.°C

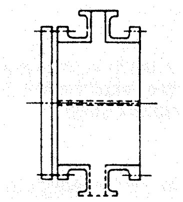
Critical pressure of n-butane = 38 bar
Saturation temperature of steam at 1.7 bar (g) = 115.2°C

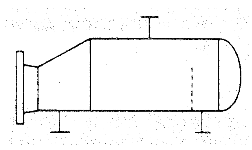
Overall heat transfer coefficient (U) for the reboiler, for the initial estimate can be taken as 1000 W/m^2.°C

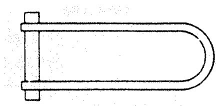
Take steam condensing coefficient as 8000 W/m^2.°C, fouling coefficient 5000 W/m^2.°C; butane fouling coefficient, essentially clean, 10,000 W/m^2.°C.
Tube material will be plain carbon steel, k_w = 55 W/m.°C

A kettle type reboiler of following specification is available:
TEMA code: AKU
Total number of U tubes: 26 (52 tube holes)
Length of one U tube: 4.8 m (average length of tubular section = 2.4 m)
Tube OD: 30 mm; ID: 25 mm, with pitch of 1.5 times the OD of tube, square pitch
Tube bundle diameter: 420 mm
Height of weir: 500 mm
OD of outer shell: 840 mm, thickness: 12 mm

(a) Find whether the above design is adequate, by making suitable calculations.
(b) Also check whether the thickness of heat exchanger shell is sufficient, including a corrosion allowance of 3 mm.
(allowable stress = 98 N/mm^2; joint efficiency = 85%)
(c) Draw to scale the above reboiler with suitable views.


Front end: A


Shell: K


Rear end: U

TEMA code explanation

Calculations:

Take steam condensing coefficient as 8000 W/m^2°C, fouling coefficient 5000 W/m^2°C; butane fouling coefficient, essentially clean, 10,000 W/m^2°C.

Tube material will be plain carbon steel, $k_w = 55$ W/m°C

Heat loads:

$$\text{sensible heat (maximum)} = (56.1 - 0)2.51 = 140.8 \text{ kJ/kg}$$

$$\text{total heat load} = (140.8 + 326) \times \frac{5000}{3600} = 648.3 \text{ kW},$$

add 5 per cent for heat losses

$$\text{maximum heat load (duty)} = 1.05 \times 648.3$$

$$= 681 \text{ kW}$$

From Figure 12.1 assume $U = 1000$ W/m^2°C.

Mean temperature difference; both sides isothermal, steam saturation temperature at 1.7 bar = 115.2°C

$$\Delta T_m = 115.2 - 56.1 = 59.1°\text{C}$$

$$\text{Area (outside) required} = \frac{681 \times 10^3}{1000 \times 59.1} = 11.5 \text{ m}^2$$

Select 25 mm i.d., 30 mm o.d. plain U-tubes,

Nominal length 4.8 m (one U-tube)

$$\text{Number of U tubes} = \frac{11.5}{(30 \times 10^{-3})\pi 4.8} = 25$$

Use square pitch arrangement, pitch = 1.5 × tube o.d.

$$= 1.5 \times 30 = 45 \text{ mm}$$

Draw a tube layout diagram, take minimum bend radius

$$1.5 \times \text{tube o.d.} = 45 \text{ mm}$$

Proposed layout gives 26 U-tubes, tube outer limit diameter 420 mm.

Boiling coefficient

Use Mostinski's equation:

heat flux, based on estimated area,

$$q = \frac{681}{11.5} = 59.2 \text{ kW/m}^2$$

$$h_{nb} = 0.104(38)^{0.69}(59.2 \times 10^3)^{0.7}\left[1.8\left(\frac{5.84}{38}\right)^{0.17} + 4\left(\frac{5.84}{38}\right)^{1.2} + 10\left(\frac{5.84}{38}\right)^{10}\right]$$

$$= 4855 \text{ W/m}^2\,^\circ\text{C}$$

Take steam condensing coefficient as 8000 W/m^2°C, fouling coefficient 5000 W/m^2°C; butane fouling coefficient, essentially clean, 10,000 W/m^2°C.

Tube material will be plain carbon steel, $k_w = 55$ W/m°C

$$\frac{1}{U_o} = \frac{1}{4855} + \frac{1}{10{,}000} + \frac{30 \times 10^{-3} \ln \frac{30}{25}}{2 \times 55} + \frac{30}{25}\left(\frac{1}{5000} + \frac{1}{8000}\right)$$

$$U_o = \underline{\underline{1341 \text{ W/m}^2\,^\circ\text{C}}}$$

Close enough to original estimate of 1000 W/m^2°C for the design to stand.

Check maximum allowable heat flux. Use modified Zuber equation.

Surface tension (estimated) = 9.7×10^{-3} N/m

$$\rho_L = 550 \text{ kg/m}^3$$

$$\rho_v = \frac{58}{22.4} \times \frac{273}{(273 + 56)} \times 5.84 = 12.6 \text{ kg/m}^3$$

$$N_t = 52$$

For square arrangement $K_b = 0.44$

$$q_c = 0.44 \times 1.5 \times \frac{326 \times 10^3}{\sqrt{52}}[9.7 \times 10^{-3} \times 9.81(550 - 12.6)12.6^2]^{0.25} \quad (12.74)$$

$$= 283{,}224 \text{ W/m}^2$$

$$= 280 \text{ kW/m}^2$$

Applying a factor of 0.7, maximum flux should not exceed $280 \times 0.7 = 196$ kW/m^2. Actual flux of 59.2 kW/m^2 is well below maximum allowable.

Layout

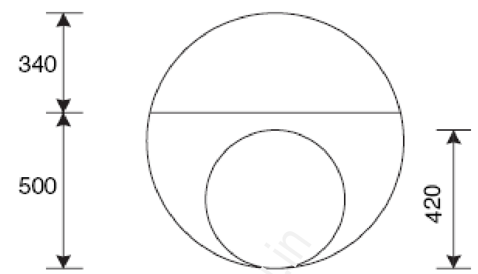
From tube sheet layout $D_b = 420$ mm.

Take shell diameter as twice bundle diameter

$$D_s = 2 \times 420 = 840 \text{ mm.}$$

Take liquid level as 500 mm from base,

$$\text{freeboard} = 840 - 500 = 340 \text{ mm, satisfactory.}$$



From sketch, width at liquid level = 0.8 m.
Surface area of liquid = $0.8 \times 2.4 = 1.9$ m^2.

$$\text{Vapour velocity at surface} = \frac{5000}{3600} \times \frac{1}{12.6} \times \frac{1}{1.9} = \underline{\underline{0.06 \text{ m/s}}}$$

Maximum allowable velocity

$$\hat{u}_v = 0.2 \left[\frac{550 - 12.6}{12.6}\right]^{1/2} = \underline{\underline{1.3 \text{ m/s}}}$$

so actual velocity is well below maximum allowable velocity. A smaller shell diameter could be considered.

Thickness of shell:

$$t = \frac{pD}{2fJ} + C$$

Where p = design pressure = 1.1 x operating pressure = 1.1 x 5.84 = 6.424 Bar

1 Bar = 1.01325 x 10^5 N/m^2 = 1.01325 x 10 N/cm^2 = 1.01325 x 10^{-1} N/mm^2

Therefore, p = 6.424 x 1.01325 x 10^{-1} N/mm^2 = 0.651 N/mm^2

t = 0.651 x 840 / (2 x 98 x 0.85) + 3 = **6.3 mm**

Required thickness = 6.3 mm; Available thickness = 12 mm

Hence the thickness of the shell is satisfactory.