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Layout

Input values:	*1.234*	or	1.234
Calculated values:	***1.234***	or	**1.234**
Critical values:	*1.234*	or	1.234
Estimated values:	*1.234*	or	1.234

Thermal and hydraulic design of shell and tube heat exchangers

		Tube-side			Shell-side	
Medium		Water			Water	
Mass flow	m_i	20	kg/s	m_a	12.15	kg/s
Volume flow	V_i	73.63	m³/h	V_a	44.01	m³/h
Inlet pressure (abs.)	P_i	4	bar	P_a	3	bar
Inlet temperature	ϑe_i	80	°C	ϑe_a	20	°C
Outlet temperature	ϑa_i	60	°C	ϑa_a	53	°C
Mean temperature	ϑm_i	70	°C	ϑm_a	36.5	°C
Actual						
Inlet temperature	ϑe_i	80	°C	ϑe_a	20	°C
Outlet temperature	ϑa_i	59.32	°C	ϑa_a	54.12	°C
Heat duty	Q_i	-1675	kW	Q_a	1675	kW
Heat loss				Qv_a	0	kW
Fouling resistance	f_i	0	m²·K/W	f_a	0	m²·K/W

Geometry

From tubesheet library

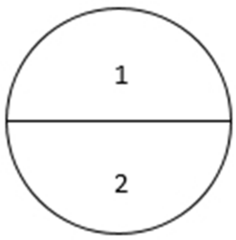
Installation position: Horizontal

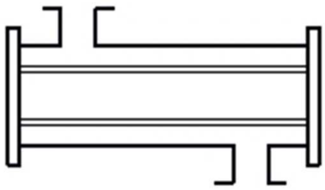
Tube-side	Shell-side
Bare tubes	Bare tubes
Straight tubes with fixed tubesheets	Segmental baffles

Shell outside diameter	D_a	406.4	mm	Shell wall thickness	s	6.3	mm
Shell inside diameter	D_i	393.8	mm				
Bundle-to-shell clearance		13.18	mm	Min. bundle-to-shell clearance		12	mm
Tube outside diameter	d_a	20	mm	Tube wall thickness	s_i	2	mm
Tube inside diameter	d_i	16	mm				
Tube pitch (transverse)	s_1	26	mm	Tube pitch (longitudinal)	s_2	22.52	mm
Pitch angle	Φ	60	°				
Tube lane width (horizontal)	b_h	32	mm				
Central baffle spacing		110	mm	Number of baffles / pass		24	
Inlet baffle spacing		235	mm	Baffle diameter		390.8	mm
Baffle borehole diameter		20.8	mm	Baffle cut in % of shell ID		22	%
Number of sealing strips pairs		0		Baffle thickness		4	mm

Tube material		Stainless steel
Thermal conductivity of tube material	λ	15 W/(m·K)

Number of tube-side passes	2
Number of shell-side passes	1
Number of serial heat exchangers	1





Evaluation

		Required			Final		Overdesign	
Heat transfer area	A	26.57	m²	Aa	28.27	m²	6.41	%
Tube length between the tubesheets	l	2819	mm	la	3000	mm		

Results

Number of tubes	N	150	
Heat transfer coefficient (inside)	α_i	**9209**	W/(m²·K)
Heat transfer coefficient (outside)	α_a	**5784**	W/(m²·K)
Overall heat transfer coefficient	k	**2186**	W/(m²·K)
Logarithmic mean temperature diff. LMTD	$\Delta\vartheta$	**33.08**	K
FN Factor (Correction factor for LMTD)	FN	**0.8717**	
Log. mean temperature diff. (corrected) CLMTD	$\Delta\vartheta_c$	**28.83**	K
Total fouling resistance	f	**0**	m²·K/W

Tube-side

Velocity (tube-side)		***1.356***	m/s
Reynolds number	Re	*52574*	
Pressure drop	Δp_i	**16607**	Pa
Mean tube wall temperature	ϑw_i	**60.06**	°C

Shell-side

Velocity (shell-side)		**1.012**	m/s
Velocity (window zone)		**0.9001**	m/s
Reynolds number	Re	*31881*	
Pressure drop	Δp_a	**25951**	Pa
Mean tube wall temperature	ϑw_a	**49.16**	°C

Inlet nozzle (tube-side)

Nominal width	DN 125	
Outside diameter	139.7	mm
Inside diameter	131.7	mm
Velocity	**1.501**	m/s

Inlet nozzle (shell-side)

Nominal width	DN 125	
Outside diameter	139.7	mm
Inside diameter	131.7	mm
Velocity	**0.8975**	m/s
ρ·v²	**800.3**	kg/(m·s²)

Outlet nozzle (tube-side)

Nominal width	DN 125	
Outside diameter	139.7	mm
Inside diameter	131.7	mm
Velocity	**1.501**	m/s

Outlet nozzle (shell-side)

Nominal width	DN 125	
Outside diameter	139.7	mm
Inside diameter	131.7	mm
Velocity	**0.8975**	m/s

Physical properties

Tube-side				Shell-side			
Density	ρ_i	*977.9*	kg/m³	Density	ρ_a	*993.6*	kg/m³
Specific heat capacity	cp_i	*4187*	J/(kg·K)	Specific heat capacity	cp_a	*4178*	J/(kg·K)
Thermal conductivity	λ_i	*0.6598*	W/(m·K)	Thermal conductivity	λ_a	*0.6242*	W/(m·K)
Dynamic viscosity	η_i	*0.4036*	mPa·s	Dynamic viscosity	η_a	*0.6981*	mPa·s

Equations

Heat balance

$$Q_i = m_i \cdot cp_i \cdot (\vartheta a_i - \vartheta e_i) = 20\ \text{kg/s} \cdot 4187\ \text{J/(kg·K)} \cdot (60°\text{C} - 80°\text{C}) = \text{-}1674976\ \text{W}$$

$$Q_a = m_a \cdot cp_a \cdot (\vartheta a_a - \vartheta e_a) = 12.15\ \text{kg/s} \cdot 4178\ \text{J/(kg·K)} \cdot (53°\text{C} - 20°\text{C}) = 1674976\ \text{W}$$

$$Q_i = -(Q_a - Qv_a) = -(1674976\ \text{W} - 0\ \text{W}) = \text{-}1674976\ \text{W}$$

Overall heat transfer coefficient

$$\frac{1}{k} = \left[\frac{1}{\alpha_i} + f_i\right] \cdot \frac{d_a}{d_i} + \frac{d_a \cdot ln\left(\frac{d_a}{d_i}\right)}{2 \cdot \lambda} + \frac{1}{\alpha_a} + f_a \Leftrightarrow$$

$$\frac{1}{2186\ \text{W/(m²·K)}} = \left[\frac{1}{9209\ \text{W/(m²·K)}} + 0\ \text{m²·K/W}\right] \cdot \frac{0.02\ \text{m}}{0.016\ \text{m}} + \frac{0.02\ \text{m} \cdot ln\left(\frac{0.02\ \text{m}}{0.016\ \text{m}}\right)}{2 \cdot 15\ \text{W/(m·K)}} + \frac{1}{5784\ \text{W/(m²·K)}} + 0\ \text{m²·K/W}$$

$$k = 2186\ \text{W/(m²·K)}$$

$$Q = k \cdot A \cdot \Delta\vartheta \cdot FN = 2186\ \text{W/(m²·K)} \cdot 26.57\ \text{m²} \cdot 33.08\ \text{K} \cdot 0.8717 = \text{-}1674976\ \text{W}$$

