Styrene Production

Styrene is the monomer used to make polystyrene, which has a multitude of uses, the most common of which are in packaging and insulated styrofoam beverage cups. Styrene is produced by the dehydrogenation of ethylbenzene. Ethylbenzene is formed by reacting ethylene and benzene, and most benzene is made by hydrodealkylation of toluene, which is obtained as a byproduct of gasoline manufacture. There is very little ethylbenzene sold commercially. Most ethylbenzene manufacturers convert it directly into styrene.

The plant at which you are employed currently manufactures ethylbenzene, styrene, and polystyrene. The unit to which you are assigned, Unit 500, converts the ethylbenzene into styrene, producing around 100,000 metric tons per year of 99.8 wt % styrene.

Styrene Production Reactions

The reactions for styrene production are as follows:

1. Ethylbenzene $\underset{1}{\overset{2}{\rightarrow}}$ Ethylene $+$ Benzene $+$ Ethylbenzene

2. Ethylbenzene $\underset{3}{\rightarrow}$ Benzene $+$ Ethylene

3. Ethylbenzene $+$ Hydrogen $\rightarrow$ Toluene $+$ Methane

Process Description

The process flow diagram is shown in Figure 1. Ethylbenzene feed is mixed with recycled ethylbenzene, heated, and then mixed with high-temperature, superheated steam. Steam is an inert in the reaction, which drives the equilibrium shown in Equation (1) to the right by reducing the concentrations of all components. Since styrene formation is highly endothermic, the superheated steam also provides energy to drive the reaction. The reactants then enter two adiabatic packed beds with interheating. The products are cooled, producing steam from the high-temperature reactor effluent. The cooled product stream is sent to a three-phase separator, in which light gases (hydrogen, methane, ethylene), organic liquid, and water each exit in
Unit 500: Production of Styrene from Ethylbenzene
separate streams. The hydrogen stream is further purified as a source of hydrogen elsewhere in our plant. The benzene/toluene stream is currently returned as a feed stream to our petrochemical facility. The organic stream containing the desired product is distilled once to remove the benzene and toluene and distilled again to separate unreacted ethylbenzene for recycle from the styrene product.

The styrene product can spontaneously polymerize at higher temperatures. Since our product styrene is sent directly to the polymerization unit, experience suggests that as long its temperature is maintained below 125°C, there is no spontaneous polymerization problem. Since this is below styrene’s normal boiling point, and since low pressure pushes the equilibrium in Equation (1) to the right, much of this process is run at vacuum.

**Problem**

Recently, Unit 500 has been periodically operating outside of standard conditions. There are significant process transients. Tables 1 and 2 show the design conditions for Unit 500. A survey of process conditions during an upset yielded the following observations:

1. The feed of ethylbenzene, Stream 1 is at design conditions. We have no information about Stream 4.

2. Production of styrene is reduced by up to 3%. The styrene that is produced is still within specifications.

3. The total flow of the recycle stream is reduced by up to 12%.

4. The total flow of the hydrogen effluent stream is approximately unchanged. An assay of this stream shows a decrease in hydrogen flowrate of up to 6%, an increase in methane flowrate of up to 3%, and an increase in ethylene flowrate of up to 13%.

5. The total flow of the benzene/toluene stream is increased by up to 7%. The ethylbenzene flowrate of this stream is reduced by up to 11%, the styrene flowrate is approximately constant, the toluene flowrate is increased by up to 2%, and the benzene flowrate is increased by up to 13%.

Your boss has solicited input from the operators with the following results. One operator says that the problem might be a new batch of catalyst. Another operator suggests that there is a problem with the ratio controller on H-501, since the problem goes away when he bangs the valve on the natural gas line with a wrench. (Your boss says this is nonsense.) Another operator says the problem is incorrect flow measurement downstream, and that styrene production has not actually been affected.

