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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

Vaporization of pure substances in shell-and-tube or double pipe heat exchangers - VDI Heat Atlas

Tube-side				Shell-side			
	Tube-side vaporization				(Condensation)		
Medium	Freie Eingabe (n-pentan)			Medium	Steam condensation		
Mass flow	m_i	7200	kg/h	Mass flow	m_a	**0.288**	kg/s
Volume flow	V_i	**13.22**	m³/h	Volume flow	V_a	**388.4**	m³/h
Standard volume flow	$V_{S,i}$		m³/h	Standard volume flow	$V_{S,a}$		m³/h
Boiling pressure (abs.)	P_i	*5*	bar	Inlet pressure (abs.)	P_a	*5*	bar
Inlet temperature	ϑe_i	***92.58***	°C	Inlet temperature	ϑe_a	***151.9***	°C
Outlet temperature	ϑa_i	***92.6***	°C	Outlet temperature	ϑa_a	***151.8***	°C
Boiling temperature	ϑm_i	*92.59*	°C	Mean temperature	ϑm_a	*151.8*	°C
Liquid mass fraction inlet	x_i	1	-	Vapour fraction inlet	x_i	1	-
Liquid mass fraction outlet	x_o	0	-	Vapour fraction outlet	x_o	0	-
Heat duty	Q_i	**606.9**	kW	Heat duty	Q_a	**-606.9**	kW
				Heat loss	Qv_a	0	kW
Fouling resistance	f_i	0	m²·K/W	Fouling resistance	f_a	0	m²·K/W

Reference data

Reference heat flux	q_0	*20000*	W/m²
Reference heat transfer coefficient	α_0	*3070*	W/(m²·K)

Evaluation

		Required			Final		Overdesign	
Heat transfer area	A	**2.342**	m²	Aa	**2.727**	m²	**16.43**	%
Tube length between the tubesheets	l	***1202***	mm	la	*1400*	mm		

Geometry

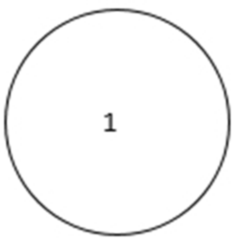
Description of type

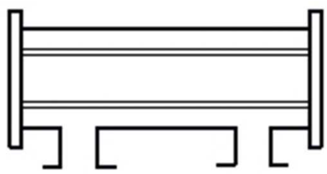
Installation position: horizontal — Shell without baffles

Straight tubes with fixed tubesheets

Shell outside diameter	D_a	***188.9***	mm	Shell wall thickness	s_a	*6.3*	mm
Shell inside diameter	D_i	*176.3*	mm				
Bundle-to-shell clearance		*12*	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	*25*	mm	Tube pitch (longitudinal)	s_2	*21.65*	mm
Pitch angle	Φ	***60***	°				
				Arithmetic mean roughness height of tubes	R_a	*0.002*	mm

Tube material		Steel	
Thermal conductivity	λ_t	*52*	W/(m·K)
Number of tube-side passes		*1*	





Results

Number of tubes	N	31	
Heat transfer coefficient (tube-side)	α_i	**16626**	W/(m²·K)
Heat transfer coefficient (shell-side)	α_o	**9044**	W/(m²·K)
Overall heat transfer coefficient	k	**4373**	W/(m²·K)
Logarithmic mean temperature diff. LMTD	$\Delta\vartheta$	**59.25**	K
FN Factor (Correction factor for LMTD)	FN	**1**	
Total fouling resistance	f	**0**	m²·K/W
Mean heat flux	q	***323912***	W/m²

Tube-side

Inlet velocity		**0.589**	m/s
Outlet velocity		**23.34**	m/s
Pressure drop	Δp_i	**12731**	Pa
Mean tube wall temperature	ϑw_i	**112.1**	°C

Inlet nozzle

Nominal width	DN 50	
Outside diameter	60.3	mm
Inside diameter	54.5	mm
Velocity	**1.574**	m/s

Outlet nozzle

Nominal width	DN 100	
Outside diameter	114.3	mm
Inside diameter	107.1	mm
Velocity	**16.15**	m/s

Shell-side

Velocity (shell-side)		**7.355**	m/s
Pressure drop	Δp_a		Pa
Mean tube wall temperature	ϑw_a	**123.2**	°C

Inlet nozzle

Nominal width	DN 100	
Outside diameter	114.3	mm
Inside diameter	107.1	mm
Velocity	**11.98**	m/s
$\rho \cdot v^2$	**382.8**	kg/(m·s²)

Outlet nozzle

Nominal width	DN 25	
Outside diameter	33.7	mm
Inside diameter	28.5	mm
Velocity	**0.4933**	m/s

Physical properties

Standard Density	$\rho_{S,i}$		kg/m³
Density	ρ_i	*544.8*	kg/m³
Specific heat capacity	cp_i	*2679*	J/(kg·K)
Thermal conductivity	λ_i	*0.1055*	W/(m·K)
Dynamic viscosity	η_i	*0.1248*	mPa·s
Surface tension	σ_i	*8.32*	mN/m
Critical pressure	P_c	*33.7*	bar
Molar mass	MW	*72.15*	kg/kmol
Density	ρ_i	*13.75*	kg/m³
Specific heat capacity	cp_i	*2118*	J/(kg·K)
Thermal conductivity	λ_i	*0.0216*	W/(m·K)
Dynamic viscosity	η_i	*0.008833*	mPa·s
Heat of evaporation	Δh_V	*303400*	J/kg