Tube sheet data

Description of type
Baffle-type Segmental baffles

Shell outside diameter	D_o	*406.4*	mm
Shell inside diameter	D_i	*393.8*	mm
Minimum bundle-to-shell clearance	D_m	*12*	mm
Bundle-to-shell clearance	D	**13.18**	mm
Bundle diameter at cross flow zone	D_B	362	mm
Bundle diameter (cross flow zone and window zone)	D_{BE}	367.4	mm
Tube outside diameter	d_a	*20*	mm
Tube inside diameter	d_i	*16*	mm
Tube pitch (transverse)	s_1	*26*	mm
Tube pitch (longitudinal)	s_2	*22.52*	mm
Pitch angle	Φ	*60*	°
Baffle diameter	D_l	*390.8*	mm
Height of baffle cut	H	**86.64**	mm
Height of the window in % of shell inside diameter		*22*	%
Tube pattern		staggered	
Arrangement		around central tube	
No tubes in window?		*No*	
Number of tube-side passes		*2*	
Number of shell-side passes		*1*	
Tube lane width (horizontal)		*32*	mm
Tube lane width (vertical)		*32*	mm
Outside diameter of the head	D_a		mm
Bolt-circle diameter	D_t		mm
Number of bolts on the bolt-circle			
Rotation angle for bolt-hole pattern			°

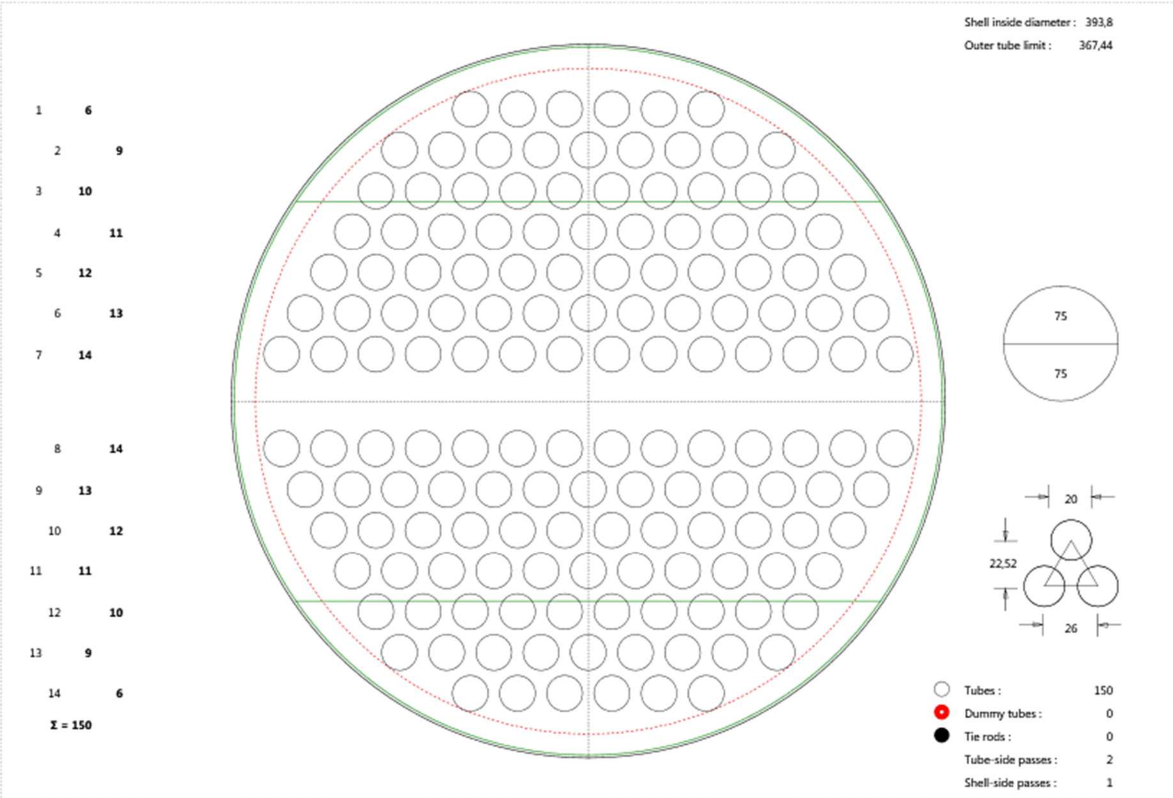
Number of tubes	n	*150*	
Number of dummy tubes	n_B	0	
Number of tie rods	n_Z	0	
Total number of tubes, dummy tubes and tie rods	n_G	150	
Number of tubes, dummy tubes and tie rods in the upper and lower window	n_F	40	
Number of tubes, dummy tubes and tie rods in the cross flow zone	n_S	110	
Number of tube rows in a window	$n_{R,F}$	2.5	
Number of tube rows in the cross flow zone	n_W	*9*	
Number of tube rows in the end zone	$n_{W,E}$	11.5	
Sum of the shortest connecting paths in the center	Le	109.8	mm
Shortest connecting path between tube and tube	e	6	mm
Shortest connecting path between tube and shell	e_1	15.91	mm
Number of connections	n_V	13	
Mean distance boundary tubes - bundle centre	r_h	155.4	mm
Number of boundary tubes required/actual RR		/ 70	
Perimeter of the tube layout	C_p	1066	mm
Total area enclosed by perimeter	A_p	0.08339	m²

Number of tubes, dummy tubes and tie rods per pass

Pass-No.	1	2	3	4	5	6	7	8
	75	75	0	0	0	0	0	0

Final bundle length	l_a	3000	mm
Total area	A_{ges}	**28.27**	m²
Number of baffles per shell-side path	N	24	
Central baffle spacing	S_1	110	mm
Distance between the tubesheet and the 1st baffle	S_2	235	mm
Baffle borehole diameter		20.8	mm
Number of pairs of sealing strips	n_D	0	
Number of exchangers in series		1	

Nozzles	Tube-side	Shell-side
Inside nozzle diameter (inlet)	131.7 mm	131.7 mm
Inside nozzle diameter (outlet)	131.7 mm	131.7 mm



Properties of Water and Steam

		State 1			State 2	
Calculation for saturation?		No			No	
Temperature	ϑ_1	36.5	°C	ϑ_2	49.15	°C
Pressure	p_1	3	bar	p_2	3	bar