Clearly, operation this much outside of standard conditions is a cause for concern, especially if the problem should begin to occur more frequently and for longer durations. The first part of your assignment is to suggest causes for this periodic problem, identify the most likely cause,
## Table 1
### Stream Tables for Unit 500

<table>
<thead>
<tr>
<th>Stream No.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (°C)</td>
<td>136</td>
<td>116</td>
<td>225</td>
<td>159</td>
<td>800</td>
<td>800</td>
</tr>
<tr>
<td>Pressure (kPa)</td>
<td>210</td>
<td>200</td>
<td>180</td>
<td>600</td>
<td>565</td>
<td>565</td>
</tr>
<tr>
<td>Vapor Mole Fraction</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Total Flow (kg/h)</td>
<td>19417</td>
<td>54890</td>
<td>54890</td>
<td>227784</td>
<td>227784</td>
<td>83664</td>
</tr>
<tr>
<td>Total Flow (kmol/h)</td>
<td>183.6</td>
<td>517.8</td>
<td>517.8</td>
<td>12644</td>
<td>12644</td>
<td>4644</td>
</tr>
</tbody>
</table>
**Component Flows**

| Water | 12644 | 12644 | 4644 |
| Ethylbenzene | 180 | 512.7 | 512.7 |
| Styrene | 1.2 | 1.2 |
| Hydrogen |
| Benzene | 1.8 | 1.8 | 1.8 |
| Toluene | 1.8 | 2.13 | 2.13 |
| Ethylene |
| Methane |

<table>
<thead>
<tr>
<th>Stream No.</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (°C)</td>
<td>800</td>
<td>799</td>
<td>632</td>
<td>609</td>
<td>650</td>
<td>640</td>
</tr>
<tr>
<td>Pressure (kPa)</td>
<td>565</td>
<td>180</td>
<td>170</td>
<td>160</td>
<td>145</td>
<td>135</td>
</tr>
<tr>
<td>Vapor Mole Fraction</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Total Flow (kg/h)</td>
<td>144120</td>
<td>144120</td>
<td>199010</td>
<td>199010</td>
<td>199010</td>
<td>199010</td>
</tr>
<tr>
<td>Total Flow (kmol/h)</td>
<td>8000</td>
<td>8000</td>
<td>8517.6</td>
<td>8614.7</td>
<td>8614.7</td>
<td>8662.7</td>
</tr>
</tbody>
</table>
**Component Flows**

| Water | 8000 | 8000 | 8000 | 8000 | 8000 |
| Ethylbenzene | 512.7 | 399.1 | 399.1 | 336.36 |
| Styrene | 1.2 | 86.8 | 86.8 | 120.67 |
| Hydrogen | 69.0 | 69.0 | 88.1 |
| Benzene | 1.8 | 13.1 | 13.1 | 27.5 |
| Toluene | 2.13 | 18.7 | 18.7 | 33.3 |
| Ethylene | 11.3 | 11.3 | 25.7 |
| Methane | 16.6 | 16.6 | 31.1 |
Table 1
Stream Tables for Unit 500 (cont’d)

<table>
<thead>
<tr>
<th>Stream No.</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
<th>17</th>
<th>18</th>
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</thead>
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<tr>
<td>Temperature (°C)</td>
<td>270</td>
<td>180</td>
<td>65</td>
<td>65</td>
<td>65</td>
<td>65</td>
</tr>
<tr>
<td>Pressure (kPa)</td>
<td>120</td>
<td>105</td>
<td>90</td>
<td>75</td>
<td>75</td>
<td>75</td>
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<td>Vapor Mole Fraction</td>
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<td>1</td>
<td>.025</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total Flow (kg/h)</td>
<td>199010</td>
<td>199010</td>
<td>199010</td>
<td>2682</td>
<td>53493</td>
<td>142715</td>
</tr>
<tr>
<td>Total Flow (kmol/h)</td>
<td>8662.7</td>
<td>8662.7</td>
<td>8662.7</td>
<td>216.3</td>
<td>517.8</td>
<td>7928.6</td>
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</table>