Standard Density	$\rho_{S,a}$		kg/m³
Density	ρ_a	*915*	kg/m³
Specific heat capacity	cp_a	*4315*	J/(kg·K)
Thermal conductivity	λ_a	*0.6833*	W/(m·K)
Dynamic viscosity	η_a	*0.1802*	mPa·s
Surface tension	σ_a	48.36	mN/m
Critical pressure	P_c	220.6	bar
Molar mass	MW	18.02	kg/kmol
Density	ρ_a	*2.669*	kg/m³
Specific heat capacity	cp_a	2413	J/(kg·K)
Thermal conductivity	λ_a	0.03103	W/(m·K)
Dynamic viscosity	η_a	0.01402	mPa·s
Heat of evaporation	Δh_V	2107420	J/kg

Physical properties at 0.1 · Pc

Reference pressure (Pc/10)	p_{ref}	**337000**	Pa
Heat of evaporation	Δhv_0	*320300*	J/kg
Density of the liquid	$\rho_{F,0}$	*564.4*	kg/m³
Density of the vapour	$\rho_{D,0}$	*9.341*	kg/m³
Surface tension	σ_0	*9.92*	mN/m

Tube sheet data

Description of type
Baffle-type — Without baffles

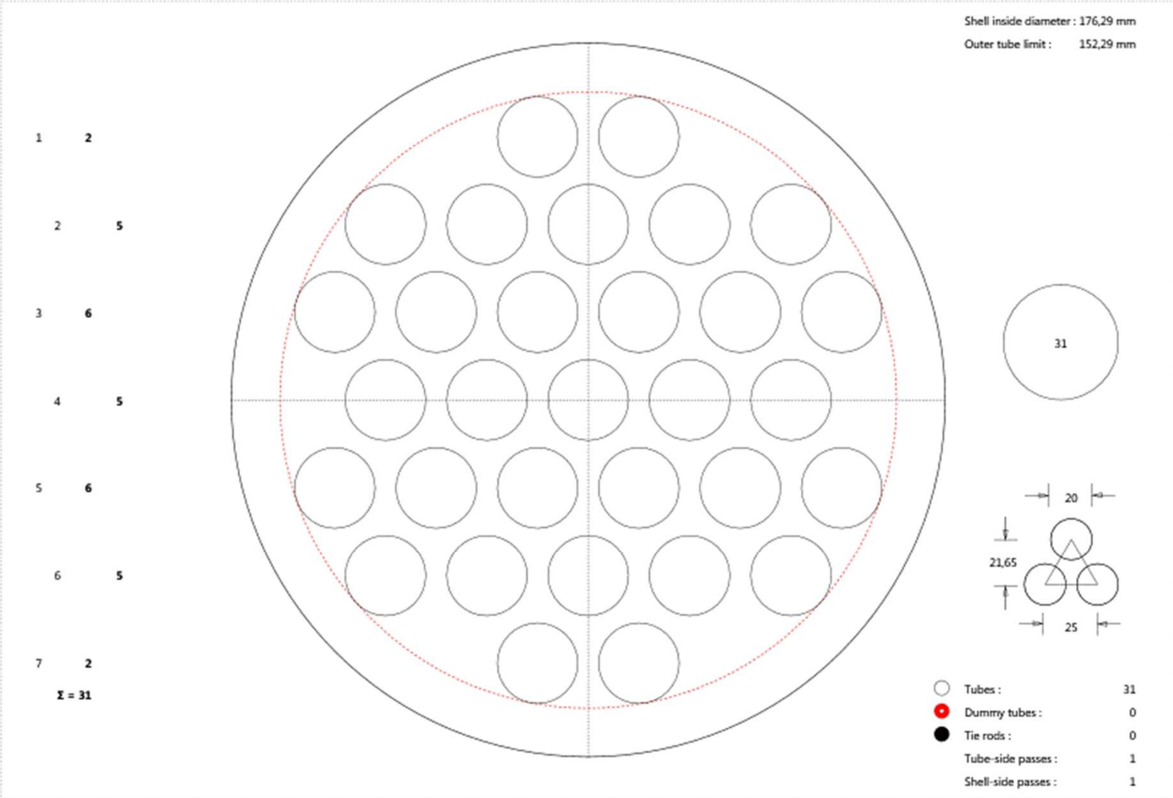
Shell outside diameter	D_o	*188.9*	mm
Shell inside diameter	D_i	*176.3*	mm
Minimum bundle-to-shell clearance	D_m	*12*	mm
Bundle-to-shell clearance	D	***12***	mm
Bundle diameter	D_B	152.3	mm
Tube outside diameter	d_a	*20*	mm
Tube inside diameter	d_i	*16*	mm
Tube pitch (transverse)	s_1	*25*	mm
Tube pitch (longitudinal)	s_2	*21.65*	mm
Pitch angle	Φ	*60*	°
Tube pattern		staggered	
Arrangement		around central tube	
Number of tube-side passes		*1*	
Number of shell-side passes		1	
		0	
Tube lane width (horizontal)		*40*	mm
Tube lane width (vertical)		*40*	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	*31*	
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	31	
Sum of the shortest connecting paths in the center	Le	76.29	mm
Shortest connecting path between tube and tube	e	5	mm
Shortest connecting path between tube and shell	e_1	28.14	mm
Number of connections	n_V	4	
Mean distance boundary tubes - bundle centre	r_h	53.98	mm
Number of boundary tubes required/actual (RR)	/	26	
Perimeter of the tube layout	C_p	425	mm
Total area enclosed by perimeter	A_p	0.01055	m²

Number of tubes, dummy tubes and tie rods per pass

Pass-No.	1	2	3	4	5	6	7	8
	31	0	0	0	0	0	0	0

Final bundle length	l_a	*1400*	mm
Total area	A_{ges}	**2.727**	m²
Number of exchangers in series		*1*	

