ChE 455
Fall 2009
Major 1

Phthalic Anhydride Production

Background

You work for an operating company that produces, among other products, phthalic anhydride via the partial oxidation of o-xylene in a fixed-bed catalytic reactor. The plant produces approximately 75,000 tonne/y of high-purity (99.9 mol%) phthalic anhydride in a plant with a stream factor of approximately 93%. The phthalic anhydride produced from this plant is used primarily as a plasticizer. Our current customers are expecting an increase in demand for their product and have asked us to increase our production of phthalic anhydride.

Process Description

Unit 1700 produces phthalic anhydride (PA) via the partial oxidation of o-xylene using air. The current process is illustrated in Figure 1, and Tables 1 and 2 are the stream tables and utility summary, respectively. Table 3 is a partial equipment summary.

Air is compressed to approximately 220 kPa in a single-stage centrifugal compressor (C-1701) and heated to 245°C using high-pressure steam in heat exchanger E-1701. This hot compressed air is then mixed with o-xylene feed that has been pumped to approximately 290 kPa using P-1701A/B and subsequently heated and vaporized in E-1702 using high-pressure steam. The combined o-xylene and air stream enters the fixed-bed catalytic reactor, R-1701, at 245°C and 200 kPa. For safety reasons, the concentration of o-xylene is kept at or below the lower explosive limit of 1 mol%. The ratio of o-xylene to air is set using a ratio controller between the compressor and the control valve on the pump.

In the reactor, the o-xylene is subject to a variety of oxidation reactions to produce the desired product of PA, byproduct maleic anhydride (MA), products of combustion, and a small amount of benzoic acid. All these reactions are highly exothermic, and the temperature of the reactor is controlled by heat exchange with a stream of cooling medium (Dowtherm A™) that flows cocurrently through the shell-side of the reactor. The Dowtherm A is circulated through the reactor in a closed loop by pumps P-1702A/B. Heat is removed from the Dowtherm A in E-1703 by vaporizing boiler feed water (bfw) to produce high-pressure steam (hps).

The reactor effluent (Stream 5) leaves the reactor at 353°C and 130 kPa. The pressure drop across the reactor is caused by the flow of the reactant gases through the catalyst-filled tubes. This stream is cooled in a series of heat exchangers (E-1704-E1706), in which the temperature of the process stream is reduced to 45°C and high-pressure (hps) and low-pressure steam (lps) are generated, and cooling water (cw) is used for the final product cooling. The cooled reactor effluent (Stream 6) is a two-phase mixture at this point, and it is then sent to a set of switch condensers (SC-1701A/B/C) to recover the PA. This is achieved by cooling and desublimating the PA as a solid in one condenser using chilled oil. Simultaneously, solid PA is melted