Component Flows

<table>
<thead>
<tr>
<th></th>
<th>8000</th>
<th>8000</th>
<th>8000</th>
<th>71.4</th>
<th>7928.6</th>
</tr>
</thead>
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<td>8000</td>
<td>8000</td>
<td>71.4</td>
<td>7928.6</td>
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<tr>
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<td>336.36</td>
<td>336.36</td>
<td>336.36</td>
<td>336.36</td>
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</tr>
<tr>
<td>Styrene</td>
<td>120.67</td>
<td>120.67</td>
<td>120.67</td>
<td>120.67</td>
<td></td>
</tr>
<tr>
<td>Hydrogen</td>
<td>88.1</td>
<td>88.1</td>
<td>88.1</td>
<td>88.1</td>
<td>88.1</td>
</tr>
<tr>
<td>Benzene</td>
<td>27.5</td>
<td>27.5</td>
<td>27.5</td>
<td>27.5</td>
<td>27.5</td>
</tr>
<tr>
<td>Toluene</td>
<td>33.3</td>
<td>33.3</td>
<td>33.3</td>
<td>33.3</td>
<td>33.3</td>
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<tr>
<td>Ethylene</td>
<td>25.7</td>
<td>25.7</td>
<td>25.7</td>
<td>25.7</td>
<td>25.7</td>
</tr>
<tr>
<td>Methane</td>
<td>31.1</td>
<td>31.1</td>
<td>31.1</td>
<td>31.1</td>
<td>31.1</td>
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<table>
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<tr>
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<th>22</th>
<th>23</th>
<th>24</th>
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</thead>
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<tr>
<td>Temperature (°C)</td>
<td>197</td>
<td>65</td>
<td>66</td>
<td>119.5</td>
<td>105</td>
<td>124.5</td>
</tr>
<tr>
<td>Pressure (kPa)</td>
<td>240</td>
<td>60</td>
<td>40</td>
<td>60</td>
<td>210</td>
<td>60</td>
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<tr>
<td>Vapor Mole Fraction</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total Flow (kg/h)</td>
<td>2682</td>
<td>53493</td>
<td>5548</td>
<td>47905</td>
<td>35473</td>
<td>12432</td>
</tr>
<tr>
<td>Total Flow (kmol/h)</td>
<td>216.3</td>
<td>517.8</td>
<td>63.9</td>
<td>453.9</td>
<td>334.2</td>
<td>119.7</td>
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Component Flows

<table>
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<tr>
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<td>Water</td>
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<tr>
<td>Ethylbenzene</td>
<td>336.36</td>
</tr>
<tr>
<td>Styrene</td>
<td>120.67</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>88.1</td>
</tr>
<tr>
<td>Benzene</td>
<td>27.5</td>
</tr>
<tr>
<td>Toluene</td>
<td>33.3</td>
</tr>
<tr>
<td>Ethylene</td>
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<tr>
<td>Methane</td>
<td>31.1</td>
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Table 1
Stream Tables for Unit 500 (cont’d)

<table>
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<tr>
<th>Stream No.</th>
<th>25</th>
<th>26</th>
<th>27</th>
<th>28</th>
<th>29</th>
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<tbody>
<tr>
<td>Temperature (°C)</td>
<td>700</td>
<td>66</td>
<td>124.5</td>
<td>65</td>
<td>105</td>
</tr>
<tr>
<td>Pressure (kPa)</td>
<td>565</td>
<td>200</td>
<td>200</td>
<td>200</td>
<td>210</td>
</tr>
<tr>
<td>Vapor Mole Fraction</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total Flow (kg/h)</td>
<td>83664</td>
<td>5548</td>
<td>12432</td>
<td>142715</td>
<td>35473</td>
</tr>
<tr>
<td>Total Flow (kmol/h)</td>
<td>4644</td>
<td>63.9</td>
<td>119.7</td>
<td>7928.6</td>
<td>334.2</td>
</tr>
<tr>
<td>Component Flows</td>
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<td></td>
<td></td>
<td></td>
</tr>
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<td>Water</td>
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<td></td>
<td></td>
<td></td>
<td>7928.6</td>
</tr>
<tr>
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<td></td>
<td>332.66</td>
</tr>
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<td>Styrene</td>
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<td>119.3</td>
<td></td>
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<td>1.20</td>
</tr>
<tr>
<td>Hydrogen</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Benzene</td>
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<td></td>
<td>27.5</td>
</tr>
<tr>
<td>Toluene</td>
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<td></td>
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<td>32.9</td>
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<tr>
<td>Ethylene</td>
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<td></td>
<td></td>
<td></td>
<td>0.33</td>
</tr>
<tr>
<td>Methane</td>
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<td></td>
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<td></td>
<td></td>
</tr>
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</table>