Nozzles	Tube-side	Shell-side
Inside nozzle diameter (inlet)	*54.5* mm	*107.1* mm
Inside nozzle diameter (outlet)	*107.1* mm	*28.5* mm


Shell inside diameter : 176,29 mm
Outer tube limit : 152,29 mm
1 2
2 5
3 6
4 5
5 6
6 5
7 2
Σ = 31
31
20
21,65
25
Tubes : 31
Dummy tubes : 0
Tie rods : 0
Tube-side passes : 1
Shell-side passes : 1

Free input of physical properties

Physical properties

Name Tube-side medium: Freie Eingabe (n-pentan)

Temperature	ϑ	92.59	°C
Pressure	p	5	bar
Properties of the boiling liquid			
Density	ρ	545	kg/m³
Specific heat capacity	cp	2679	J/(kg·K)
Thermal conductivity	λ	0.1055	W/(m·K)
Dynamic viscosity	η	0.1248	mPa·s
Kinematic viscosity	ν	**2.29e-7**	m²/s
Prandtl number	Pr	**3.169**	
Surface tension	σ	8.32	mN/m
Properties of the saturated vapour			
Density	ρ	13.76	kg/m³
Specific heat capacity	cp	2118	J/(kg·K)
Thermal conductivity	λ	0.0216	W/(m·K)
Dynamic viscosity	η	0.00883	mPa·s
Kinematic viscosity	ν	**6.417e-7**	m²/s
Prandtl number	Pr	**0.8658**	
Heat of evaporation	Δhv	303400	J/kg
Critical pressure	P_c	33.7	bar
Molar mass	M	72.15	kg/kmol
Reference values at the reduced pressure of 0.1 P_c			
Reduced pressure	$p_r = P_c/10$	**3.37**	bar
Saturated vapour			
Density of saturated vapour	$\rho_{G,0.1}$	9.34	kg/m³
Boiling liquid			
Density	$\rho_{L,0.1}$	564.6	kg/m³
Specific heat capacity	$cp_{L,0.1}$	2595	J/(kg·K)
Thermal conductivity	$\lambda_{L,0.1}$	0.1131	W/(m·K)
Dynamic viscosity	$\eta_{L,0.1}$	0.1507	mPa·s
Kinematic viscosity	$\nu_{L,0.1}$	**2.669e-7**	m²/s
Prandtl number	$Pr_{L,0.1}$	**3.458**	
Heat of evaporation	$\Delta hv_{L,0.1}$	320300	J/kg
Surface tension	$\sigma_{L,0.1}$	9.92	mN/m

Properties of water - IAPWS-IF97

		State 1			State 2	
Calculation for saturation?		Yes			No	
Temperature	ϑ_1	151.8	°C	ϑ_2	123.3	°C
Pressure	p_1	**5.001**	bar	p_2	5	bar

Properties of liquid water or superheated steam

		State 1			State 2	
		Liquid			Liquid	
Density	ρ	**915.3**	kg/m³	ρ	**940.6**	kg/m³
Spec. isob. heat capacity	c_p	**4315**	J/(kg·K)	c_p	**4251**	J/(kg·K)
Thermal conductivity	λ	**0.6836**	W/(m·K)	λ	**0.6843**	W/(m·K)
Dynamic viscosity	η	**0.1802**	mPa·s	η	**0.2255**	mPa·s
Kinematic viscosity	ν	**1.969e-7**	m²/s	ν	**2.397e-7**	m²/s
Prandtl number	Pr	**1.138**		Pr	**1.401**	
Thermal diffusivity	a	**1.731e-7**	m²/s	a	**1.711e-7**	m²/s
Specific volume	v	**0.001093**	m³/kg	v	**0.001063**	m³/kg
Spec. isoc. heat capacity	c_v	**3518**	J/(kg·K)	c_v	**3652**	J/(kg·K)
Specific enthalpy	h	**640217**	J/kg	h	**517916**	J/kg
Spec. internal energy	u	**639671**	J/kg	u	**517384**	J/kg
Specific entropy	s	**1861**	J/(kg·K)	s	**1563**	J/(kg·K)
Compressibility factor	Z	**0.002786**		Z	**0.002905**	
Surface tension	σ	**48.35**	mN/m	σ	**54.31**	mN/m
Coefficient of thermal expansion	β	**0.001037**	1/K	β	**8.75e-4**	1/K
Isentropic exponent	κ	**3912**		κ	**4327**	
Speed of sound	w	**1462**	m/s	w	**1517**	m/s
Dielectric constant	ε	**43.65**		ε	**49.87**	

Properties of vapour fraction of wet steam

		State 1			State 2	
Density	ρ	**2.669**	kg/m³	ρ		kg/m³
Spec. isob. heat capacity	c_p	**2413**	J/(kg·K)	c_p		J/(kg·K)
Thermal conductivity	λ	**0.03103**	W/(m·K)	λ		W/(m·K)
Dynamic viscosity	η	**0.01402**	mPa·s	η		mPa·s
Kinematic viscosity	ν	**5.255e-6**	m²/s	ν		m²/s
Prandtl number	Pr	**1.09**		Pr		
Thermal diffusivity	a	**4.82e-6**	m²/s	a		m²/s
Specific volume	v	**0.3747**	m³/kg	v		m³/kg
Spec. isoc. heat capacity	c_v	**1761**	J/(kg·K)	c_v		J/(kg·K)
Specific enthalpy	h	**2748116**	J/kg	h		J/kg
Spec. internal energy	u	**2560712**	J/kg	u		J/kg
Specific entropy	s	**6821**	J/(kg·K)	s		J/(kg·K)
Compressibility factor	Z	**0.9554**		Z		
Coefficient of thermal expansion	β	**0.002935**	1/K	β		1/K
Isentropic exponent	κ	**1.301**		κ		
Speed of sound	w	**493.8**	m/s	w		m/s
Dielectric constant	ε	**1.023**		ε		
Heat of evaporation	Δh_v	**2107899**	J/kg	Δh_v		J/kg
Entropy of evaporation	Δs_v	**4960**	J/(kg·K)	Δs_v		J/(kg·K)
Fraction vaporized	x		-	x		-
Enthalpy of wet steam	hx		J/kg	hx		J/kg
Entropy of wet steam	sx		J/(kg·K)	sx		J/(kg·K)