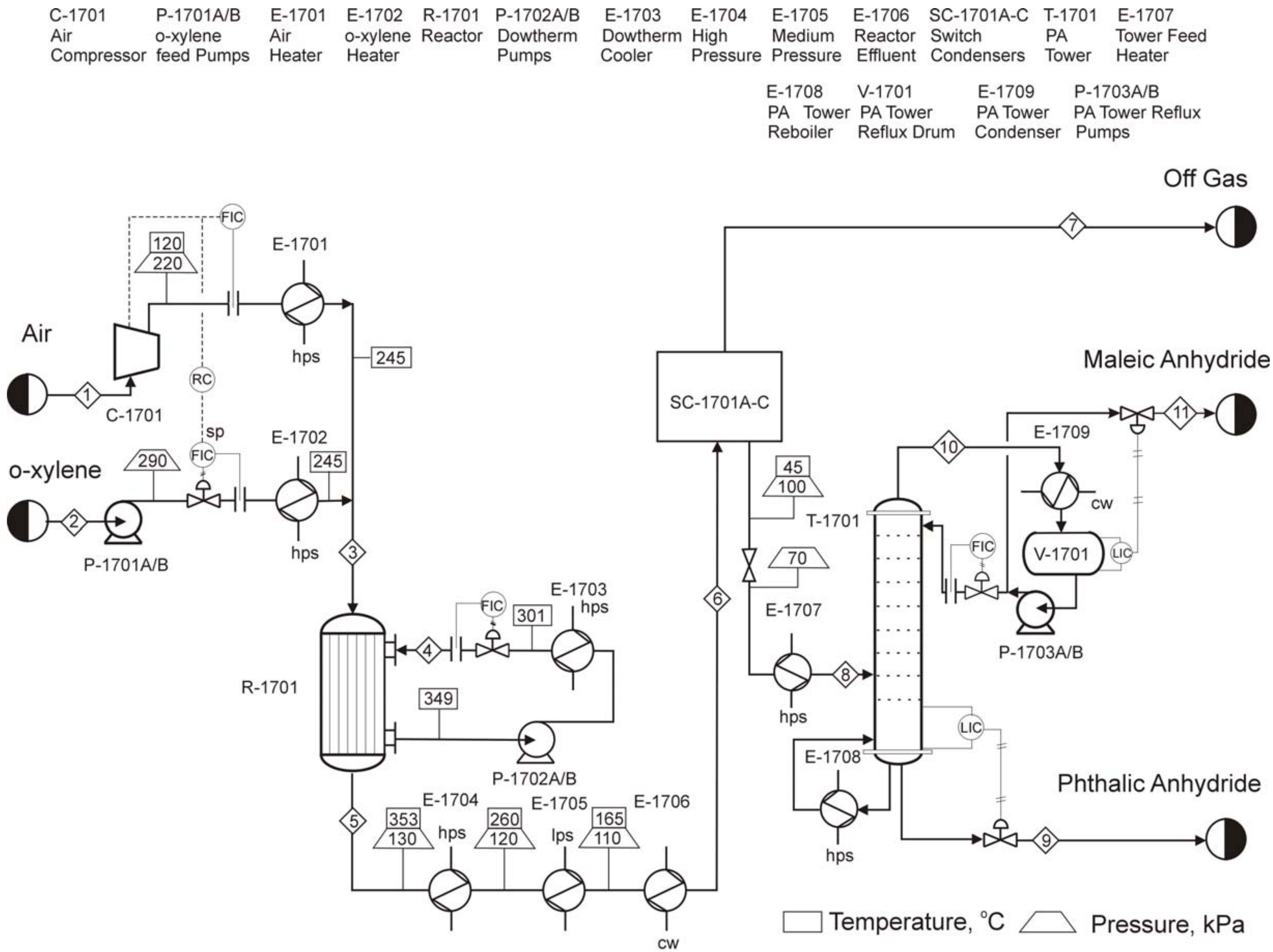


Figure 1: Unit 1700 - Phthalic Anhydride Manufacturing Process

Figure 1: Phthalic anhydride production facility – Unit 1700

Table 1: Stream Table for Unit 1700

Stream No	**1**	**2**	**3**	**4**
Temp °C	25	25	245	301
Pres kPa	101	101	200	600
Vapor fraction	0	1	1	0
Total kg/h	11,678	317,360	329,038	1,660,000
Total kmol/h	110.00	11,000.00	11,110.00	10,000.00
Component kmol/h				
o-xylene	110.00		110.00	
oxygen		2310.00	2310.00	
nitrogen		8690.00	8690.00	
water				
carbon dioxide				
phthalic anhydride				
maleic Anhydride				
benzoic acid				
Dowtherm A				10,000

Stream No.	**5**	**6**	**7**	**8**
Temp °C	353	45	45	230
Pres kPa	130	100	100	60
Vapor fraction	1	0.9876	1	0
Total kg/h	329,038	329,038	319,670	9,367
Total kmol/h	11,157.73	11,157.73	11,093.88	63.85
Component kmol/h				
o-xylene	4.05	4.05	4.05	
oxygen	1721.15	1721.15	1721.15	
nitrogen	8960.00	8960.00	8960.00	
water	386.20	386.20	386.20	
carbon dioxide	276.82	276.82	276.82	
phthalic anhydride	62.66	62.66	0.63	62.03
maleic Anhydride	16.16	16.16	14.38	1.78
benzoic acid	0.70	0.70	0.66	0.04
Dowtherm A				

Table 1: Stream Table for Unit 600 (continued)

Stream No.	**9**	**10**	**11**
Temp °C	245	155	155
Pres kPa	41.1	25.5	25
Vapor fraction	0	1	0
Total kg/h	9,185	1,825	181.8
Total kmol/h	62.0240	18.2898	1.8221
Component kmol/h			
o-xylene			
oxygen			
nitrogen			
water			
carbon dioxide			
phthalic anhydride	61.9713	0.6223	0.0620
maleic Anhydride	0.0178	17.6675	1.7601
benzoic acid	0.0349	0.00	0.00
Dowtherm A			

Table 2
Utility Stream Flow Summary for Unit 800

E-1701	**E-1702**	**E-1703**
hps	hps	bfw
24,100 kg/h	5,170 kg/h	83,400 kg/h
E-1704	**E-1705**	**E-1706**
bfw	bfw	cw
14,300 kg/h	14,400 kg/h	1.17×10^{6} kg/h
E-1707	**E-1708**	**E-1709**
hps	hps	cw
1,720 kg/h	680 kg/h	22,100 kg/h

Table 3
Partial Equipment Summary

Heat Exchangers

E-1701 *A* = 3,309 m^2 1-2 exchanger, floating head, carbon steel process stream in tubes *Q* = 11.344 MW maximum pressure rating of process side = 300 kPa	**E-1702** *A* = 301 m^2 1-2 exchanger, floating head, carbon steel Process stream in shell *Q* = 2.445 MW maximum pressure rating of process side = 300 kPa
E-1703 *A* = 2,376 m^2 1-2 exchanger, floating head, carbon steel Dowtherm (process) in tubes *Q* = 54.012 MW maximum pressure rating of process side = 800 kPa	**E-1704** *A* = 3,771 m^2 1-2 exchanger, floating head, carbon steel Process stream in tubes *Q* = 9.266 MW maximum pressure rating of process side = 250 kPa
E-1705 *A* = 3,690 m^2 1-2 exchanger, floating head, carbon steel Process stream in tubes *Q* = 9.198 MW maximum pressure rating of process side = 250 kPa	**E-1706** *A* = 4,028 m^2 1-2 exchanger, floating head, carbon steel Process stream in shell *Q* = 13.634 MW maximum pressure rating of process side = 250 kPa
E-1707 *A* = 128 m^2 1-2 exchanger, floating head, carbon steel Process stream in tubes *Q* = 0.810 MW maximum pressure rating of process side = 120 kPa	**E-1708** *A* = 80.0 m^2 1-2 exchanger, floating head, carbon steel Process stream in shell *Q* = 0.320 MW maximum pressure rating process side = 120 kPa
E-1709 *A* = 5.3 m^2 1-2 exchanger, floating head, carbon steel Process stream in shell *Q* = 0.256 MW maximum pressure rating of process side = 120 kPa	

Reactors

R-1701 – Heat Exchanger Portion *Q* = 53,976 kW Carbon steel construction 22,000, 2” diameter tubes each 10 m long Catalyst – ½ “spheres Triangular arrangement 2.5” pitch Overall heat transfer coefficient = 95 W/m^2K Overall reactor diameter = 10 m Overall reactor length = 12 m Process side pressure drop = 70 kPa Co-current flow Process stream in tubes, Dowtherm A in shell Maximum pressure rating of 300 kPa

Pumps and Compressors

C-1701 carbon steel power = 8.25 MW (design) Motor rated for a maximum of 9.0 MW 80% efficient See compressor curve for details	**P-1701 A/B** carbon steel power = 1.10 kW 65% efficient See pump curve for details
P-1702A/B carbon steel power = 36.0 kW 75% efficient	**P-1703A/B** carbon steel power = 0.50 kW 65% efficient

Towers and Vessels

T-1701 Carbon Steel Diameter = 0.86 m Height = 14.3 m Number of trays = 13 theoretical (39 actual) Tray efficiency = 0.33 (O'Connell) Tray type = sieve Weir height – 1” (0.0254 m) Tray spacing = 1ft (0.3048 m) Overall column pressure drop = 15.6 kPa Max pressure rating = 150 kPa	**V-1701** carbon steel length = 2.5 m diameter = 1 m maximum pressure rating of 150 kPa

using hot oil in a second condenser, while a third condenser is on standby. The raw PA is further purified by sending the liquid stream from the switch condenser through a pressure-reducing valve and through E-1707, where the temperature is increased to 230°C prior to feeding it to the PA tower (T-1701). In the PA tower, 99.9 mol% PA is produced as a bottom product and MA of purity >95 mol% is produced overhead. The MA by-product is eventually combined with the MA recovered from the switch condenser off gas, Stream 7, and sold. The equipment for recovering the MA from Stream 7 and the details of the switch condenser are not shown in Figure 1 and are operated separately by contractors. They have determined that they can process up to 20% additional feed to the switch condensers as long as it is delivered at a minimum pressure of 100 kPa pressure and at a maximum temperature of 50°C.