Table 2
Utility Summary for Unit 500

<table>
<thead>
<tr>
<th></th>
<th>E-501</th>
<th>E-503</th>
<th>E-504</th>
<th>E-505</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>hps</td>
<td>bfw → hps</td>
<td>bfw → lps</td>
<td>cw</td>
</tr>
<tr>
<td>hps</td>
<td>17,566 kg/h</td>
<td>67,256 kg/h</td>
<td>14,790 kg/h</td>
<td>9,455,376 kg/h</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>E-506</th>
<th>E-507</th>
<th>E-508</th>
<th>E-509</th>
</tr>
</thead>
<tbody>
<tr>
<td>lps</td>
<td>15,878 kg/h</td>
<td>671,941 kg/h</td>
<td>163,505 kg/h</td>
<td>8,173,446 kg/h</td>
</tr>
</tbody>
</table>
and suggest potential remedies for this problem. We need your answer quickly, since a scheduled plant shut down occurs next month.

Current market conditions for polystyrene are very tight. Whatever we can do to improve the economic performance of Unit 500 will help the bottom line. Therefore, the second part of your assignment is to suggest process improvements that will enhance the profitability of Unit 500, especially ones that can reasonably be implemented during the upcoming shut down. Detailed economic calculations are not expected.

Other Information

Table 3 contains an equipment list. Other pertinent information and calculations are contained in the appendix.

Assignment

Specifically, you are to prepare the following by 9:00 am, Monday, September 27, 1999:

1. a diagnosis of the operating problems with the plant, explanations of their relevance, and recommendations for solving these problems

2. a list of suggested process improvements which can enhance the profitability of Unit 500

3. a written report, conforming to the guidelines, detailing the information in items 1 and 2, above

4. a legible, organized set of calculations justifying your recommendations, including any assumptions made

5. a signed copy of the attached confidentiality statement

Report Format

This report should be brief and should conform to the guidelines. It should be bound in a folder that is not oversized relative to the number of pages in the report. Most of the report should be an executive summary, which summarizes your diagnosis, recommendations, and rationale. Figures and tables should be included as appropriate. An appendix should be attached that includes items such as the requested calculations. These calculations 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. Poorly written and/or organized written reports may require re-writing. Be sure to follow the format outlined in the guidelines for written reports. Failure to follow the prescribed format may be grounds for a re-write.
### Table 3
**Partial Equipment Summary**