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	

Real logarithmic temperature difference for different heat exchanger types

Rohrbündelwärmeübertrager

Code number for exchanger type		50	
Inlet temperature outside	ϑ_{a1}	151.9	°C
Outlet temperature outside	ϑ_{a2}	151.8	°C
Inlet temperature inside	ϑ_{i1}	92.58	°C
Outlet temperature inside	ϑ_{i2}	92.6	°C
Logarithmic temperature difference (counterflow)	$d\vartheta_{counter}$	**59.25**	K
Correction factor	FN	**1**	
Real logarithmic temperature difference	$d\vartheta_m$	**59.25**	K

Pressure drop in flow through evaporator tubes - VDI Heat Atlas, 11. Edition 2013, H3.2

Calculation of local variables
Physical properties
Liquid

Density	ρ_l	*544.8*	kg/m³	
Dynamic viscosity	η_l	*0.1248*	mPa·s	
Vapour				
Density	ρ_g	*13.75*	kg/m³	
Dynamic viscosity	η_g	*0.008833*	mPa·s	
Geometry				
Tube length	l	*1400*	mm	
Tube inside diameter	d	*16*	mm	
Absolute roughness	k	**0.09992**	mm	
Relative tube roughness	k/d	0.00625		
Angle of inclination of the tube	θ	0	°	
Boundary conditions				
Mass flow (liquid + vapour)	m_{total}	**0.06452**	kg/s	
Mass flux	m	320.9	kg/(m²·s)	
Local vapour mass fraction	x	0.5		
Vapour mass fraction at the inlet	x_1	0		
Vapour mass fraction at the outlet	x_2	1		
Number of iteration steps	n	4		
Speed of sound in the vapour phase	a	211.1	m/s	
Results				
Froude number	Fr	**21.89**		[3]
Auxiliary value of Froude number	HW	**33.65**		[2b]
	1/β	**39.62**		[2a]
Liquid volume fraction	β	**0.02524**		

Distinction between dispersed and continuous vapour phase

1/β	≤	HW		
39.62		**33.65**	Continuous vapour phase	[2]

1. Frictional pressure drop
a) Dispersed vapour phase

Two phase Reynolds number	Re_{ZP}	**53587**		[6]
Drag coefficient	ξ	**0.034**		[5]
K2 for β ≤ 0.4 or β > 0.4	K2	**1.007**		[7]/[8]
Local frictional pressure drop	dp/dl	**1999**	Pa/m	[4]

b) Continuous vapour phase

Froude number	Fr_1	**0.5525**		[21]
Reynolds number	Re_1	**20569**		[20]
	ψ	**0.002046**		[19]
	ε_2	**0.01862**		[18]
	ε_1	**0.04351**		[16]/[17]
	ε	**0.01816**		[15]
	γ_E	**0.2531**		[14]
	γ_F	**0.6455**		[13]
	E	**0.2902**		[12]
	Φ	**4.558**		[11]
Drag coefficient	ξ	**0.01455**		[10]
Local frictional pressure drop	dp/dl	**3880**	Pa/m	[9]

2. Local static pressure drop

Range differentiation for 1/β

Range 1			1/β	≤	HW			
Range 2	HW	<	1/β	≤	500		1/β	39.62
Range 3	500	<	1/β	≤	10000		HW	33.65
Range 4			1/β	>	10000			Range 2

				1	2	3	4
		Range					
	K	0.9839		[24]	[29]	[30]	[31]
	κ_{tt}	0.2212			[28]	[25]	[25]
	H2	0.1811		[23]	[27]		
	H1	0.1561			[26]		
	H	0.1324			[25]		
Vapour volume fraction	α	0.8676					
Local static pressure drop	dp/dl	0	psi/ft				[22]

3. Acceleration pressure drop

Momentum flux	I	0.5056	kg·m/s²	[33]

4. Integration with the evaporator tube length

Frictional pressure drop	Δp_R	4368	Pa	[21a]
Static pressure drop	Δp_S	0	Pa	
Acceleration pressure drop	Δp_B	7299	Pa	[34a]
Total pressure drop	Δp_{total}	11667	Pa	[1]

Flow patterns of saturated flow boiling - VDI Heat Atlas , 11. Edition 2013, H3.1

Flow patterns in horizontal and slightly inclined tubes

Input variables

Mass flux	$\dot{m}$	320.9	kg/(m²·s)
Vapour mass fraction	$\dot{x}$	0.9	
Hydraulic diameter (tube = di)	d	*16*	mm
Angle of inclination of the tube	Θ	0	° (≤10°)

Physical properties

Liquid

Density	ρ_L	*544.8*	kg/m³
Dynamic viscosity	η_L	*0.1248*	mPa·s
Surface tension	σ	*8.32*	mN/m

Vapour

Density	ρ_G	*13.75*	kg/m³
Dynamic viscosity	η_G	*0.008833*	mPa·s

Flow pattern

0 = Unknown flow
1 = Stratified flow
2 = Wave flow
3 = Bubble flow
4 = Slug / plug flow
5 = Turbulent gas and laminar liquid flow
6 = Mist flow
7 = Annular flow
Flow pattern **7**