Properties of liquid water or superheated steam

		State 1			State 2	
		Liquid			Liquid	
Density	ρ	**993.6**	kg/m³	ρ	**988.5**	kg/m³
Spec. isob. heat capacity	c_p	**4178**	J/(kg·K)	c_p	**4179**	J/(kg·K)
Thermal conductivity	λ	**0.6242**	W/(m·K)	λ	**0.6397**	W/(m·K)
Dynamic viscosity	η	**0.6981**	mPa·s	η	**0.5544**	mPa·s
Kinematic viscosity	ν	**7.026e-7**	m²/s	ν	**5.608e-7**	m²/s
Prandtl number	Pr	**4.673**		Pr	**3.622**	
Thermal diffusivity	a	**1.503e-7**	m²/s	a	**1.548e-7**	m²/s
Specific volume	v	**0.001006**	m³/kg	v	**0.001012**	m³/kg
Spec. isoc. heat capacity	c_v	**4088**	J/(kg·K)	c_v	**4028**	J/(kg·K)
Specific enthalpy	h	**153177**	J/kg	h	**206052**	J/kg
Spec. internal energy	u	**152875**	J/kg	u	**205749**	J/kg
Specific entropy	s	**525.4**	J/(kg·K)	s	**692.7**	J/(kg·K)
Compressibility factor	Z	**0.002113**		Z	**0.00204**	
Surface tension	σ	**70.16**	mN/m	σ	**68.09**	mN/m
Coefficient of thermal expansion	β	**3.576e-4**	1/K	β	**4.516e-4**	1/K
Isentropic exponent	κ	**7705**		κ	**7862**	
Speed of sound	w	**1525**	m/s	w	**1545**	m/s
Dielectric constant	ε	**74.39**		ε	**70.2**	

Characteristics

				Validity
Molar mass	M	18.02	g/mol	0.01°C ≤ ϑ ≤ 800°C
Gas constant	R	461.5	J/(kg·K)	0.00612 bar ≤ p ≤ 1000 bar
Critical temperature	T_c	373.9	°C	0.01°C ≤ ϑ ≤ 2000°C
Critical pressure	p_c	2.206e+7	Pa	0.00612 bar ≤ p ≤ 500 bar
Critical density	ρ_c	322	kg/m³	

Properties of Water and Steam

		State 1			State 2	
Calculation for saturation?		No			No	
Temperature	ϑ_1	70	°C	ϑ_2	60.06	°C
Pressure	p_1	4	bar	p_2	4	bar

Properties of liquid water or superheated steam

		State 1			State 2	
		Liquid			Liquid	
Density	ρ	**977.9**	kg/m³	ρ	**983.3**	kg/m³
Spec. isob. heat capacity	c_p	**4187**	J/(kg·K)	c_p	**4182**	J/(kg·K)
Thermal conductivity	λ	**0.6598**	W/(m·K)	λ	**0.651**	W/(m·K)
Dynamic viscosity	η	**0.4036**	mPa·s	η	**0.4657**	mPa·s
Kinematic viscosity	ν	**4.128e-7**	m²/s	ν	**4.736e-7**	m²/s
Prandtl number	Pr	**2.562**		Pr	**2.992**	
Thermal diffusivity	a	**1.611e-7**	m²/s	a	**1.583e-7**	m²/s
Specific volume	v	**0.001023**	m³/kg	v	**0.001017**	m³/kg
Spec. isoc. heat capacity	c_v	**3922**	J/(kg·K)	c_v	**3973**	J/(kg·K)
Specific enthalpy	h	**293320**	J/kg	h	**251707**	J/kg
Spec. internal energy	u	**292911**	J/kg	u	**251300**	J/kg
Specific entropy	s	**954.8**	J/(kg·K)	s	**831.7**	J/(kg·K)
Compressibility factor	Z	**0.002583**		Z	**0.002645**	
Surface tension	σ	**64.48**	mN/m	σ	**66.23**	mN/m
Coefficient of thermal expansion	β	**5.838e-4**	1/K	β	**5.233e-4**	1/K
Isentropic exponent	κ	**5935**		κ	**5940**	
Speed of sound	w	**1558**	m/s	w	**1554**	m/s
Dielectric constant	ε	**63.78**		ε	**66.77**	

Characteristics

				Validity
Molar mass	M	18.02	g/mol	0.01°C ≤ ϑ ≤ 800°C
Gas constant	R	461.5	J/(kg·K)	0.00612 bar ≤ p ≤ 1000 bar
Critical temperature	T_c	373.9	°C	0.01°C ≤ ϑ ≤ 2000°C
Critical pressure	p_c	2.206e+7	Pa	0.00612 bar ≤ p ≤ 500 bar
Critical density	ρ_c	322	kg/m³	

Heat transfer in pipe flow

Constant wall temperature

Process data

Total mass flow	m_{tot}		kg/h
Total volume flow	V_{tot}		m³/h
Number of tubes with parallel flow	Z		
Mass flow per tube	m	**960**	kg/h
Inlet temperature	ϑ_e	80	°C
Outlet temperature	ϑ_a	60	°C
Mean temperature	ϑ_m	**70**	°C
Pressure (abs.)	p	4	bar

Physical properties

Fluid liquid / gaseous? liquid

Density	ρ	*977.9*	kg/m³
Specific heat capacity	cp	*4187*	J/(kg·K)
Thermal conductivity	λ	*0.6598*	W/(m·K)
Dynamic viscosity	η	*0.4036*	mPa·s
Kinematic viscosity	ν	**4.128e-7**	m²/s
Prandtl number	Pr	**2.562**	
Prandtl number at wall temperature	Pr_W	2.992	
Wall temperature	ϑ_W	60.06	°C

Geometry

Tube circular / non-circular? Circular tubes

Tube length	l	*3000*	mm
Tube inside diameter	d_i	**16**	mm
Cross sectional area of the tube	f	**2.011e-4**	m²
Perimeter of the tube	u	**50.26**	mm
Hydraulic diameter	d_h	*16*	mm

Heat transfer

Flow velocity	w	*1.356*	m/s
Reynolds number	Re	***52574***	
Nusselt number	Nu	**223.3**	
Heat transfer coefficient	α	**9209**	W/(m²·K)

Heat duty $Q = m_{tot} \cdot c_p \cdot (\vartheta_a - \vartheta_e)$ Q kW

Equations Constant wall temperature

Turbulent flow (Re > 10000)

$$\alpha=\frac{Nu\cdot\lambda}{d_h}=\frac{223.3\cdot 0.6598\ \mathrm{W/(m\cdot K)}}{0.016\ \mathrm{m}}=9209\ \mathrm{W/(m^2\cdot K)}$$

$$Nu=Nu_{m,T}\cdot K=227.2\cdot 0.9831=223.3$$

$$Re=\frac{w\cdot d_h\cdot\rho}{\eta}=\frac{1.356\ \mathrm{m/s}\cdot 0.016\ \mathrm{m}\cdot 977.9\ \mathrm{kg/m^3}}{0.4036\ \mathrm{mPa\cdot s}}=52574$$

$$\xi=[1.8\cdot\log Re-1.5]^{-2}=[1.8\cdot\log 52574-1.5]^{-2}=0.02042$$

$$Nu_{m,T}=\frac{\frac{\xi}{8}\cdot Re\cdot Pr}{1+12.7\cdot\sqrt{\frac{\xi}{8}}\cdot(Pr^{2/3}-1)}\cdot\left[1+\left(\frac{d_h}{l}\right)^{2/3}\right]=\frac{\frac{0.02042}{8}\cdot 52574\cdot 2.562}{1+12.7\cdot\sqrt{\frac{0.02042}{8}}\cdot((2.562)^{2/3}-1)}\cdot\left[1+\left(\frac{0.016\ \mathrm{m}}{3\ \mathrm{m}}\right)^{2/3}\right]=227.2$$