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Material</th>
<th>Area $A$</th>
<th>Type of Condenser</th>
<th>Shell</th>
<th>Tube Passes</th>
<th>Heat Input $Q$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>E-501</strong></td>
<td>Carbon Steel</td>
<td>541 m²</td>
<td>Boiling in shell, condensing in tubes</td>
<td>1 shell – 2 tube passes</td>
<td>$Q = 29695$ MJ/h</td>
<td></td>
</tr>
<tr>
<td><strong>E-503</strong></td>
<td>316 SS</td>
<td>2006 m²</td>
<td>Boiling in shell, process fluid in tubes</td>
<td>1 shell – 2 tube passes</td>
<td>$Q = 162.8$ GJ/h</td>
<td></td>
</tr>
<tr>
<td><strong>H-501</strong></td>
<td>Fired heater</td>
<td>1000 m³</td>
<td>5 reactors in parallel at 200 m³</td>
<td>20 m tall, 3.6 m diameter</td>
<td>$Q = 88.26$ MW</td>
<td></td>
</tr>
<tr>
<td><strong>E-504</strong></td>
<td>Carbon Steel</td>
<td>2133 m²</td>
<td>Boiling in shell, process fluid in tubes</td>
<td>1 shell – 2 tube passes</td>
<td>$Q = 35.16$ GJ/h</td>
<td></td>
</tr>
<tr>
<td><strong>R-501</strong></td>
<td>316 SS, packed bed</td>
<td>1000 m³</td>
<td>Cylindrical catalyst pellet (1.6 mm × 3.2 mm)</td>
<td>Void fraction = 0.4</td>
<td>$Q = 19237$ MJ/h</td>
<td></td>
</tr>
<tr>
<td><strong>R-502</strong></td>
<td>316 SS, packed bed</td>
<td>700 m³</td>
<td>5 reactors in parallel at 140 m³</td>
<td>20 m tall, 3.0 m diameter</td>
<td>$Q = 33.4$ GJ/h</td>
<td></td>
</tr>
<tr>
<td><strong>E-505</strong></td>
<td>Carbon Steel</td>
<td>2904 m²</td>
<td>Boiling in shell, process fluid in tubes</td>
<td>1 shell – 2 tube passes</td>
<td>$Q = 395.9$ GJ/h</td>
<td></td>
</tr>
<tr>
<td><strong>V-501</strong></td>
<td>Carbon Steel</td>
<td>34.7 m³</td>
<td>5 reactors in parallel at 200 m³</td>
<td>20 m tall, 3.0 m diameter</td>
<td>$Q = 3.4$ GJ/h</td>
<td></td>
</tr>
<tr>
<td><strong>E-502</strong></td>
<td>316 SS</td>
<td>456 m²</td>
<td>Steam in shell, process fluid in tubes</td>
<td>1 shell – 2 tube passes</td>
<td>$Q = 260$ GJ/h</td>
<td></td>
</tr>
<tr>
<td><strong>C-501</strong></td>
<td>Carbon Steel</td>
<td>36.4 kW</td>
<td>80% adiabatic efficiency</td>
<td>80% efficient</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>P-501</strong></td>
<td>Carbon Steel</td>
<td>6.4 kW (actual)</td>
<td>80% efficient</td>
<td>80% efficient</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>P-505</strong></td>
<td>Carbon Steel</td>
<td>0.75 kW (actual)</td>
<td>80% efficient</td>
<td>80% efficient</td>
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<td><strong>P-504</strong></td>
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<td>80% efficient</td>
<td>80% efficient</td>
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</tr>
<tr>
<td><strong>P-506</strong></td>
<td>Carbon Steel</td>
<td>2.65 kW (actual)</td>
<td>80% efficient</td>
<td>80% efficient</td>
<td></td>
<td></td>
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</table>
Table 3 (cont’d)
Partial Equipment Summary

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Material</th>
<th>Description</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>T-501</td>
<td>carbon steel</td>
<td>46 sieve trays</td>
<td>55% efficient total condenser (E-507) feed on tray 26 reflux ratio = 11.4 24 in tray spacing, 2 in weirs column height = 92 ft = 28 m top diameter = 3.6 m bottom diameter = 2.7 m tapered column</td>
</tr>
<tr>
<td>T-502</td>
<td>carbon steel</td>
<td>total condenser (E-509) feed at location equivalent to tray 36 reflux ratio = 25.8 structured packing</td>
<td></td>
</tr>
<tr>
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<td>carbon steel</td>
<td>condensing in shell, condensing in tubes</td>
<td>1 shell – 2 tube passes Q = 331.2 GJ/h</td>
</tr>
<tr>
<td>E-507</td>
<td>carbon steel</td>
<td>1 shell – 2 tube passes</td>
<td>Q = 281.1 GJ/h</td>
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<tr>
<td>E-508</td>
<td>carbon steel</td>
<td>1 shell – 2 tube passes</td>
<td>Q = 341.1 GJ/h</td>
</tr>
</tbody>
</table>

Oral Presentation

You will be expected to present and defend your results some time between September 27 and October 2, 1999. Your presentation should be 10-15 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.

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
Appendix
Calculations and Other Pertinent Information

Reactor

Styrene reaction may be equilibrium limited

\[ K = \left( \frac{y_{st} y_{hyd} P}{y_{eb}} \right) \]

\[ \ln K = 15.5408 - \frac{14852.6}{T} \]

where \( T \) is in K and \( P \) is in bar.

Equilibrium calculation:

\[ C_6H_5C_2H_5 \overset{1}{\underset{2}{\rightarrow}} C_6H_5C_2H_3 + H_2 \]

\[ \begin{array}{ccc}
1 & 0 & 0 \\
1-x & x & x \\
\end{array} \]

\[ \text{total} = N + 1 + x \quad \text{includes} \quad N \text{ moles of inert steam} \]

\[ K = \frac{x^2 P}{(1-x)(N+1+x)} \]

where \( P \) is in bar

can generate data for equilibrium conversion, \( x \), versus \( P, T, \) and \( N \)