Equations

$$X = f\left(\dot{x};\rho_G;\rho_L;\eta_G;\eta_L\right) = f(0.9;13.75\ \text{kg/m}^3;544.8\ \text{kg/m}^3;0.008833\ \text{mPa·s};0.1248\ \text{mPa·s}) = 0.03235$$

$$\xi_L = \frac{0.3164}{Re_L^{\ 0.25}} = \frac{0.3164}{(4114)^{0.25}} = 0.03951$$

$$Re_L = \dot{m} \cdot \left(1-\dot{x}\right) \cdot \frac{d}{\eta_L} = 320.9\ \text{kg/(m}^2\text{·s)} \cdot (1-0.9) \cdot \frac{0.016\ \text{m}}{0.1248\ \text{mPa·s}} = 4114$$

$$Re_G = \dot{m} \cdot \dot{x} \cdot \frac{d}{\eta_G} = 320.9\ \text{kg/(m}^2\text{·s)} \cdot 0.9 \cdot \frac{0.016\ \text{m}}{0.008833\ \text{mPa·s}} = 523110$$

$$(Re_L \cdot Fr_G)^{0.5} = f\left(\dot{m};\dot{x};\rho_G;\rho_L;\eta_L;\Theta\right) =$$

$$f(320.9\ \text{kg/(m}^2\text{·s)};0.9;13.75\ \text{kg/m}^3;544.8\ \text{kg/m}^3;0.1248\ \text{mPa·s};0°) = 547.1$$

$$Fr_{Gm}^{0.5} = f\left(\dot{m};\dot{x};d;\rho_L;\rho_G\right) = f(320.9\ \text{kg/(m}^2\text{·s)};0.9;0.016\ \text{m};544.8\ \text{kg/m}^3;13.75\ \text{kg/m}^3) = 8.422$$

$$(FrEu)_L^{0.5} = f\left(\xi_L;\dot{m};\dot{x};d;\rho_L;\rho_G;\Theta\right) =$$

$$f(0.03951;320.9\ \text{kg/(m}^2\text{·s)};0.9;0.016\ \text{m};544.8\ \text{kg/m}^3;13.75\ \text{kg/m}^3;0°) = 0.02116$$

$$\left(\frac{We}{Fr}\right)_L = f(d;\rho_L;\sigma) = f(0.016\ \text{m};544.8\ \text{kg/m}^3;8.32\ \text{mN/m}) = 164.4$$

$$\varphi = 5.445\ \text{RAD}$$

$$\varepsilon = 0.9848$$

$$\tilde{h}_L = 0.05859$$

$$\tilde{f}_L = f(\tilde{h}_L) = f(0.05859) = 0.01857$$

$$\tilde{f}_G = \frac{\pi}{4} - \tilde{f}_L = \frac{\pi}{4} - 0.01857 = 0.7668$$

$$\tilde{U}_i = f(\tilde{h}_L) = f(0.05859) = 0.4697$$

Nucleate Flow Boiling in Horizontal Tubes (flow boiling pure saturated liquids) - VDI Heat Atlas, 11. Edition 2013, H3.4

Nucleate flow boiling in horizontal tubes

Boundary conditions

Boundary condition	*Constant wall temperature*
Type of substance	Non-cryogen
Flow pattern	*Annular flow*

Input variables

Heat flux	$\dot{q}$	*323912*	W/m²
Number of tubes	n		
Inside tube diameter	d_i	*16*	mm
Tube wall thickness	s	*2*	mm
Thermal conductivity of tube	λ_W	*52*	W/(m·K)
Wall heat conduction	$\lambda_W \cdot s$	**0.104**	W/K
Arithmetic mean roughness height	R_a	*0.002*	mm
Mass flow	m		kg/s
Mass flux	$\dot{m}$	*320.9*	kg/(m²·s)
Vapour mass fraction	$\dot{x}$	*0.9*	
Coordinate in direction of flow	z	*1202*	mm
Boiling temperature	T_S	*92.59*	°C
Boiling pressure	p_S	*500000*	Pa
Critical pressure	p_c	*3370000*	Pa
Reduced pressure ($p^* = p / p_c$)	p^*	**0.1484**	

Physical properties at boiling pressure p_S

Liquid

Density	ρ_L	*544.8*	kg/m³
Specific heat capacity	cp_L	*2679*	J/(kg·K)
Thermal conductivity	λ_L	*0.1055*	W/(m·K)
Dynamic viscosity	η_L	*0.1248*	mPa·s
Prandtl number	Pr	**3.169**	
Surface tension	σ	*8.32*	mN/m
Heat of evaporation	Δh_v	*303400*	J/kg

Vapour

Density	ρ_G	*13.75*	kg/m³
Specific heat capacity	cp_G	*2118*	J/(kg·K)
Thermal conductivity	λ_G	*0.0216*	W/(m·K)
Dynamic viscosity	η_G	*0.008833*	mPa·s

Properties at reference boiling pressure $p_0 = 0.1 \cdot p_c$

Reference boiling pressure ($p_0 = 0.1 \cdot p_c$)	p_0	**337000**	Pa
Liquid			
Density	$\rho_{L,0}$	*564.4*	kg/m³
Specific heat capacity	$cp_{L,0}$	*2595*	J/(kg·K)
Thermal conductivity	$\lambda_{L,0}$	*0.1131*	W/(m·K)
Dynamic viscosity	$\eta_{L,0}$	*0.1507*	mPa·s
Kinematic viscosity	$\nu_{L,0}$	**2.67e-7**	m²/s
Prandtl number	$Pr_{L,0}$	**3.458**	
Surface tension	σ_0	*9.92*	mN/m
Heat of evaporation	$\Delta h_{v,0}$	*320300*	J/kg