Correction factor K (Effect of temperature dependent property variations)
Liquids

$$K=\left(\frac{Pr}{Pr_w}\right)^{0.11}=\left(\frac{2.562}{2.992}\right)^{0.11}=0.9831$$

Heat transfer on the shell side in baffeled shell and tube heat exchangers

Geometrical data			
Tube arrangement	staggered		
Shell inside diameter	D_i	*393.8*	mm
Bundle diameter at cross flow zone	D_B	362	mm
Tube outside diameter	d_a	*20*	mm
Tube pitch (transverse)	s_1	*26*	mm
Tube pitch (longitudinal)	s_2	*22.52*	mm
Baffle diameter	D_l	*390.8*	mm
Height of baffle cut	H	86.64	mm
Diameter of the bore holes in the baffles	d_B	*20.8*	mm
Baffle spacing	S	*110*	mm
Number of tubes including blanks and support tubes	n	150	
Number of tubes in the upper and lower windows	n_F	40	
Number of main resistances in a cross-flow zone	n_W	9	
Number of connections	n_V	13	
Distance between boundary tubes and shell	e_1	15.91	mm
Shortest connecting path between tube and tube	e	**6**	mm
Sum of the shortest connecting paths in the center	L_E	**109.8**	mm
Number of sealing strip pairs	n_S	*0*	
Number of shell-side passes	N_D	*1*	
Fluid			
Mass flow	m	**43732**	kg/h
Volume flow	V	*44.01*	m³/h
Inlet temperature	ϑ_e	20	°C
Outlet temperature	ϑ_a	53	°C
Mean temperature	ϑ_m	**36.5**	°C
Fluid liquid /gaseous?		liquid	
Density	ρ	*993.6*	kg/m³
Specific heat capacity	cp	*4178*	J/(kg·K)
Thermal conductivity	λ	*0.6242*	W/(m·K)
Dynamic viscosity	η	*0.6981*	mPa·s
Kinematic viscosity	ν	**7.026e-7**	m²/s
Prandtl number	Pr	**4.673**	
Prandtl number at tube wall temperature	Pr_W	3.622	
Reynolds number	$Re_{\psi,1}$	***31881***	
Heat transfer coefficient	α	**6136**	W/(m²·K)

Results

$$\alpha=\frac{Nu_{0,AW}\cdot\lambda}{\frac{\pi}{2}\cdot d_a}\cdot K=\frac{289.8\cdot 0.6242\ \text{W/(m·K)}}{\frac{\pi}{2}\cdot 0.02\ \text{m}}\cdot 1.066=6136\ \text{W/(m²·K)}$$

$$Nu_{0,AW}=f_W\cdot Nu_{0,Bundle}=0.5413\cdot 535.3=289.8$$

$$f_W=f_G\cdot f_L\cdot f_B=1.077\cdot 0.6906\cdot 0.728=0.5413$$

Calculation of $Nu_{0,Bundle}$

$$a=\frac{s_1}{d_a}=\frac{0.026\ \text{m}}{0.02\ \text{m}}=1.3 \qquad b=\frac{s_2}{d_a}=\frac{0.02252\ \text{m}}{0.02\ \text{m}}=1.126$$

$$\psi=1-\frac{\pi}{4\cdot a}=1-\frac{\pi}{4\cdot 1.3}=0.3958$$

$$w=\frac{V}{D_i\cdot S}=\frac{0.01223\ \text{m³/s}}{0.3938\ \text{m}\cdot 0.11\ \text{m}}=0.2822\ \text{m/s}$$

$$Re_{\psi,1}=\frac{\frac{\pi}{2}\cdot d_a\cdot w}{\psi\cdot v}=\frac{\frac{\pi}{2}\cdot 0.02\ \text{m}\cdot 0.2822\ \text{m/s}}{0.3958\cdot 7.026\text{e-7}\ \text{m²/s}}=31881$$

$$Nu_{1,lam}=0.664\cdot\sqrt{Re_{\psi,1}}\cdot\sqrt[3]{Pr}=0.664\cdot\sqrt{31881}\cdot\sqrt[3]{4.673}=198.2$$

$$Nu_{1,\text{turb}}=\frac{0.037\cdot Re_{\psi,1}^{0.8}\cdot Pr}{1+2.443\cdot Re_{\psi,1}^{-0.1}\cdot(Pr^{2/3}-1)}=\frac{0.037\cdot(31881)^{0.8}\cdot 4.673}{1+2.443\cdot(31881)^{-0.1}\cdot((4.673)^{2/3}-1)}=271.2$$

$$Nu_{1,0}=0.3+\sqrt{Nu_{1,\text{lam}}^2+Nu_{1,\text{turb}}^2}=0.3+\sqrt{(198.2)^2+(271.2)^2}=336.2$$

$$Nu_{0,Bundle}=f_A\cdot Nu_{1,0}=1.592\cdot 336.2=535.3$$

$$f_A=1+\frac{2}{3\cdot b}=1+\frac{2}{3\cdot 1.126}=1.592$$

Calculation of f_G

$$R_G=\frac{n_F}{\left(\frac{n}{N_D}\right)}=\frac{40}{\left(\frac{150}{1}\right)}=0.2667$$

$$f_G=1-R_G+0.524\cdot R_G^{0.32}=1-0.2667+0.524\cdot(0.2667)^{0.32}=1.077$$

Calculation of f_L

$$A_{SRU}=\left(\frac{n}{N_D}-\frac{n_F}{2}\right)\cdot\frac{\pi\cdot(d_B{}^2-d_a{}^2)}{4}=\left(\frac{150}{1}-\frac{40}{2}\right)\cdot\frac{\pi\cdot((0.0208\ \text{m})^2-(0.02\ \text{m})^2)}{4}=0.003333\ \text{m}^2$$

$$\gamma=2\cdot arccos\left(1-\frac{2\cdot H}{D_1}\right)=2\cdot arccos\left(1-\frac{2\cdot 0.08664\ \text{m}}{0.3908\ \text{m}}\right)=112.4°$$

$$A_{SMU}=\frac{\pi}{4}\cdot(D_i{}^2-D_1{}^2)\cdot\frac{(360-\gamma)}{360\cdot N_D}=\frac{\pi}{4}\cdot((0.3938\ \text{m})^2-(0.3908\ \text{m})^2)\cdot\frac{(360-112.4°)}{360\cdot 1}=0.001272\ \text{m}^2$$

$$A_{SG}=A_{SRU}+A_{SMU}=0.003333\ \text{m}^2+0.001272\ \text{m}^2=0.004604\ \text{m}^2$$

$$A_E=S\cdot L_E=0.11\ \text{m}\cdot 0.1098\ \text{m}=0.01208\ \text{m}^2$$

$$R_L=\frac{A_{SG}}{A_E}=\frac{0.004604\ \text{m}^2}{0.01208\ \text{m}^2}=0.3811$$

$$f_L=0.4\cdot\frac{A_{SRU}}{A_{SG}}+\left[1-0.4\cdot\frac{A_{SRU}}{A_{SG}}\right]\cdot exp(-1.5\cdot R_L)=$$

$$0.4\cdot\frac{0.003333\ \text{m}^2}{0.004604\ \text{m}^2}+\left[1-0.4\cdot\frac{0.003333\ \text{m}^2}{0.004604\ \text{m}^2}\right]\cdot exp(-1.5\cdot 0.3811)=0.6906$$