Kinetics (subscripts on \( r \) refer to reactions in Equation (1) – (3) (adapted from Snyder, J. D. and B. Subramaniam, Chem. Engr. Sci., 49, 5585-5601 (1994) – the positive activation energy can arise from non-elementary kinetics – perhaps these kinetics are an elementary approximation to non-elementary kinetics):

\[ r_1 = 4.24 \times 10^6 \exp \left( -\frac{21708}{RT} \right) p_{eb} \]

\[ r_2 = 0.755 \exp \left( \frac{7804}{RT} \right) p_{st} p_{hyd} \]
\[ r_3 = 7.21 \times 10^8 \exp \left( -\frac{49675}{RT} \right) p_{eb} \]

\[ r_4 = 1723 \exp \left( -\frac{26857}{RT} \right) p_{eb} p_{hyd} \]

where \( p \) is in kPa, \( T \) is in K, \( R = 1.987 \text{ cal/mol K} \), and \( r_i \) is in mol/m\(^3\) reactor s

other data:

bulk catalyst density = 1282 kg/m\(^3\)
void fraction = 0.4

**Vessel (V-501)**

assume 10 min residence time based on total liquid flow

organic liquid at 53493 kg/h = 892 kg/min, \( \rho = 835 \text{ kg/m}^3 \), 892/835 = 1.07 m\(^3\)/min
water at 144120 kg/h = 2402 kg/min, \( \rho = 1000 \text{ kg/m}^3 \), 2402/1000 = 2.40 m\(^3\)/min
total liquid flow = 3.47 m\(^3\)/min, 3.47(10) = 34.7 m\(^3\)
total volume = 69 m\(^3\)

**Heat Exchangers**

key data:

latent heats
\( \lambda_{hps} = 1794 \text{ kJ/kg} \)
\( \lambda_{mps} = 2002 \text{ kJ/kg} \)
\( \lambda_{lps} = 2086 \text{ kJ/kg} \)

sensible heats (\( C_p \Delta T \))
\( \text{hps} \quad 4.184 \text{ kJ/kg°C}(254-90) = 686 \text{ kJ/kg} \)
\( \text{lps} \quad 4.184 \text{ kJ/kg°C}(160-90) = 293 \text{ kJ/kg} \)
zone 1
\( Q_1 = 5200 \text{ MJ/h} \)
\( \Delta T_{lm} = 114.6 ^\circ C \)
liquid organic \( h = 600 \text{ W/m}^2\text{K} \)
condensing steam \( h = 6000 \text{ W/m}^2\text{K} \)
\( U \approx \frac{1}{h_i} + \frac{1}{h_o} = 545 \text{ W/m}^2\text{K} \)
\( A = 23.1 \text{ m}^2 \)

zone 2
\( Q_2 = 19000 \text{ MJ/h} \)
\( \Delta T_{lm} = 88.9 ^\circ C \)
boiling organic \( h = 6000 \text{ W/m}^2\text{K} \)
condensing steam \( h = 6000 \text{ W/m}^2\text{K} \)
\( U = 3000 \text{ W/m}^2\text{K} \)
\( A = 19.8 \text{ m}^2 \)

zone 3
\( Q_3 = 5500 \text{ MJ/h} \)
\( \Delta T_{lm} = 51.7 ^\circ C \)
vapor organic \( h = 60 \text{ W/m}^2\text{K} \)
condensing steam \( h = 6000 \text{ W/m}^2\text{K} \)
\( U = 59.4 \text{ W/m}^2\text{K} \)
\( A = 497.5 \text{ m}^2 \)

total \( A = 540 \text{ m}^2 \)
steam flow from Chemcad in Table 2
E-502

\[ Q = 19237 \text{ MJ/h} \]
\[ \Delta T_{lm} = 122^°C \]
hot desuperheating steam \( h = 200 \text{ W/m}^2\text{K} \)
hot vapor organic \( h = 200 \text{ W/m}^2\text{K} \)
\( U = 100 \text{ W/m}^2\text{K} \)
LMTD corr factor – 1-2 exchanger = 0.96
\( A = 456 \text{ m}^2 \)