Vapour

Density	$\rho_{G,0}$	*9.341*	kg/m³
Molar mass of the medium	M	*72.15*	kg/kmol
Factor C_F for horizontal tubes	$C_{F,h}$	**1.169**	
Factor C_F for vertical tubes	$C_{F,v}$	**1.143**	

Reference values

Reference heat flux	$\dot{q}_0$	*20000*	W/m²
Reference heat transfer coefficient	α_0	*3070*	W/(m²·K)

(Reference value for the heat transfer coefficient in nucleate boiling at q_0, p_0 and R_{a0} = 1.0 µm)

Reference tube diameter	d_0	10	mm
Arithmetic mean roughness height	R_{a0}	0.001	mm

Correction factors

Correction factor for the exponent n (p*)	κ	**1**
Correction factor for $C_{F,h}$	ψ	**1**

Results

Heat flux		$\dot{q}$	*323912*	W/m²
Heat flux at the onset of nucleate boiling		q_{onb}	**8414**	W/m²
Heat transfer coefficient (convective boiling)		$\alpha(z)_K$	**7125**	W/(m²·K)
Heat transfer coefficient (nucleate boiling)	$q \geq q_{onb}$	$\alpha(z)_B$	**6903**	W/(m²·K)

Heat transfer coefficient (Superposition of convective and nucleate boiling)	$\alpha(z)$	**8840**	W/(m²·K)

Design variables

$$q_{onb}=\frac{2\cdot\sigma\cdot T_s\cdot\alpha_{LO}}{r_{cr}\cdot\rho_G\cdot\Delta h_v}=\frac{2\cdot 8.32\ \text{mN/m}\cdot 365.7\ \text{K}\cdot 1730\ \text{W/(m}^2\cdot\text{K)}}{3\text{e-}7\ \text{m}\cdot 13.75\ \text{kg/m}^3\cdot 303400\ \text{J/kg}}=8414\ \text{W/m}^2$$

$$p^*=\frac{p}{p_c}=\frac{500000\ \text{Pa}}{3370000\ \text{Pa}}=0.1484$$

$n(p^*)$ = **0.6191**
$F(p^*)$ = **1.185**
$F(d)$ = **0.7906**
$F(W)$ = **1.097**
$F\left(\dot{m},\dot{x}\right)$ = **0.3338**

$$\frac{\alpha(z)_B}{\alpha_0}=C_F\cdot\left[\frac{\dot{q}}{\dot{q}_0}\right]^n\cdot F(p^*)\cdot F(d)\cdot F(W)\cdot F\left(\dot{m},\dot{x}\right)=$$

$$1.169\cdot\left[\frac{323912\ \text{W/m}^2}{20000\ \text{W/m}^2}\right]^{0.6191}\cdot 1.185\cdot 0.7906\cdot 1.097\cdot 0.3338=2.249$$

$\alpha(z)_B$ = **6903** W/(m²·K) $q \geq q_{onb}$

$$\alpha(z)=\sqrt[3]{(\alpha(z)_B)^3+(\alpha(z)_K)^3}=\sqrt[3]{(6903\ \text{W/(m}^2\cdot\text{K)})^3+(7125\ \text{W/(m}^2\cdot\text{K)})^3}=8840\ \text{W/(m}^2\cdot\text{K)}$$

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	Freie Eingabe (n-pentan)				Steam condensation		
Inlet pressure (abs.)	p_i	*500000*	Pa	p_a	*500000*	Pa
Pressure stage	PN	6		PN	6	
Inlet temperature	$\vartheta_{e,i}$	*92.58*	°C	$\vartheta_{e,a}$	*151.9*	°C
Outlet temperature	$\vartheta_{a,i}$	*92.6*	°C	$\vartheta_{a,a}$	*151.8*	°C
Mean temperature	$\vartheta_{m,i}$	**92.59**	°C	$\vartheta_{m,a}$	**151.8**	°C
Design temperature		110	°C		180	°C
Design pressure		600000	Pa		600000	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	50		DN	100	
Outside diameter		60.3	mm		114.3	mm
Nozzle wall thickness		**2.9**	mm		**3.6**	mm
Inside diameter		*54.5*	mm		*107.1*	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	100		DN	25	
Outside diameter		114.3	mm		33.7	mm
Nozzle wall thickness		**3.6**	mm		**2.6**	mm
Inside diameter		*107.1*	mm		*28.5*	mm

