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Flooding Velocity in Vertical Shell and Tube Condensers

Use this calculation procedure to calculate the minimum flooding velocity in a vertically mounted shell and tube condenser.

This procedure includes helpful worksheets to obtain the necessary physical properties for the calculation as well as heat exchanger tube data.

The spreadsheet includes both english and metric units.

Do not rename sheets in this workbook

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Revision History :

Flooding Velocity in Vertical Shell and Tube Condensers

Applicable to: Vertically oriented shell and tube condensers with upflow vapors on the tubeside

Assumption of Method:

- Methods used are based on correlations derived from experimental data
- Actual vapor velocity calculated is the velocity at the tube entrance

Calculation Details:

Begin by defining the physical properties of the fluids in the system.

Define the liquid density at the condensing temperature:

$$\rho_L = 880 \text{ kg/m}^3 \quad \text{Liquid Density Worksheet}$$

Define the vapor density at the condensing temperature and pressure:

$$\rho_V = 14.4 \text{ kg/m}^3 \quad \text{Vapor Density Worksheet}$$

Define the surface tension of the liquid:

$$\sigma = 28 \text{ dynes/cm} \quad \text{Surface Tension Worksheet}$$

Define the liquid viscosity at the condensing temperature:

$$\mu_L = 0.33 \text{ cP} \quad \text{Liquid Viscosity Worksheet}$$

Next, identify the heat exchanger geometry:

$$\begin{aligned} \text{Number of Tubes} &= 200 \\ \text{Inside Diameter (D}_i\text{)} &= 18.59 \text{ mm} \quad \text{Tube Data Lookup Chart} \\ A_x &= 0.05428 \text{ m}^2 \end{aligned}$$

Identify the mass flow rates at the end of the exchanger:

$$\text{Liquid Mass Flow Rate} = 2273 \text{ kg/h (condensate flow out of exchanger)}$$

$$\text{Vapor/Gas Mass Flow Rate} = 2273 \text{ kg/h (vapor flow into exchanger)}$$

**For total condensation, enter "1" here --> (for partial condensation, leave blank)

*** Vapor flow into exchanger must be larger than or equal to the condensate flow out of the exchanger

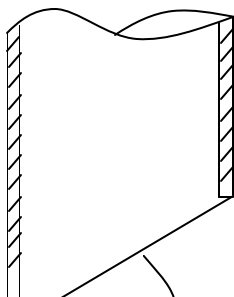
Choose tube end style:

Cut tubes can result in a significant increase in the maximum allowable flooding velocity:

Angle	% increase in allowable gas flow rate
30°	5
60°	25
70°	55

Square End (standard tubes)

Cut Tubes (below)

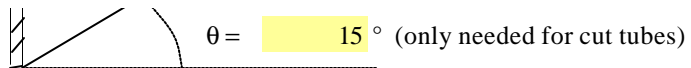


References:

Alekseev and English, et.al, presented by ESDU, "Reflux Condensation in Vertical Tubes", Data Item 89038, 1989. HEDH, page 2.6.2-7

Nomenclature

ρ_L = liquid density (kg/m³)
 ρ_V = vapor density (kg/m³)
 σ = liq. surface tension (dynes/cm)
 μ_L = liquid viscosity (cP)
 D_i = tube inside diameter (mm)
 A_x = cross sectional area (m²)
 M_L = liquid mass flow rate (kg/h)
 M_V = vapor mass flow rate (kg/h)
 θ = tube cut angle (degrees)
 V_{flood} = flooding velocity (m/s)
 V_{actual} = actual vapor velocity (m/s)



Cut Tubes

For cut tubes, the following relation applies:

$$V_{\text{flood}} = \frac{0.3 D_i^{0.30}}{(\cos \theta)^{0.32}} \left\{ \frac{\rho_L^{0.46} \sigma^{0.09}}{\rho_V^{0.50} \mu_L^{0.14}} \right\} (M_L/M_V)^{-0.07}$$

0.094834
13.2719
1

this correlation is based on experimental data and the correlation was formed with SI units.

$$\begin{aligned} \rho_L &= 880 \text{ kg/m}^3 &= 880 \text{ kg/m}^3 \\ \rho_V &= 14.4 \text{ kg/m}^3 &= 14.4 \text{ kg/m}^3 \\ \sigma &= 28 \text{ dynes/cm} &= 0.028 \text{ N/m} \\ \mu_L &= 0.33 \text{ cP} &= 0.00033 \text{ Pa s} \\ D_i &= 18.59 \text{ mm} &= 0.01859 \text{ m} \end{aligned}$$

$$V_{\text{flood}} = 1.26 \text{ m/s}$$

$$\text{Maximum design velocity} = V_{\text{flood}} \times \text{Safety Factor} = 1.26 \times 0.8 = \underline{0.94} \text{ m/s}$$

$$V_{\text{actual}} = 0.81 \text{ m/s} \text{ should be less than } 0.94 \text{ m/s}$$

If the actual vapor velocity exceeds the maximum design velocity, increase tube size or increase the number of tubes. When conducting heat transfer calculations, this geometry should be your starting point to avoid flooding.