E-503

\[ Q = 162767 \text{ MJ/h} \]
\[ \Delta T_{lm} = 116.2^°C \]
boiling water \( h = 6000 \text{ W/m}^2\text{K} \)
hot vapor organic \( h = 200 \text{ W/m}^2\text{K} \)
\( U = 194 \text{ W/m}^2\text{K} \)
\( A = 2006 \text{ m}^2 \)
\( m = \frac{Q}{(1794 + 686)} = 61191 \text{ kg/h} \) (denominator is \( \lambda + C_p\Delta T \) in kJ/kg)
E-504

\[ Q = 35163 \text{ MJ/h} \]
\[ \Delta T_{lm} = 46.54^\circ C \]
boiling water \( h = 6000 \text{ W/m}^2\text{K} \)
warm vapor organic \( h = 100 \text{ W/m}^2\text{K} \)
\( U = 98.4 \text{ W/m}^2\text{K} \)
\( A = 2133 \text{ m}^2 \)
\[ m = \frac{Q}{(2086 + 293)} = 14781 \text{ kg/h} \] (denominator is \( \lambda + C_p\Delta T \) in kJ/kg)

E-505

\[ Q = 395921 \text{ MJ/h} \]
\[ \Delta T_{lm} = 75.74^\circ C \]
water \( h = 3000 \text{ W/m}^2\text{K} \)
condensing organic \( h = 600 \text{ W/m}^2\text{K} \)
\( U = 500 \text{ W/m}^2\text{K} \)
LMTD corr factor \( = 1 \)
\( A = 2904 \text{ m}^2 \)
\[ m = \frac{Q}{[(4.184)(10)]} = 9.46 \times 10^6 \text{ kg/h} \] (denominator is \( C_p\Delta T \) of water in kJ/kg)
**E-506**

\[ Q = 33122 \text{ MJ/h} \]
\[ \Delta T_{lm} = 40^\circ \text{C} \]
boiling organic \( h = 6000 \text{ W/m}^2\text{K} \)
condensing steam \( h = 6000 \text{ W/m}^2\text{K} \)
\( U \approx 3000 \text{ W/m}^2\text{K} \)
\( A = 76.7 \text{ m}^2 \)
\( m = \frac{Q}{(2086)} = 15878 \text{ kg/h} \) (denominator is in kJ/kg)

**E-507**

\[ Q = 28114 \text{ MJ/h} \]
\[ \Delta T_{lm} = 30.73^\circ \text{C} \]
water \( h = 3000 \text{ W/m}^2\text{K} \)
condensing organic \( h = 600 \text{ W/m}^2\text{K} \)
\( U = 500 \text{ W/m}^2\text{K} \)
\( A = 508 \text{ m}^2 \)
\( m = \frac{Q}{[(4.184)(10)]} = 671941 \text{ kg/h} \) (denominator is \( C_p\Delta T \) of water in kJ/kg)
E-508

\[ Q = 341071 \text{ MJ/h} \]
\[ \Delta T_{lm} = 35^\circ C \]
boiling organic \( h = 6000 \text{ W/m}^2\text{K} \)
condensing steam \( h = 6000 \text{ W/m}^2\text{K} \)
\( U = 3000 \text{ W/m}^2\text{K} \)
\( A = 902 \text{ m}^2 \)
\[ m = \frac{Q}{2086} = 163505 \text{ kg/h} \text{ (denominator is in kJ/kg)} \]

E-509

\[ Q = 341977 \text{ MJ/h} \]
\[ \Delta T_{lm} = 69.88^\circ C \]
water \( h = 3000 \text{ W/m}^2\text{K} \)
condensing organic \( h = 600 \text{ W/m}^2\text{K} \)
\( U = 500 \text{ W/m}^2\text{K} \)
\( A = 2720 \text{ m}^2 \)
\[ m = \frac{Q}{(4.184)(10)} = 8.17 \times 10^6 \text{ kg/h} \text{ (denominator is } C_p \Delta T \text{ of water in kJ/kg)} \]