CAD Data

Diameter of bore in tube sheet mm

CAD Tubesheet Configuration

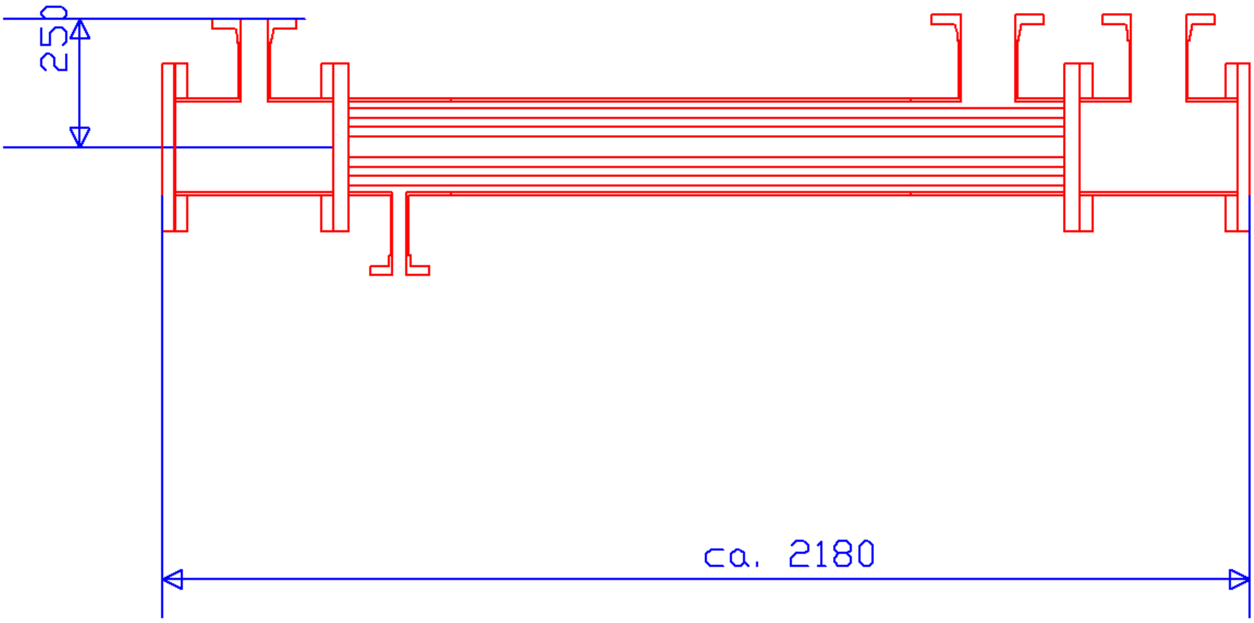
Front head a - tubesheet integral with shell and channel

Rear head a - tubesheet integral with shell and channel

Geometry

Shell outside diameter	D_a	*188.9*	mm	Shell wall thickness	s_a	*6.3*	mm
Shell inside diameter	D_I	**176.3**	mm				
Bundle-shell distance		*12*	mm				
Tube outside diameter	d_a	*20*	mm	Tube inside diameter	d_I	*16*	mm
Tube pitch (transverse)	s_1	*25*	mm	Tube pitch (longitudinal)	s_2	*21.65*	mm
Pitch angle	Φ	**60**	°	Pass lane width	b	*40*	mm

Number of tube-side passes	n_t	*1*	
Number of shell-side passes	n_s	1	
Final bundle length	l_a	*1400*	mm
Final shell length	l_a	**1400**	mm
Number of tubes	R	*31*	
Expansion joint diameter			mm
Plate thickness (fixed plate)		30	mm
Outside diameter of tube sheet		168	mm
Plate thickness (free plate)		30	mm
Outside diameter of tube sheet (floating head)		168	mm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Film condensation at horizontal tubes (pure vapours) - VDI Heat Atlas, 11. Edition 2013, J1

Condensation around single tubes or tube rows, stationary vapour

Number of tubes	n_R	*31*	
Number of tube rows	n_{RR}	5	
Tube length	L	*1202*	mm
Condensate mass flow	M_F	0.288	kg/s
Condensate mass flow per tube	$M_{F,R}$	**0.009289**	kg/s
Correction factor for Nu number of tube rows	i	**-0.1667**	
Saturation temperature	ϑ_S	*151.8*	°C
Physical properties of liquid at saturation temperature			
Specific heat capacity	cp_F	*4315*	J/(kg·K)
Density	ρ_F	*915*	kg/m³
Thermal conductivity	λ_F	*0.6833*	W/(m·K)
Dynamic viscosity	η_F	*0.1802*	mPa·s
Kinematic viscosity	ν_F	**1.97e-7**	m²/s
Prandtl number	Pr_F	**1.138**	
Physical properties of vapour at saturation temperature			
Density	ρ_D	*2.669*	kg/m³
Results			
Characteristic length	L_C	**0.01582**	mm
Trickle density	Γ	**0.007726**	kg/(m·s)
Reynolds number	Re_F	**42.86**	
Single tube			
Nu number single tube	$Nu_{F,L}$	**0.2738**	
Mean heat transfer coefficient	$\alpha_{F,L}$	**11827**	W/(m²·K)
Tube rows			
Nu number horizontal tube rows	$Nu_{F,L,RR}$	**0.2093**	
Mean heat transfer coefficient	$\alpha_{F,L,RR}$	**9044**	W/(m²·K)

Equations

$$\Gamma=\frac{M_{F,R}}{L}=\frac{0.009289\ \text{kg/s}}{1.202\ \text{m}}=0.007726\ \text{kg/(m·s)}$$

$$Re_{F}=\frac{M_{F,R}}{L\cdot\eta_{F}}=\frac{0.009289\ \text{kg/s}}{1.202\ \text{m}\cdot 0.1802\ \text{mPa·s}}=42.86$$

$$L_{C}=\sqrt[3]{\frac{v_{F}^{2}}{g}}=\sqrt[3]{\frac{(1.97\text{e-7}\ \text{m²/s})^{2}}{g}}=1.582\text{e-5}\ \text{m}$$

Single tube

$$Nu_{F,L}=0.959\cdot\left[\frac{\left[1-\frac{\rho_{D}}{\rho_{F}}\right]}{Re_{F}}\right]^{\frac{1}{3}}=0.959\cdot\left[\frac{\left[1-\frac{2.669\ \text{kg/m³}}{915\ \text{kg/m³}}\right]}{42.86}\right]^{\frac{1}{3}}=0.2738$$

$$\alpha_{F,L}=\frac{Nu_{F,L}\cdot\lambda_{F}}{L_{C}}=\frac{0.2738\cdot 0.6833\ \text{W/(m·K)}}{1.582\text{e-5}\ \text{m}}=11827\ \text{W/(m²·K)}$$

Tube rows

$$Nu_{F,l,RR}=Nu_{F,l}\cdot n_{RR}^{\,i}=0.2738\cdot(5)^{-0.1667}=0.2093$$

$$\alpha_{F,L,RR}=\frac{Nu_{F,L,RR}\cdot\lambda_{F}}{L_{C}}=\frac{0.2093\cdot 0.6833\ \text{W/(m·K)}}{1.582\text{e-5}\ \text{m}}=9044\ \text{W/(m²·K)}$$