Reaction Chemistry and Kinetics

In order to operate safely, the reaction mixture (Stream 3) must be kept below the lower explosive limit of 1 mol% of o-xylene in air. The oxidation of o-xylene occurs in catalyst-filled tubes that are cooled using a circulating stream of Dowtherm A. The reactions that take place are highly exothermic, and the temperature everywhere in the reactor must be very carefully controlled. The catalyst, vanadium pentoxide (V_2O_5), sinters above a temperature of 400°C. The reactions taking place are:

$$C_6H_4(CH_3)_2 + 3O_2 \rightarrow C_6H_4(CO)_2O + 3H_2O \tag{1}$$
o-xylene phthalic anhydride

$$C_6H_4(CO)_2O + \frac{15}{2}O_2 \rightarrow 8CO_2 + 2H_2O \tag{2}$$
phthalic anhydride

$$C_6H_4(CH_3)_2 + \frac{21}{2}O_2 \rightarrow 8CO_2 + 5H_2O \tag{3}$$
o-xylene

$$C_6H_4(CH_3)_2 + \frac{15}{2}O_2 \rightarrow C_2H_2(CO)_2O + 4CO_2 + 4H_2O \tag{4}$$
o-xylene maleic anhydride

$$C_2H_2(CO)_2O + 3O_2 \rightarrow 4CO_2 + H_2O \tag{5}$$
maleic anhydride

$$C_6H_4(CH_3)_2 + 3O_2 \rightarrow C_6H_5(COOH) + CO_2 + 2H_2O \tag{6}$$
o-xylene benzoic acid

$$C_6H_5(COOH) + \frac{15}{2}O_2 \rightarrow 7CO_2 + 3H_2O \quad (7)$$

benzoic acid

The kinetic expressions for these reactions all have the form:

$$-r_A = k_o e^{-\frac{E_a}{RT}} p_1 p_2 \quad (8)$$

where k_o has units of kmol/m^3-reactor/h, E_a has units of kcal/kmol, and p_i are partial pressures in atm. The constants for these reactions are given in Table 4:

Table 4: Kinetic Constants used for Reactions (Equations 1-7)

Reaction Number	k_o	E_a	**1**	**2**
1	4.12×10^{11}	27,000	o-xylene	oxygen
2	1.15×10^{12}	31,000	phthalic anhydride	oxygen
3	1.73×10^{11}	28,600	o-xylene	oxygen
4	2.25×10^{11}	27,900	o-xylene	oxygen
5	7.76×10^{11}	30,400	maleic anhydride	oxygen
6	5.00×10^{09}	27,000	o-xylene	oxygen
7	5.00×10^{11}	29,500	benzoic acid	oxygen

For additional information on phthalic anhydride production, consult the literature. A good starting point is given at the end of this assignment[1]. It is suggested that you read some background information about phthalic anhydride production before proceeding with this assignment.

Assignment

The aim of the current assignment is to determine the maximum achievable scale-up in plant capacity. You may consider the purchase of small equipment items to achieve this, such as pumps and small vessels, but purchases of new, major equipment are not recommended. You are asked to address the following issues:

- Determine the maximum scale-up possible for the current plant. You may assume that any additional raw material deliveries required by the plant can be handled in the existing off-site facilities. Do not consider the switch condenser and related MA purification facilities as the scale-up issues for these units will be evaluated by our contractor.

- Identify which equipment is the bottleneck for further scale-up and suggest further debottlenecking strategies.
- Identify any safety issues that relate to your proposed scale-up.
- Identify any improvements that would benefit (economically or safety-wise) the current operations.

Deliverables

Specifically, the following is to be completed by 9:00 a.m., Monday, November 16, 2009:

1. Prepare a written report, conforming to the guidelines, detailing the information in the bulleted items above.

2. Include a legible, organized set of calculations justifying your recommendations, including any assumptions made. These should be placed in a well-indexed appendix to the main report.

3. Provide an updated PFD and stream table for the scaled-up process. Also provide details of any new equipment required to achieve the scale-up.

4. Attach a signed copy of the attached confidentiality statement.

Report Format

This report should be brief and should conform to the guidelines, which are available at the end of the following web page: http://www.che.cemr.wvu.edu/publications/projects/index.php. It should be bound in a 3-ring binder/folder that is not oversized relative to the number of pages in the report. Figures and tables should be included as appropriate. An appendix should be attached that includes items such as the requested calculations and a converged Chemcad simulation for your recommended case. Stream properties **are not** to be included in the Chemcad report. The calculations in the appendix should be easy to follow. The confidentiality statement should be the very last page of the report.

The written report is a very important part of the assignment. Reports that do not conform to the guidelines will receive severe deductions and will have to be rewritten to receive credit. Poorly written and/or organized written reports may also require re-writing. Be sure to follow the format outlined in the guidelines for written reports.

Oral Presentation

You will be expected to present and defend your results some time between November 16, 2009 and November 20, 2009. Your presentation should be 15-20 minutes, followed by about a 30-minute question and answer period. Make certain that you prepare for this presentation since it is an important part of your assignment. You should bring at least one hard copy of your slides to the presentation and hand it out before beginning the presentation.

Other Rules

You may not discuss this major with anyone other than the instructors. Discussion, collaboration, or any interaction with anyone other than the instructor is prohibited. This means that any cross talk among students about anything relating to this assignment, no matter how insignificant it may seem to you, is a violation of the rules and is considered academic dishonesty. Violators will be subject to the penalties and procedures outlined in the University Procedures for Handling Academic Dishonesty Cases (see p. 45 of 2009-11 Undergraduate Catalog (http://coursecatalog.wvu.edu/fullcatalogs/09-11catalog.pdf) or follow the link http://www.arc.wvu.edu/rightsa.html).