Calculation of f_B
for $n_S \le n_W / 2$

$$A_B=S\cdot(D_i-D_B-e)=$$

$$0.11\ \text{m}\cdot(0.3938\ \text{m}-0.362\ \text{m}-0.006\ \text{m})=0.002841\ \text{m}^2$$

for $e < (D_i - D_B)$

$$R_B=\frac{A_B}{A_E}=\frac{0.002841\ \text{m}^2}{0.01208\ \text{m}^2}=0.2351$$

$$f_B=exp\left[-\beta\cdot R_B\cdot\left(1-\sqrt[3]{\frac{2\cdot n_S}{n_W}}\right)\right]=exp\left[-1.35\cdot 0.2351\cdot\left(1-\sqrt[3]{\frac{2\cdot 0}{9}}\right)\right]=0.728$$

Correction factor K (Effect of temperature dependent property variations)

Heating of liquids

$$K=\left(\frac{Pr}{Pr_W}\right)^{0.25}=\left(\frac{4.673}{3.622}\right)^{0.25}=1.066$$

Corrected logarithmic mean temperature difference (CLMTD) and temperature distribution according to cell method

Corrected logarithmic mean temperature difference (CLMTD) and distribution with cell method for shell and tube heat exchangers

Tube-side inlet temperature	t_{i1}	80	°C
Shell-side inlet temperature	t_{a1}	20	°C
Tube-side mass flow	m_i	72000	kg/h
Shell-side mass flow	m_a	43732	kg/h
Specific heat capacity tube-side	$c_{p,i}$	4187	J/(kg·K)
Specific heat capacity shell-side	$c_{p,a}$	4178	J/(kg·K)
Heat capacity flow tube-side; $W_{w,i} = m_i \cdot c_{p,i}$	$W_{w,i}$	**83749**	W/K
Heat capacity flow shell-side; $W_{w,a} = m_a \cdot c_{p,a}$	$W_{w,a}$	**50757**	W/K
Number of baffles	N_U	20	
Number of shell-side passes	N_s	1	
Number of tube-side passes	N_t	2	
Sheet plus shell type		1	
Number of tube rows per cell		4	
Actual overall heat transfer coefficient	k	2186	W/(m²·K)
Actual heat transfer area	A	28.27	m²
0 = unmixed; 0.5 = mixed		0	
Tube flow: countercurrent = 1; cocurrent = 2		1	
Flow pattern: countercurrent = 1; cocurrent = 2		101	
Tube-side outlet temperature	t_{i2}	**59.32**	°C
Shell-side outlet temperature	t_{a2}	**54.12**	°C
LMTD countercurrent flow	ΔT_{Geg}	**32.14**	K
FN factor	FN	**0.8717**	
CLMTD corrected log. mean temperature difference	ΔT_m	**28.01**	K
Number of cells		**42**	
Product k·A		**61817**	W/K
Product k·A per cell		**1472**	W/K
Tube-side efficiency		**0.3446**	
Shell-side efficiency		**0.5686**	
Tube-side cell efficiency		**0.01717**	
Shell-side cell efficiency		**0.02834**	
Maximum tube-side temperature	$t_{i,max}$	80	°C
Maximum shell-side temperature	$t_{a,max}$	54.12	°C
Minimum tube-side temperature	$t_{i,min}$	59.32	°C
Minimum shell-side temperature	$t_{a,min}$	20	°C
Max. temperature inversion in one cell	t_{inv}	0	°C

Tube-side pressure drop in shell and tube heat exchangers

Physical properties		**Mean temperature**		**Wall temperature**	
Fluid: liquid / gaseous?		*liquid*			
Inlet temperature	ϑ_e	80	°C		
Outlet temperature	ϑ_a	60	°C		
Mean temperature $\vartheta_m = (\vartheta_e + \vartheta_a) / 2$	ϑ_m	**70**	°C	60.06	°C
Inlet pressure (abs.)	P_e	*4*	bar		
Density	ρ	*977.9*	kg/m³	*982.6*	kg/m³
Specific heat capacity	cp	*4187*	J/(kg·K)		
Thermal conductivity	λ	*0.6598*	W/(m·K)		
Dynamic viscosity	η	*0.4036*	mPa·s	*0.4657*	mPa·s

Geometrical data			
Type: Straight tube / U-tube?		Straight tube	
Tube outside diameter	d_a	*20*	mm
Tube wall thickness	s	**2**	mm
Tube inside diameter	d_i	*16*	mm
Number of tube-side passes	n_P	*2*	
Number of tubes per pass	n_R	75	
Length of one tube	L	*3000*	mm
Inside nozzle diameter (inlet)	$d_{N,e}$	131.7	mm
Inside nozzle diameter (outlet)	$d_{N,a}$	131.7	mm
Acceleration due to gravity	g	9.81	m/s²
Mass flow	m	*20*	kg/s
Volume flow	V	**73.63**	m³/h
Mean velocity in the tube	w	**1.356**	m/s
Mean velocity in the inlet nozzle	$w_{N,e}$	**1.501**	m/s
Mean velocity in the outlet nozzle	$w_{N,a}$	**1.501**	m/s
Reynolds number	Re	**52564**	
Prandtl number	Pr	**2.562**	
Grashof number	Gr	**1136330**	
Friction factor (inlet, outlet and baffle)	Ke	**3.2**	
Fanning friction factor (tube, isothermal)	ξ_{is}	**0.006247**	
Correction factor for the viscosity	Φ	**1.022**	
Correction factor for the convection	ψ	**1**	
Friction factor (tube) $(\xi = \xi_{is} \cdot \Phi \cdot \psi)$	ξ	**0.006386**	
Pressure drop (inlet nozzle)	$\Delta P_{N,e}$	**991.9**	Pa
Pressure drop (outlet nozzle)	$\Delta P_{N,a}$	**991.9**	Pa
Pressure drop (inlet, outlet and baffle)	ΔP_e	**2877**	Pa
Pressure drop (friction)	ΔP_t	**8612**	Pa
Fouling factor	F_t	**1.364**	
Total pressure drop $(\Delta P = F_t \cdot \Delta P_t + \Delta P_e + \Delta P_{N,e} + \Delta P_{N,a})$	ΔP	**16607**	Pa