Convective Flow Boiling in Horizontal Tubes (saturated pure liquids) - VDI Heat Atlas, 11. Edition 2013, H3.4

Convective flow boiling in horizontal tubes

Boundary condition	*Constant wall temperature*		
Flow pattern	*Annular flow*		
Mass flux	$\dot{m}$	*320.9*	kg/(m²·s)
Vapour mass fraction	$\dot{x}$	*0.9*	
Coordinate in direction of flow	z	*1202*	mm
Tube inside diameter	d_i	*16*	mm
Wall thickness	s	*2*	mm
Thermal conductivity	λ_W	*52*	W/(m·K)
Physical properties			
Liquid			
Density	ρ_L	*544.8*	kg/m³
Specific heat capacity	cp_L	*2679*	J/(kg·K)
Thermal conductivity	λ_L	*0.1055*	W/(m·K)
Dynamic viscosity	η_L	*0.1248*	mPa·s
Surface tension	σ	*8.32*	mN/m
Heat of evaporation	Δh_v	*303400*	J/kg
Vapour			
Density	ρ_G	*13.75*	kg/m³
Specific heat capacity	cp_G	*2118*	J/(kg·K)
Thermal conductivity	λ_G	*0.0216*	W/(m·K)
Dynamic viscosity	η_G	*0.008833*	mPa·s
Results			
$\alpha(z)_k / \alpha_{LO}$		**5.39**	
Heat transfer coefficient	$\alpha(z)_k$	**7125**	W/(m²·K)

Convective flow boiling in horizontal tubes

Interim results

Liquid		**Vapour**		**Only for stratified flow**	
Pr_L	**3.169**	Pr_G	**0.8661**		
Re_{LO}	**41138**	Re_{GO}	**581233**	Re_{hG}	**525226**
ξ_L	**0.0219**	ξ_G	**0.01276**	ξ_{hG}	**0.013**
$Nu_{\infty,L}$	**196.8**	$Nu_{\infty,G}$	**840.8**	$Nu_{\infty,hG}$	**773.9**
Nu_{L0}	**200.5**	Nu_{G0}	**856.6**	Nu_{hG}	**788.3**
α_{LO}	**1322**	α_{GO}	**1156**	α_G	**1076**
				α_{Lb}	**7125**
				M	**48.69**
				Φ	**0.4333**
				Ψ	**1**

Excel Specification Sheet

Customer					Job No. Reference No.	
Address					Proposal No.	
Plant Location					Date	07.11.2019
TEMA-Type: AEL		Installation position: Horizontal			Connected in 1 series	paralell
PERFORMANCE OF ONE UNIT						
Fluid Allocation			**Shell-Side (Condensation)**		**Tube-Side (Vaporization)**	
Fluid Name			Steam condensation		Freie Eingabe (n-pentan)	
Fluid Quantity, Total		kg/s	0,29		2	
Vapour	(In / Out)	kg/s	0,29	0	0	2
Liquid	(In / Out)	kg/s	0	0,29	2	0
Fluid Volume Flow, Total		m³/h	388,43		13,22	
Steam						
Water						
Noncondensables						
Temperature	(In / Out)	°C	151,9	151,8	92,6	92,6
Density		kg/m³	2,67	915	544,8	13,8
Viscosity		mPa·s	0,014	0,1802	0,1248	0,0088
Molecular Weight, Vapour		kg/kmol				
Molecular Weight, Noncondensables		kg/kmol				
Specific Heat		J/(kg·K)	2412,7	4314,9	2679	2118
Thermal Conductivity		W/(m·K)	0,031	0,6833	0,1055	0,0216
Latent Heat		J/kg	2107420		303400	
Inlet Pressure (abs.)		bar	5		5	
Velocity		m/s	7,36			
Pressure Drop, Allow. / Calc.		Pa				11667
Fouling Resistance		m²·K/W	0		0	
Heat Exchanged		kW	606,9			
Transfer Rate, Service		W/(m²·K)	4373,2			
MTD (Corrected)		K (diff)	59,25			
Heat Transfer Area		m²	2,7			
CONSTRUCTION OF ONE SHELL					Sketch (Bundle/Nozzle Orientation)	
			Shell-Side	**Tube-Side**		
Design / Test Pressure		Pa				
Design Temperature		°C				
No. Passes per Shell			1	1		
Corrosion Allowance		mm				
Connections	In		DN 100	DN 50		
Size &	Out		DN 25	DN 100		
Rating	Intermediate					
Tube Length		mm	1400	Tube Material		Steel
Tube Dimensions (OD x Thk)		mm	20 x 2	No. of Tubes		31
Pitch (Transverse)		mm	25	Pitch (Longitudinal)		21,7
Shell ID		mm	176,3	Shell Dimensions (OD x Thk)		188,89 x 6,3
Channel or Bonnet				Channel Cover		
Tubesheet-Stationary				Tubesheet-Floating		
Floating Head Cover				Impingement Protection		
Baffles-Cross				Baffle Cut in % of Shell ID		
Central Baffle Spacing				Number of Baffles / Shell-Side Path		
Inlet Baffle Spacing				Number of Sealing Strips Pairs		
Expansion Joint				Type		
$\rho \cdot v^2$ Bundle Entrance		kg/(m·s²)	383	$\rho \cdot v^2$ Bundle Exit		
Gaskets-Shell Side				Tube Side		
- Floating Head						
Code Requirements				TEMA Class		
Weight / Shell		kg		Filled with Water		
Weight / Bundle		kg				
Remarks