Consulting is available from the instructors. Chemcad consulting, *i.e.*, questions on how to use Chemcad, not how to interpret results, is unlimited and free, but only from the instructors. Each individual may receive five free minutes of consulting from the instructors. After five minutes of consulting, the rate is 2.5 points deducted for 15 minutes or any fraction of 15 minutes, on a cumulative basis. The initial 15-minute period includes the 5 minutes of free consulting.

Late Reports

Late reports are unacceptable. The following severe penalties will apply:

- late report on due date before noon: one letter grade (10 points)
- late report after noon on due date: two letter grades (20 points)
- late report one day late: three letter grades (30 points)
- each additional day late: 10 additional points per day

References

1. "Phthalic Acids and other Benzenepolycarboxylic Acids," *Kirk-Othmer Encyclopedia of Chemical Technology*, on-line version, 10/18/2001. (This encyclopedia is accessible from any University computer at http://www.libraries.wvu.edu/databases. An older print version is available in the Evansdale Library reference section.)

Appendix 1
Chemcad Hints

A converged simulation for the plant at current operating conditions is included with this project.

The kinetic equations for all the reactions (Equations 1-7) are given in the kinetic reactor module in the flowsheet. This reactor is set-up to operate as a packed bed with catalyst in the tubes with circulating Dowtherm A on the shell side. The Dowtherm A flows co-currently with the reaction mixture. The configuration could be made to operate with the Dowtherm A flowing countercurrently if desired. However, such a change would only be made after careful analysis. Plug flow reactor profiles (components and temperature) are available using the "PLOT" menu option in CHEMCAD.

The thermodynamics and enthalpy models are UNIFAC and latent heat and have shown to be accurate for the portions of the plant that are modeled in the flowsheet.

A warning message will appear when running Chemcad stating that heat of formation data are missing for Dowtherm. Ignore this warning, since it makes no difference to the simulation because Dowtherm does not take place in any reactions.

The recovery of phthalic anhydride is done using a set of switch condensers that desublimate the PA using cooled oil. This unit operation has been modeled as a component separator with the following fractions leaving in the off gas.

o-xylene	1.0000
Oxygen	1.0000
Nitrogen	1.0000
Water	1.0000
Carbon Dioxide	1.0000
Phthalandione	0.0100 (phthalic anhydride)
Maleic Anhydride	0.8900
Benzoic Acid	0.9500

The maleic anhydride is purified from the off-gas (Stream 7), mixed with Stream 11, and sold. The maleic anhydride purification and recovery equipment is not shown on the process flow diagram. The remainder of the off-gas is incinerated

The tower is simulated using the SDCS unit operation. Tower sizing calculations using sieve trays with 1" weir heights, the Fair flooding correlation, O'Connell tray efficiency, and other pertinent tray and column data are included in the simulation under the "tower sizing" tab. These values have been confirmed against current plant operating data.

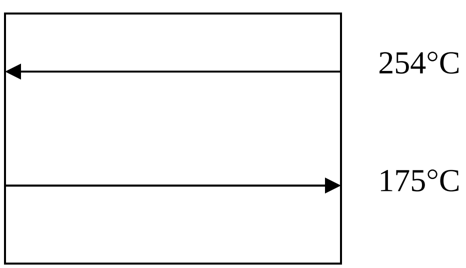
Appendix 2

Calculations and Other Pertinent Information
Heat Exchanger Calculations

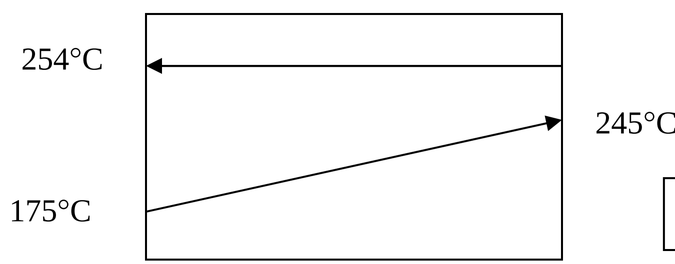
	E-1701	E-1702b	E-1702sh	E-1703	E-1704	E-1705	E-1706	E-1707	E-1708	E-1709	
T_1	120	254	254	301	353	260	30	45	245	30	°C
T_2	245	254	254	349	260	165	40	230	245	40	°C
t_1	254	25*	175	110*†	110*†	110*†	165	254	254	155	°C
t_2	254	175*	245	254*	254*	159*	45	254	254	155	°C
ΔT_{lm}	46.3	79.0	32.2	68.2	33.2	33.6	51.9	85.5	9	120	°C
h_i	80	1000	1000	500	80	80	800	80	800	800	W/m^2°C
h_o	1000	800	60	1000	1000	1000	80	1000	1000	800	W/m^2°C
U	74.1	444.4	56.6	333.3	74.1	74.1	72.7	74.1	444.4	400.0	W/m^2°C
F	1	1	1	1	1	1	0.897	1	1	1	
Q	11,344	2,000	445	54,012	9,266	9,198	13,634	810	320	256	kW
A	3,309	57	244	2,376	3,771	3,690	4,028	128	80	5	m^2
Process	Tube	Shell	Shell	Tube	Tube	Tube	Shell	Tube	Shell	Shell	
Utility	Shell	Tube	Tube	Shell	Shell	Shell	Tube	Shell	Tube	Tube	

* assume that shell-side fluid (liquid) is well mixed at the outlet or saturation temperature
† bfw is available at 110°C and at the pressure of the steam to be produced

Heat Exchanger E-1702 has two zones with temperature profiles as shown below – it is assumed that the inlet o-xylene mixes immediately with the boiling liquid on the shell side. Note that the outlet of E-1702 is at the mixing point with the heated air and is at a P = 200 kPa.