Equations

$$w=\frac{4\cdot m}{\pi\cdot d_i^{\,2}\cdot n_R\cdot\rho}=\frac{4\cdot 20\ \text{kg/s}}{\pi\cdot(0.016\ \text{m})^2\cdot 75\cdot 977.9\ \text{kg/m³}}=1.356\ \text{m/s}$$

$$w_{N,e}=\frac{4\cdot m}{\pi\cdot d_{N,e}^{\,2}\cdot\rho}=\frac{4\cdot 20\ \text{kg/s}}{\pi\cdot(0.1317\ \text{m})^2\cdot 977.9\ \text{kg/m³}}=1.501\ \text{m/s}$$

$$w_{N,a}=\frac{4\cdot m}{\pi\cdot d_{N,a}^{\,2}\cdot\rho}=\frac{4\cdot 20\ \text{kg/s}}{\pi\cdot(0.1317\ \text{m})^2\cdot 977.9\ \text{kg/m³}}=1.501\ \text{m/s}$$

$$Re=\frac{w\cdot d_i\cdot\rho}{\eta}=\frac{1.356\ \text{m/s}\cdot 0.016\ \text{m}\cdot 977.9\ \text{kg/m³}}{4.036\text{e-}4\ \text{Pa·s}}=52564$$

$$Pr=\eta\cdot\frac{cp}{\lambda}=4.036\text{e-}4\ \text{Pa·s}\cdot\frac{4187\ \text{J/(kg·K)}}{0.6598\ \text{W/(m·K)}}=2.562$$

$$Gr=\frac{g\cdot d_i^{\,3}}{\left(\frac{\eta}{\rho}\right)^2}\cdot\frac{|\rho-\rho_W|}{\rho}=\frac{9.81\ \text{m/s²}\cdot(0.016\ \text{m})^3}{\left(\frac{4.036\text{e-}4\ \text{Pa·s}}{977.9\ \text{kg/m³}}\right)^2}\cdot\frac{|977.9\ \text{kg/m³}-982.6\ \text{kg/m³}|}{977.9\ \text{kg/m³}}=1136330$$

$Ke=1.6\cdot n_P=1.6\cdot 2=3.2$ Straight tubes, multiple passes

$$\xi_{is}=0.0035+0.264\cdot Re^{-0.42}=0.0035+0.264\cdot(52564)^{-0.42}=0.006247$$

$$\Phi=\Phi\left(Re;\eta/\eta_W\right)=\Phi(52564;0.8667)=1.022$$

$$\psi=\psi\left(Re;Gr\cdot Pr\cdot\eta/\eta_W\right)=\psi(52564;2522981)=1$$

$$\xi=\xi_{is}\cdot\Phi\cdot\psi=0.006247\cdot 1.022\cdot 1=0.006386$$

$$\Delta P_e=Ke\cdot\rho\cdot\frac{w^2}{2}=3.2\cdot 977.9\ \text{kg/m³}\cdot\frac{(1.356\ \text{m/s})^2}{2}=2877\ \text{Pa}$$

$$\Delta P_t=2\cdot\xi\cdot\frac{\rho\cdot w^2\cdot n_P\cdot L}{d_i}=2\cdot 0.006386\cdot\frac{977.9\ \text{kg/m³}\cdot(1.356\ \text{m/s})^2\cdot 2\cdot 3\ \text{m}}{0.016\ \text{m}}=8612\ \text{Pa}$$

$$\Delta P_{N,e}=0.9\cdot\frac{\rho_e}{2}\cdot w_{N,e}^{\,2}=0.9\cdot\frac{977.9\ \text{kg/m³}}{2}\cdot(1.501\ \text{m/s})^2=991.9\ \text{Pa}$$

$$\Delta P_{N,a}=0.9\cdot\frac{\rho_a}{2}\cdot w_{N,a}^{\,2}=0.9\cdot\frac{977.9\ \text{kg/m³}}{2}\cdot(1.501\ \text{m/s})^2=991.9\ \text{Pa}$$

$$F_t=\left[\frac{d_a-2\cdot s}{d_a-2.2\cdot s-0.00182\cdot d_a^{\,0.3}}\right]^5=\left[\frac{0.02\ \text{m}-2\cdot 0.002\ \text{m}}{0.02\ \text{m}-2.2\cdot 0.002\ \text{m}-0.00182\cdot(0.02\ \text{m})^{0.3}}\right]^5=1.364$$

$$\Delta P=F_t\cdot\Delta P_t+\Delta P_e+\Delta P_{N,e}+\Delta P_{N,a}=1.364\cdot 8612\ \text{Pa}+2877\ \text{Pa}+991.9\ \text{Pa}+991.9\ \text{Pa}=16607\ \text{Pa}$$

Tube bundle vibration analysis

General formulation							
Tube outside diameter		d_a	20	mm			
Tube wall thickness		s	**2**	mm			
Tube inside diameter		d_i	16	mm			
Tube pitch (transverse)		s_1	26	mm			
Tube pitch (longitudinal)		s_2	22.52	mm			
Transverse pitch ratio		s_1/d_a	**1.3**				
Longitudinal pitch ratio		s_2/d_a	**1.126**				
Cross-sectional area of the tubes		A	**113**	mm²			
Second moment of area of the tubes		J	**4629**	mm^4			
Modulus of elasticity		E	200000	N/mm²			
Effective density		ρ	7850	kg/m³			
Support for the tubes		jointed - fixed					
Factor for the support		C	3.93				
Factor for additional forces		C_f	1				
Arrangement of the tubes		Staggered bare tubes					
Strouhal number of the bundle		Sr	**0.2292**				
Final span		L	235	mm		345	mm
Velocity in the narrowest cross section		w_e	0.8975	m/s		1.012	m/s
Natural frequency of the tubes		f_R	**1438**	1/s		**667.1**	1/s
Safety factor		S	1.5				
Allowable excitation frequency	$f_z = f_R/S$	f_z	**958.5**	1/s		**444.7**	1/s
Excitation frequency of the flow		f_{err}	**10.29**	1/s		**11.6**	1/s

Vibration probable, if $f_{err} > f_z$

Equations

$$d_i = d_a - 2 \cdot s = 20\ \text{mm} - 2 \cdot 2\ \text{mm} = 16\ \text{mm}$$

$$A = \frac{\pi}{4} \cdot [d_a^{\ 2} - d_i^{\ 2}] = \frac{\pi}{4} \cdot [(20\ \text{mm})^2 - (16\ \text{mm})^2] = 113\ \text{mm}^2$$

$$J = \frac{\pi}{64} \cdot [d_a^{\ 4} - d_i^{\ 4}] = \frac{\pi}{64} \cdot [(20\ \text{mm})^4 - (16\ \text{mm})^4] = 4629\ \text{mm\^{}4}$$

$$f_R = \frac{10^6}{2 \cdot \pi} \cdot \left[\frac{C}{L}\right]^2 \cdot \sqrt{\frac{E \cdot J}{\rho \cdot A}} \cdot C_f = \frac{10^6}{2 \cdot \pi} \cdot \left[\frac{3.93}{235\ \text{mm}}\right]^2 \cdot \sqrt{\frac{200000\ \text{N/mm}^2 \cdot 4629\ \text{mm\^{}4}}{7850\ \text{kg/m}^3 \cdot 113\ \text{mm}^2}} \cdot 1 = 1438\ \text{1/s}$$

$$f_z = \frac{f_R}{S} = \frac{1438\ \text{1/s}}{1.5} = 958.5\ \text{1/s}$$

$$f_{err} = \frac{Sr \cdot w_e}{\frac{d_a}{1000}} = \frac{0.2292 \cdot 0.8975\ \text{m/s}}{\frac{20\ \text{mm}}{1000}} = 10.29\ \text{1/s}$$