Liquid Density Calculation Worksheet

[Return to English Units](#)

[Return to Metric Units](#)

1. For pure fluids, check the [table below](#)
If your fluid is not listed, consult one of many good source in print or online.
2. For mixtures, use a weighted average of the liquid densities of each component:

$$\rho_{\text{mix}} = \sum x_i \rho_i$$

Mass Fractions	Liquid Densities	Weighted Densities	
0.2	62	12.4	
0.1	95	9.5	
0.3	55	16.5	
0.5	58	29	
		0	
		0	
		<hr/>	
		67.4	Estimated Mixture Density

Vapor Density Calculation Worksheet

[Return to English Units](#)

[Return to Metric Units](#)

1. For pure vapor below 10 bar or 150 psi, employ the ideal gas law:

English Units

$$\rho_{\text{vap}} = \frac{P (\text{MW})}{R T} = \frac{25.5 \text{ psia}}{11 \text{ ft}^3 \text{ psia}} \times \frac{85 \text{ lb}}{\text{lb-mole}} \times \frac{1 \text{ lb-mole } ^\circ\text{F}}{250 \text{ } ^\circ\text{F}}$$

$$= 0.808 \text{ lb / ft}^3$$

Metric Units

$$\rho_{\text{vap}} = \frac{P (\text{MW})}{R T} = \frac{1.8 \text{ bar}}{0.08 \text{ L bar}} \times \frac{85 \text{ g}}{\text{mol}} \times \frac{1 \text{ mol } ^\circ\text{C}}{120 \text{ } ^\circ\text{C}}$$

$$= 15.336 \text{ g / L or kg / m}^3$$

2. For pure vapors above 10 bar or 150 psi, employ the Redlick-Kwong relationship to calculate the compressibility:

$$Z^3 - Z^2 + (A-B-B^2)Z - AB = 0$$

where:

$$A = \frac{0.4278 Pr}{Tr^{2.5}} \quad \text{and} \quad B = \frac{0.08664 Pr}{Tr}$$

$$Tr = T / Tc$$

$$Pr = P / Pc$$

[Lookup Chart for Critical Temperatures and Pressures](#)

English Units

$$Tc = 455.36 \text{ } ^\circ\text{F} \quad \text{Operating Temperature} = 600 \text{ } ^\circ\text{F}$$

$$Pc = 734.8 \text{ psia} \quad \text{Operating Pressure} = 100 \text{ psia}$$

$$Tr = 1.31764 \text{ } ^\circ\text{F} \quad Pr = 0.136091 \text{ psia}$$

$$A = 0.029213 \quad B = 0.008949$$

$$Z = \text{####} \quad \text{Solver Cell} = 0.000 \quad (\text{set equal to zero})$$

If you have Solver installed, press "Ctrl+s" to solve

Then, compressibility can be added to the gas equation for improved accuracy:

$$\rho_{\text{vap}} = \frac{P (\text{MW})}{R T Z} = \frac{100 \text{ psia}}{11 \text{ ft}^3 \text{ psia}} \times \frac{85 \text{ lb}}{\text{lb-mole}} \times \frac{1 \text{ lb-mole } ^\circ\text{F}}{600 \text{ } ^\circ\text{F}} \times \frac{1}{0.980}$$

$$= 1.348 \text{ lb / ft}^3$$

[Lookup Chart for Critical Temperatures and Pressures](#)

Metric Units

$T_c = 235.2 \text{ }^\circ\text{C}$ Operating Temperature = $200 \text{ }^\circ\text{C}$

$P_c = 50.6 \text{ bara}$ Operating Pressure = 20 bara

$T_r = 0.850340 \text{ }^\circ\text{C}$ $P_r = 0.395257 \text{ bara}$

$A = 0.253594$ $B = 0.040272$

$Z = \text{####}$ Solver Cell = 0.000 (set equal to zero)

If you have Solver installed, press "Ctrl+d" to solve

Then, compressibility can be added to the gas equation for improved accuracy:

Metric Units

$$\rho_{\text{vap}} = \frac{P (\text{MW})}{R T Z} = \frac{20 \text{ bar} \quad | \quad 85 \text{ g} \quad | \quad \text{mol } ^\circ\text{C}}{\text{mol} \quad | \quad 0.08 \text{ L bar} \quad | \quad 200 \text{ }^\circ\text{C} \quad | \quad 0.729}$$
$$= 140.3 \text{ g / L} \quad \text{or} \quad \text{kg / m}^3$$

3. For vapor mixtures where the density is not known consult the following online calculation which utilizes Peng-Robinson:
<http://www.questconsult.com/~jrm/thermot.html>

If one or more of your components are not available in the component list at this site, you may have to utilize another EOS along with Kay's method and generalized compressibility charts.