E-1702b Q = 2000 kW

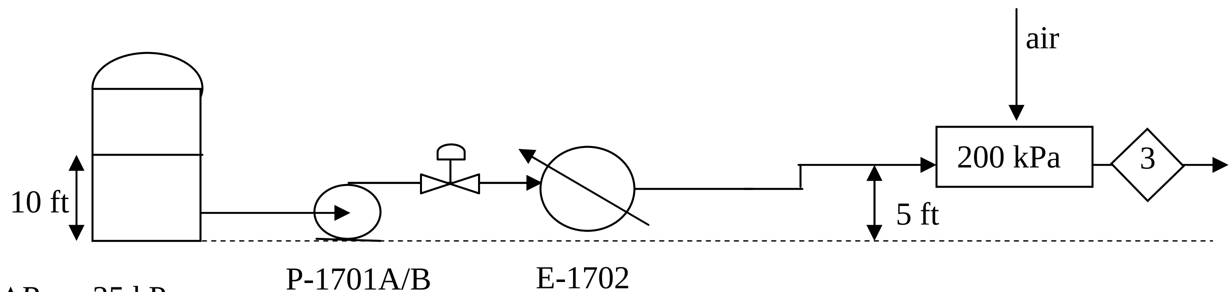


E-1702sh Q = 245 kW

Total Area = 57 + 244 = 301 m^2

P-1701 A/B

The o-xylene feed pump is located in the tank farm approximately 10 ft from the base of the o-xylene storage tank. Suction pipe diameter is 4" sch 40 and the discharge pipe diameter is 2" sch 40. It is estimated that the equivalent length of suction piping is 35 ft and 250 ft of discharge piping. A control valve is placed on the discharge side of the pump and the pressure drop across the valve is 35 kPa when the design flowrate of 13.2 m^3/h flows through the line and the level of o-xylene in the tank is 10 ft above ground level. The pump curve and *NPSH* curves for P-1701 are shown below along with the design calculations.



ΔP_{cv} = 35 kPa
$\dot{m}_{o-xylene}$ = 11,680 kg/h
V = (11,680 kg/h)/(885) = 13.2 m^3/h = 0.003667 m^3/s
Pipe diameter = ((2.067/12)(0.3048) = 0.0525 m   CSA = 0.002165 m^2
Velocity, v = (0.003667)/(0.002165)= 1.684 m/s
commercial steel pipe $\varepsilon / d = (46\times10^{-6})/(0.0525) = 8\times10^{-4}$
Re = $d v \rho / \mu$ = (0.0525)(1.684)(885)/(0.000758) = 102.8×10^3
from Pavlov equation:

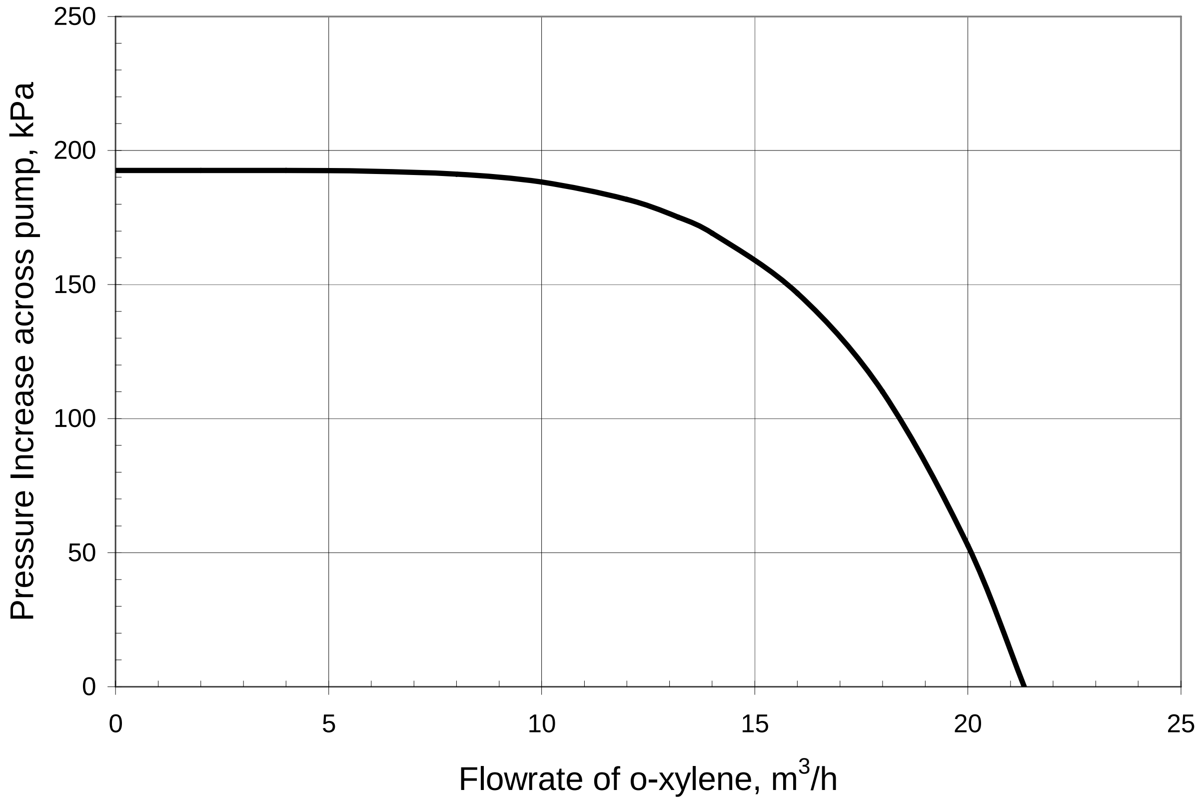
$$\frac{1}{\sqrt{f}} = -4\log\left\{\frac{1}{3.7}\frac{\varepsilon}{d} + \left(\frac{6.81}{\text{Re}}\right)^{0.9}\right\}$$