Pressure drop in the outer shell of heat exchangers

Shell-side pressure drop in shell-and-tube heat exchangers with segmental baffles

Shell inside diameter	D_i	*393.8*	mm
Bundle diameter at cross flow zone	D_B	362	mm
Bundle diameter (cross flow zone and window zone)	D_{BE}	367.4	mm
Tube outside diameter	d_a	*20*	mm
Tube pitch (transverse)	s_1	*26*	mm
Tube pitch (longitudinal)	s_2	*22.52*	mm
Pitch angle		*60*	°
Baffle diameter	D_l	*390.8*	mm
Number of baffles	n_U	*24*	
Height of baffle cut	H	86.64	mm
Diameter of the bore holes in the baffles	d_B	*20.8*	mm
Central baffle spacing	S	*110*	mm
Distance between the tubesheet and the 1st baffle	S_E	*235*	mm
Number of tubes including dummy tubes and tie rods	n	150	
Number of tubes in the upper and lower windows	n_F	40	
Number of tube rows in a window	n_{RF}	2.5	
Number of main resistances in the crossflow zone	n_W	9	
Number of main resistances in the end zone	n_{WE}	11.5	
Number of connection lines	n_V	13	
Distance between boundary tubes and shell	e_1	15.91	mm
Number of sealing strip pairs	n_S	*0*	
Number of shell-side passes	N_D	*1*	
Inside nozzle diameter (inlet)	d_{Ni}	131.7	mm
Inside nozzle diameter (outlet)	d_{No}	131.7	mm
Fluid			
Mass flow	m	**43732**	kg/h
Volume flow	V	*44.01*	m³/h
Inlet pressure	P_E	*300000*	Pa
Inlet temperature	ϑ_E	20	°C
Outlet temperature	ϑ_A	53	°C
Mean temperature	ϑ	**36.5**	°C
Fluid liquid / gaseous?		liquid	
Density	ρ	*993.6*	kg/m³
Specific heat capacity	cp	*4178*	J/(kg·K)
Thermal conductivity	λ	*0.6242*	W/(m·K)
Dynamic viscosity	η	*0.6981*	mPa·s
Prandtl number	Pr	**4.673**	
Mean wall temperature	ϑ_W	49.16	°C
Dynamic viscosity at mean wall temperature	η_W	*0.5544*	mPa·s
Total pressure drop	Δp_{total}	**25951**	Pa

Shell-side pressure drop in shell-and-tube heat exchangers with segmental baffles

Cross-flow zone

$(n_U-1) \cdot N_D \cdot \Delta p_Q$ =	(24 - 1) · 1 ·	301.7	Pa	= 6939	Pa

End zone

$2 \cdot \Delta p_{Q,E}$ =	2 ·	265.9	Pa	= 531.7	Pa

Window zone

$n_U \cdot N_D \cdot \Delta p_F$ =	24 · 1 ·	715.5	Pa	= 17173	Pa

Shell nozzles

$\Delta p_{N,i} + \Delta p_{N,o}$ =	746.8 Pa +	560.3	Pa	= 1307	Pa

Total pressure drop

Δp_{total}	= 25951	Pa

Results

a	1.3	b	1.126	c	1.3	e	6	mm

Cross-flow zone

L_E	109.8	mm	A_E	0.01208	m²	w_e	1.012	m/s
$f_{a,l,f}$	205.1		$f_{a,t,f}$	0.6908		$f_{a,l,v}$	205.1	
$f_{a,t,v}$	5.342		$f_{z,l}$	0.9896		$f_{z,t}$	0.9682	
ξ_l	0.00712		ξ_t	0.41		ξ	0.404	
A_{SRU}	0.003333	m²	A_{SMU}	0.001272	m²	A_{SG}	0.004604	m²
R_M	0.2762		R_L	0.3811		r	0.6086	
γ	112.4	°	Re	28808		β	3.7	
R_S	0		R_B	0.2351		A_B	0.002841	m²
f_L	0.3892		f_B	0.4189		$\Delta p_{Q,0}$	1850	Pa
Δp_Q	301.7	Pa						

End zone

Re_E	13485		$A_{E,E}$	0.02581	m²	$w_{e,E}$	0.4737	m/s
$f_{B,E}$	0.4189		$\Delta p_{QE,0}$	634.6	Pa	Δp_{QE}	265.9	Pa

Window zone

A_{FG}	0.02036	m²	A_{FR}	0.006283	m²	A_F	0.01407	m²
w_p	0.8687	m/s	w_z	0.9376	m/s	n_{WF}	3.078	
d_h	34.27	mm	U_F	1643	mm			
$\Delta p_{F,l}$	884.5	Pa	$\Delta p_{F,t}$	1680	Pa	Δp_F	715.5	Pa

Shell nozzles

$w_{N,i}$	0.8975	m/s	$w_{N,o}$	0.8975	m/s			
$\xi_{N,i}$	1.866		$\xi_{N,o}$	1.4				
$\Delta p_{N,i}$	746.8	Pa	$\Delta p_{N,o}$	560.3	Pa	Δp_N	1307	Pa

CAD program for shell and tube heat exchangers

TEMA type AEL

TEMA Front head A Shell E Rear head L

		Tube-side			Shell-side	
Medium		Water			Water	
Inlet pressure (abs.)	p_i	*400000*	Pa	p_a	*300000*	Pa
Pressure stage	PN	5		PN	5	
Inlet temperature	$\vartheta_{e,i}$	*80*	°C	$\vartheta_{e,a}$	*20*	°C
Outlet temperature	$\vartheta_{a,i}$	*60*	°C	$\vartheta_{a,a}$	*53*	°C
Mean temperature	$\vartheta_{m,i}$	**70**	°C	$\vartheta_{m,a}$	**36.5**	°C
Design temperature		100	°C		70	°C
Design pressure		500000	Pa		400000	Pa

Inlet nozzle	Set-on			Set-on		
Type of flange	Integral flange (welding-neck) with hub			Integral flange (welding-neck) with hub		
Flange connection nominal width	DN	125		DN	125	
Outside diameter		139.7	mm		139.7	mm
Nozzle wall thickness		**4**	mm		**4**	mm
Inside diameter		131.7	mm		131.7	mm

Outlet nozzle	Set-on			Set-on		
Type of flange	Integral flange (welding-neck) with hub			Integral flange (welding-neck) with hub		
Flange connection nominal width	DN	125		DN	125	
Outside diameter		139.7	mm		139.7	mm
Nozzle wall thickness		**4**	mm		**4**	mm
Inside diameter		131.7	mm		131.7	mm