Liquid Surface Tension Calculation Worksheet

[Return to English Units](#)
[Return to Metric Units](#)

1. For pure liquids, check the following source of online data:

<http://www.chem.org/kdb/index.html>

<http://gpengineeringsoft.com/pages/products.html>

(Download PhysProps)

If you still cannot find the data that you need, email support at:

support@cheresources.com

and request the following parameters for your chemical:

A =	132.674	Default data is	Conversion	
Tc =	647.13 K	for water	54 °C =	327 K
n =	0.955		100 °F =	311 K

Then enter the temperature of your system = 298.15 K

Surface Tension = 73.56 dynes/cm

Please refer to "Chemical Properties Handbook", page 216 with your request.

2. If your system is a mixture of organic compounds and does not contains water, employ the following to estimate the surface tension for the mixture:

$$\sigma_m^{1/4} = \rho_{Lm} \Sigma((x_i \sigma_i^{1/4}) / \rho_{Li})$$

where:

σ_m =	surface tension of the mixture (dynes/cm)
ρ_{Lm} =	liquid density of the mixture (g/cm ³)
x_i =	mole fraction for each component
σ_i =	surface tension of each component (dynes/cm)
ρ_{Li} =	liquid density for each component (g/cm ³)

Density Conversion:

58.5 lb/ft³ = 0.93708 g/cm³

Enter the data below, employing the units described above:

	Components	Mole Fractions	Component Surface Tensions	Component Liquid Densities
1	Benzene	0.577	28.23	0.8722
2	Diethyl Ether	0.423	16.47	0.7069
3				
4				
5				
6				

Enter the mixture liquid density = 0.7996 g/cm³

$$((x_1 \sigma_1^{1/4}) / \rho_{L1}) = 1.52489$$

$$((x_2 \sigma_2^{1/4}) / \rho_{L2}) = 1.20547$$

$$((x_3 \sigma_3^{1/4}) / \rho_{L3}) = 0$$

$$((x_4 \sigma_4^{1/4}) / \rho_{L4}) = 0$$

$$((x_5 \sigma_5^{1/4}) / \rho_{L5}) = 0$$

$$((x_6 \sigma_6^{1/4}) / \rho_{L6}) = 0$$

2.73035

$$\sigma_m = \underline{\underline{22.72}} \text{ dynes/cm}$$

This method is best for mixtures that are soluble in one another. It assumes that the surface of the liquid will act like the bulk of the liquid.

3. If your system contains water and one other component, request a surface tension estimate from support or reference the following:
"Properties of Gases and Liquids" by Reid, et. Al, page 648
support@cheresources.com
4. If your system contains water and multiple other components, consult a process simulator or a known reliable model for your fluid. These types of systems are best suited to experimentation.

Liquid Viscosity Calculation Worksheet

1. For pure fluids, lookup the constant values on the [Table](#) below and enter them into the following calculation:

		Conversion	
System Temperature =	373 K	100 °C =	373 K
Constant B =	658.23	100 °F =	311 K
Constant C =	283.16		

Default constants are for water (B=658.25, C=283.16)

Liquid Viscosity = 0.275 cP

This method is best for saturated liquids.

If your liquid is not shown in the list below, consult the following online source:

<http://www.cheric.org/kdb/index.html>

2. For liquid mixtures, there has been much experimental work performed and the error level for most of these correlations does not justify the complexity of their use for a property that can be easily measured. If measurements are not available, utilize the following estimate for the properties of the mixture:

This method assume that the components are soluble in one another.

$$\text{LN } \mu_{\text{mix}} = x_1 \text{ LN } \mu_1 + x_2 \text{ LN } \mu_2 + \dots$$

	<u>Component</u>	<u>Mole Fraction in Process Stream</u>	<u>Viscosity of Component at System Pressure (cP)</u>
1	Benzene	0.6	0.608
2	Toluene	0.4	0.558
3			
4			
5			
6			

$$x_1 \text{ LN } (\mu_1) = -0.2985$$

$$x_2 \text{ LN } (\mu_2) = -0.2334$$

$$x_3 \text{ LN } (\mu_3) = 0$$

$$x_4 \text{ LN } (\mu_4) = 0$$

$$x_5 \text{ LN } (\mu_5) = 0$$

$$x_6 \text{ LN } (\mu_6) = 0$$

$$\hline -0.5319$$

$$\mu_{\text{mix}} = \underline{0.587} \text{ cP}$$