f = 0.005377

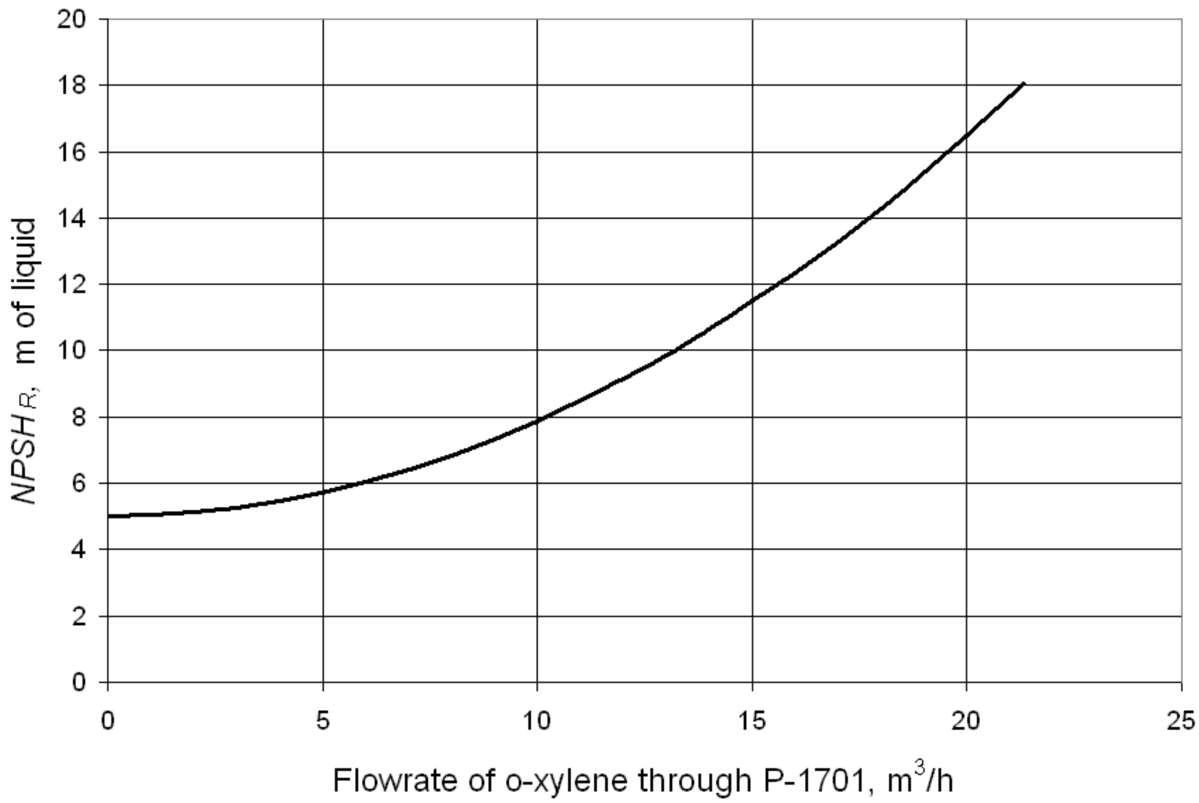
Length of pipe discharge piping = (250)(0.3948) = 76.2 m (includes fittings and straight pipe)

$$\Delta P_{pipe} = \frac{2 f \rho v^2 L_{eq}}{d} = \frac{(2)(0.005377)(855)(1.684)^2(76.2)}{(0.0.0525)(1000)} = 39.2\,\text{kPa}$$

$\Delta P_{E\text{-}1702}$ = 15 kPa
$\Delta P_{1\text{-}2}$ = 200 – 101 kPa = 99 kPa
$\Delta h \rho g$ = (5-10)(0.3048)(876)(9.81)/(1000) = -13.1 kPa
ΔP_{pump} = 35+39+15+99-13.1 = 175.1 kPa



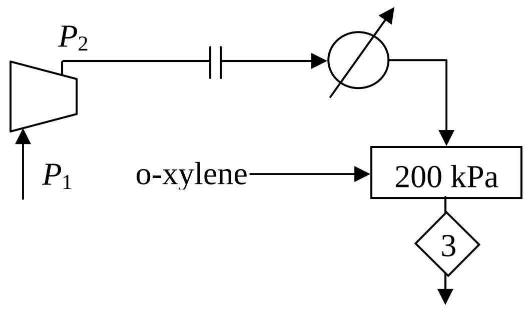
Equation for pump curve: $\Delta P(\mathrm{kPa}) = 175.1\left\{1.1 - 0.1\left(\frac{V[\mathrm{m^3/h}]}{13.2}\right)^5\right\}$



20
18
16
14
12
10
8
6
4
2
0
NPSH R, m of liquid
0
5
10
15
20
25
Flowrate of o-xylene through P-1701, m3/h

C-1701 A/B

Flowrate of air (STP) = 246,550 m^3/h = 68.5 m^3/s
Flowrate of air (compressor discharge, ρ = 1.9395 kg/m^3) = 163,630 m^3/h = 45.44 m^3/s
$\Delta P_{E\text{-}1701}$ = 9.1 kPa



From compressor to mix point with o-xylene is 250 ft equivalent of 36" diameter sch 40 pipe

Pipe ID = 35.25" = 0.8954 m CSA = 0.6296 m^2
Gas velocity, u = (45.44)/(0.6296) = 72.2 m/s
Re = (72.2)(0.8954)(1.9395)/(22.6×10^{-6}) = 5.55×10^6
ε/d = 46×10^{-6}/0.8954 = 46.9×10^{-6}

$$\frac{1}{\sqrt{f}} = -4\log\left\{\frac{1}{3.7}\frac{\varepsilon}{d} + \left(\frac{6.89}{\text{Re}}\right)^{0.9}\right\}$$

f = 0.00295

$$\Delta P_{pipe} = \frac{2 f \rho v^2 L_{eq}}{d} = \frac{(2)(0.00295)(1.9395)(72.2)^2(76.2)}{(0.8954)(1000)} = 4.78\,\text{kPa}$$