CAD Data

Diameter of bore in tube sheet mm

CAD Tubesheet Configuration

Front head a - tubesheet integral with shell and channel

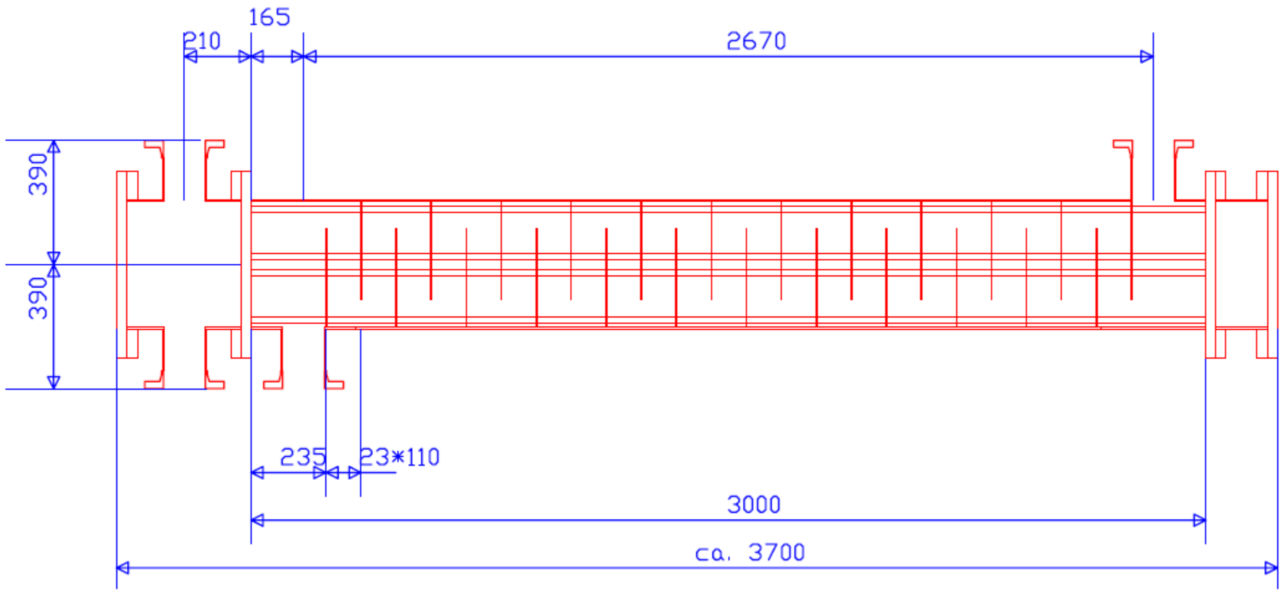
Rear head b - tubesheet extended as flange / integral with shell / gasketed with channel / narrow-face gasket

Geometry

Shell outside diameter	D_a	*406.4*	mm	Shell wall thickness	s_a	*6.3*	mm
Shell inside diameter	D_I	**393.8**	mm				
Bundle-shell distance		*13.18*	mm				
Tube outside diameter	d_a	*20*	mm	Tube inside diameter	d_I	*16*	mm
Tube pitch (transverse)	s_1	*26*	mm	Tube pitch (longitudinal)	s_2	*22.52*	mm
Pitch angle	Φ	**60**	°	Pass lane width	b	*32*	mm
Central baffle spacing		*110*	mm	Number of baffles/pass		*24*	
Inlet baffle spacing		*235*	mm	Baffle diameter		*390.8*	mm
Baffle borehole diameter		*20.8*	mm	Baffle cut		*22*	%
Sealing strips pairs		*0*					

Number of tube-side passes	n_t	*2*	
Number of shell-side passes	n_s	*1*	
Final bundle length	l_a	*3000*	mm
Final shell length	l_a	**3000**	mm
Number of tubes	R	*150*	
Expansion joint diameter			mm
Plate thickness (fixed plate)		30	mm
Outside diameter of tube sheet		370	mm
Plate thickness (free plate)		30	mm
Outside diameter of tube sheet (floating head)		370	mm

CAD sketch from WCAD



WTS-2017

MS Excel specification sheet

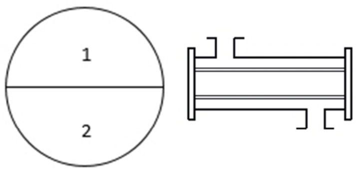
Customer		Job No.	
		Reference No.	
Address		Proposal No.	
Plant Location		Date	20.11.2017
TEMA-Type: AEL	Installation position: Horizontal	Connected in 1 series	parallel

PERFORMANCE OF ONE UNIT

			Shell-Side		Tube-Side	
Fluid Allocation			Shell-Side		Tube-Side	
Fluid Name			Water		Water	
Fluid Quantity, Total		kg/s	12,15		20	
Vapour	(In / Out)	kg/s				
Liquid	(In / Out)	kg/s	12,15		20	
Fluid Volume Flow, Total		m³/h	44,01		73,63	
Steam						
Water						
Noncondensables						
Temperature	(In / Out)	°C	20	53	80	60
Density		kg/m³	993,6		977,9	
Viscosity		mPa·s	0,6981		0,4036	
Molecular Weight, Vapour		kg/kmol				
Molecular Weight, Noncondensables		kg/kmol				
Specific Heat		J/(kg·K)	4178,3		4187,4	
Thermal Conductivity		W/(m·K)	0,6242		0,6598	
Latent Heat		J/kg				
Inlet Pressure (abs.)		bar	3		4	
Velocity		m/s	1,01		1,36	
Pressure Drop, Allow. / Calc.		Pa		25951		16607
Fouling Resistance		m²·K/W	0		0	
Heat Exchanged		kW	1675			
Transfer Rate, Service		W/(m²·K)	2186,3			
MTD (Corrected)		K (diff)	28,83			
Heat Transfer Area		m²	28,3			

CONSTRUCTION OF ONE SHELL — Sketch (Bundle/Nozzle Orientation)

			Shell-Side	Tube-Side
Design / Test Pressure		Pa		
Design Temperature		°C		
No. Passes per Shell			1	2
Corrosion Allowance		mm		
Connections	In		DN 125	DN 125
Size &	Out		DN 125	DN 125
Rating	Intermediate			



Tube Length	mm	3000	Tube Material	Stainless steel
Tube Dimensions (OD x Thk)	mm	20 x 2	No. of Tubes	150
Pitch (Transverse)	mm	26	Pitch (Longitudinal)	22,5
Shell ID	mm	393,8	Shell Dimensions (OD x Thk)	406,4 x 6,3
Channel or Bonnet			Channel Cover	
Tubesheet-Stationary			Tubesheet-Floating	
Floating Head Cover			Impingement Protection	
Baffles-Cross	mm	390,8	Baffle Cut in % of Shell ID	22
Central Baffle Spacing	mm	110	Number of Baffles / Shell-Side Path	24
Inlet Baffle Spacing	mm	235	Number of Sealing Strips Pairs	
Expansion Joint			Type	
$\rho \cdot v^2$ Bundle Entrance	kg/(m·s²)	800	$\rho \cdot v^2$ Bundle Exit	
Gaskets-Shell Side			Tube Side	
- Floating Head				
Code Requirements			TEMA Class	
Weight / Shell	kg		Filled with Water	
Weight / Bundle	kg			

Remarks