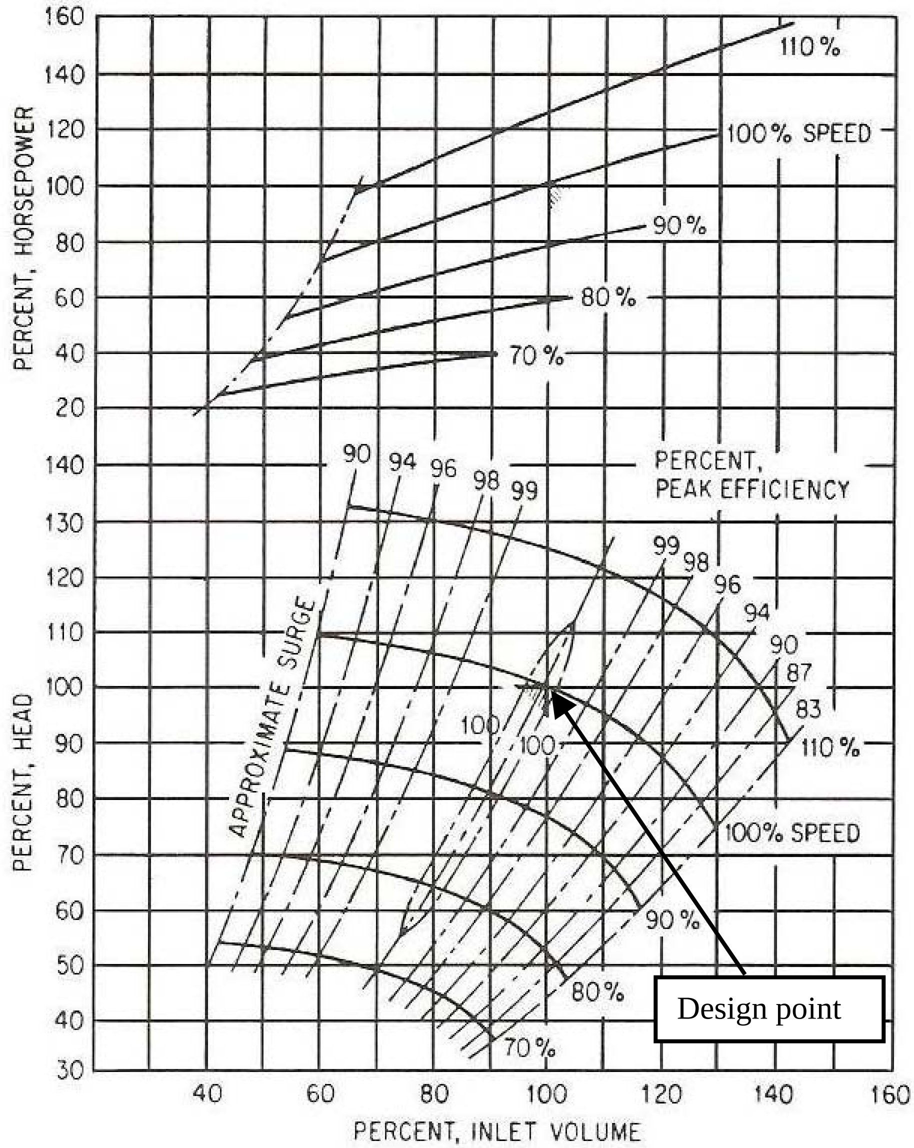
unrecovered pressure drop across orifice use 50% of full-scale gauge reading of 50" water
~ $0.5\Delta P_{orifice}$ = (0.5)(50)(0.0254)(1000)(9.81) = 6.2 kPa

P_2 = 200 + 4.78 + 6.2 + 9.1 = 220.1 kPa

ΔP_{compr} = 220.1 – 101.3 = 118.8 kPa

P_2/P_1 = (220.1)/(101.3) = 2.18 at 3600 rpm

The design point for this compressor (100% flow, 100% head is shown below on the supplied compressor charts. This point corresponds to an inlet flowrate of 68.5 m^3/s air at STP and a pressure head of 118.8 kPa and a compressor efficiency of 80%. Note that the % of peak efficiency in the compressor curves is relative to the 80% efficiency, e.g., if the compressor is operating at 90% of peak efficiency then the overall compressor efficiency is (0.9)(0.8) = 0.72 or 72%.



No equations are available for these curves

P-1702A/B and Loop

Keep Dowtherm pressurized at ~700 kPa to reduce volatility and avoid cavitation

- Pressure drop through reactor at design flowrate measured as = 13.7 kPa
- Pressure drop through E-1703 at design flowrate measured as = 12.3 kPa

Dowtherm properties:
C_p = 2.5 kJ/kg°C, ρ = 751 kg/m^3, μ = 16.22×10^{-5} Pa-s
Vapor pressure at 349°C = 551 kPa
Pump inlet located 2 m below reactor outlet
Dowtherm enters reactor at 301°C and exits reactor at 349°C
$\dot{m}_{Dowtherm}$ = 1.66×10^6 kg/h
V = (1.66×10^6 kg/h)/(3600)/(751) = 0.6140 m^3/s
Use a velocity of ~ 3m/s to give a A_{pipe} = (0.614)/(3) = 0.205 m^2
Pipe diameter = ((0.204)(4)/π)$^{0.5}$ = 0.51 m ~ 20”
use 24” Sch 40 pipe with d_i = 22.63 inch = 0.5748 m
Velocity, v = (0.6140)(4)/π/(0.5748)^2 = 2.366 m/s
commercial steel pipe ε/d = (46×10^{-6})/(0.5748) = 8×10^{-5}
Re = $dv\rho/\mu$ = (0.5748)(2.366)(751)/(16.22×10^{-5}) = 6.25×10^{-6}
from Pavlov equation:

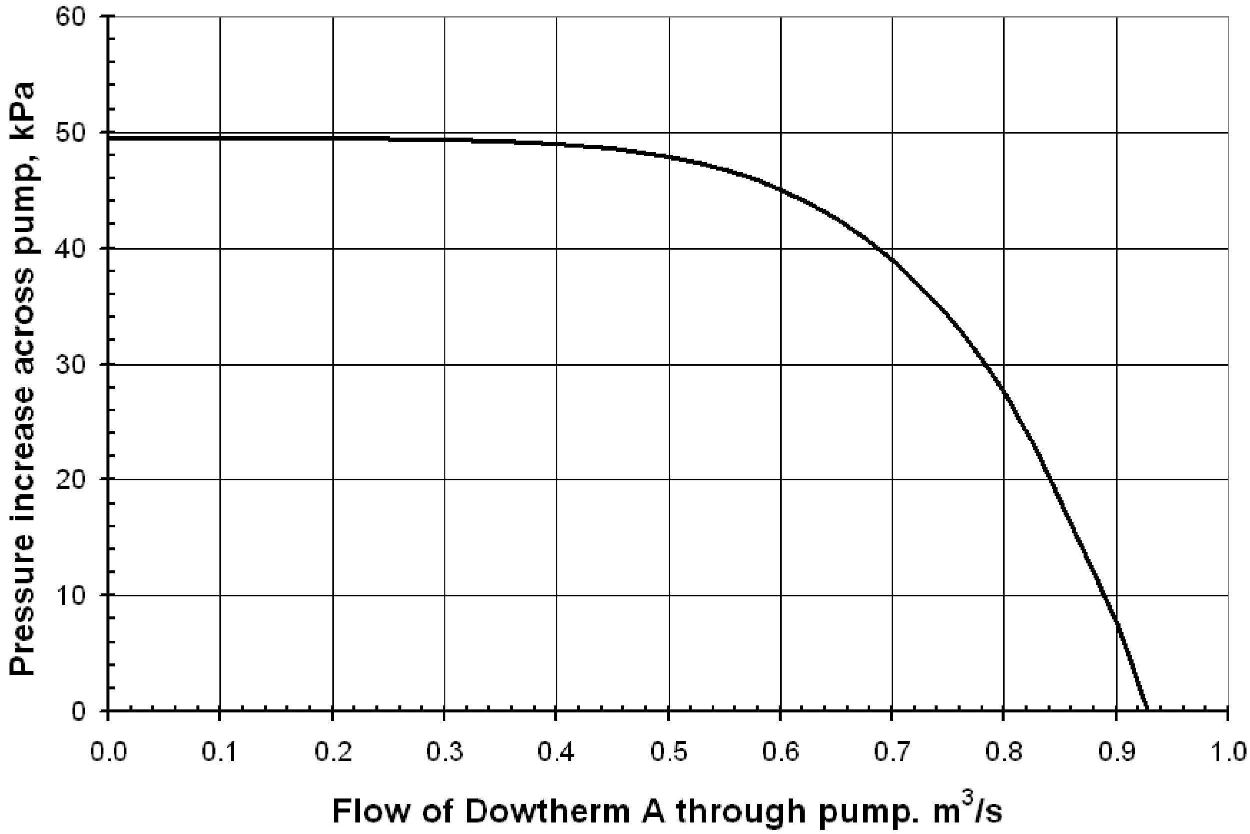
$$\frac{1}{\sqrt{f}} = -4\log\left\{\frac{1}{3.7}\frac{\varepsilon}{d} + \left(\frac{6.81}{\text{Re}}\right)^{0.9}\right\}$$

f = 0.002971

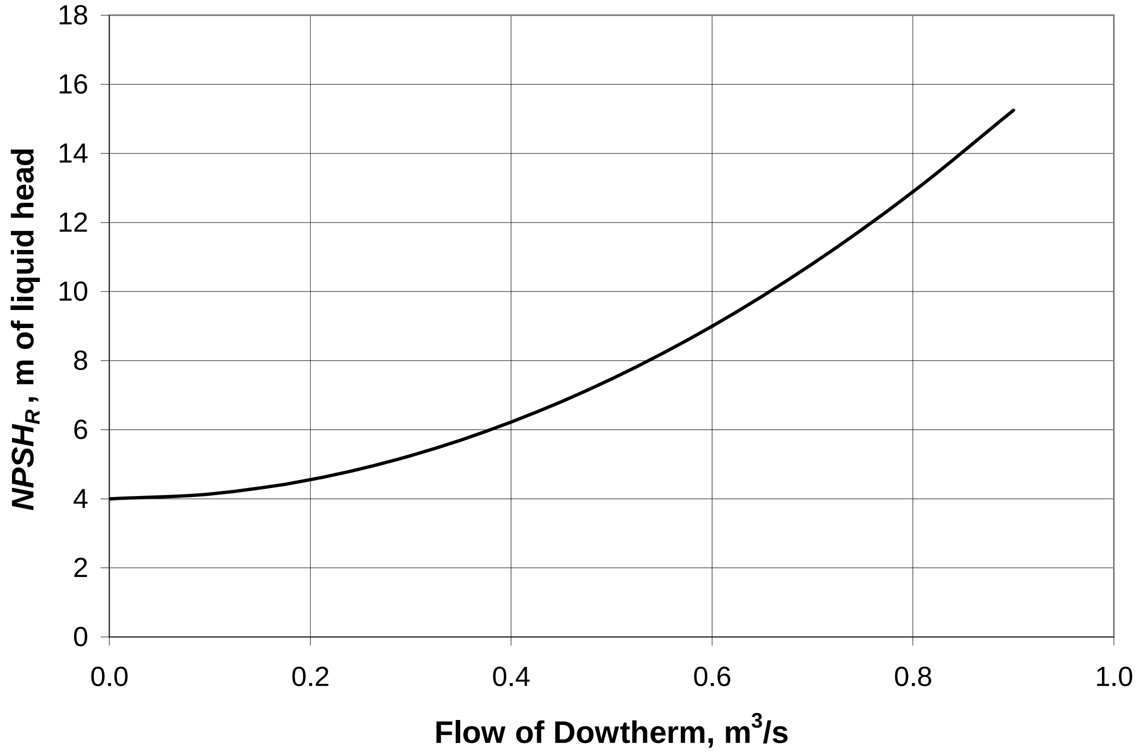
Length of pipe in Dowtherm cooling loop = 115 m (includes fittings and straight pipe)

$$\Delta P_{pipe} = \frac{2 f \rho v^2 L_{eq}}{d} = \frac{(2)(0.002971)(751)(2.366)^2(115)}{(0.5748)(1000)} = 5.0\,\text{kPa}$$

Pump and *NPSH* curve for P-1702A/B given below:



Equation for pump curve: $\Delta P(\text{kPa}) = 45\left\{1.1 - 0.1\left(\frac{V[\text{m}^3/\text{s}]}{0.6}\right)^{5.5}\right\}$


NPSHR , m of liquid head
18
16
14
12
10
8
6
4
2
0
0.0
0.2
0.4
0.6
0.8
1.0
Flow of Dowtherm, m3/s