T-501

from Chemcad 25 ideal stages, feed at 14
average flows above and below feed:
above feed: \( L = 65000 \text{ kg/h}, V = 73000 \text{ kg/h} \)
below feed: \( L = 140000 \text{ kg/h}, V = 92000 \text{ kg/h} \)
top \( T = 66^\circ C, M = 85 \text{ kg/kmol} \); bottom \( T = 120^\circ C, M = 105 \text{ kg/kmol} \)
\[ \rho_L = 835 \text{ kg/h} \]
\[ \rho_G = \frac{PM}{RT} \]
top: \( \rho_G = (40 \text{ kPa})(85 \text{ kg/kmol})/[(8.314 \text{ kPa m}^3/\text{kmol K})(339 \text{ K})] = 1.206 \text{ kg/m}^3 \)

bottom: \( \rho_G = (60 \text{ kPa})(105 \text{ kg/kmol})/[(8.314 \text{ kPa m}^3/\text{kmol K})(393 \text{ K})] = 1.92 \text{ kg/m}^3 \)

24 in tray spacing

calculations for top of column:
\( (L/V)(\rho_G/\rho_L)^{0.5} = 0.034 \)
from flooding graph (C. J. King, *Separation Processes*, 2\(^{nd}\) ed, McGraw-Hill, 1980, p. 594, which is similar to Fig. 6.24 in J. D. Seader and E. J. Henley, *Separation Process Principles*, Wiley, 1998)

\( K_v = 0.37 \)

\( u_f = 9.73 \text{ ft/s} = 2.97 \text{ m/s} \)

at 75\% of flooding, \( u = 2.23 \text{ m/s} \)

\( A = (L/3600)/(\rho_G u) = 7.54 \text{ m}^2 \)

if 75\% active area, \( A = 10.05 \text{ m}^2 \)

\( D = 3.58 \text{ m} \)

calculations for bottom of column:
\( (L/V)(\rho_G/\rho_L)^{0.5} = 0.073 \)
from flooding graph

\( K_v = 0.35 \)

\( u_f = 14.0 \text{ ft/s} = 4.27 \text{ m/s} \)

at 75\% of flooding, \( u = 3.20 \text{ m/s} \)

\( A = (L/3600)/(\rho_G u) = 4.16 \text{ m}^2 \)

if 75\% active area, \( A = 5.55 \text{ m}^2 \)

\( D = 2.67 \text{ m} \)

use tapered column to avoid flooding at top and weeping at bottom

different diameters above and below feed as specified above

25 ideal stages

top \( \alpha = 2.35 \), bottom \( \alpha = 2.17 \), \( (2.35)(2.17))^{0.5} = 2.26 \)

\( \mu \alpha = 0.4 \text{ cp (2.26) = 0.9} \)

from O’Connell correlation, 0.55 overall column efficiency

\( \Rightarrow \) 46 stages (so column about 92 ft tall)

feed at 46(14/25) = 26

\( \Delta P = \rho g h N \)

\( 20000 \text{ kg m}^2/\text{s}^2 = (835 \text{ kg/m}^3)(9.8 \text{ m/s}^2)(h_{weir})(46) \)

\( h_{weir} = 0.053 \text{ m} = 2.1 \text{ in} \)

**T-502**

from Chemcad 80 ideal stages, feed at 25

average flows above and below feed:

above feed: \( L = 920000 \text{ kg/h}, V = 950000 \text{ kg/h} \)

below feed: \( L = 970000 \text{ kg/h}, V = 960000 \text{ kg/h} \)

top \( T = 150^\circ \text{C}, M = 106 \text{ kg/kmol}; \) bottom \( T = 125^\circ \text{C}, M = 145 \text{ kg/kmol} \)
\[ \rho_L = 800 \text{ kg/h} \]
\[ \rho_G = \frac{PM}{RT} \]

top: \( \rho_G = \frac{(40 \text{ kPa})(106 \text{ kg/kmol})}{[(8.314 \text{ kPa m}^3/\text{kmol K})(378 \text{ K})]} = 1.35 \text{ kg/m}^3 \)
bottom: \( \rho_G = \frac{(60 \text{ kPa})(104 \text{ kg/kmol})}{[(8.314 \text{ kPa m}^3/\text{kmol K})(398 \text{ K})]} = 2.32 \text{ kg/m}^3 \)

calculations for top of column:
\[ \frac{(L/G)(\rho_G/\rho_L)}{0.5} = 0.040 \]
from flooding graph
\[ K_v = 0.22 \]
\[ u_f = 7.58 \text{ ft/s} = 2.31 \text{ m/s} \]
at 75\% of flooding, \( u = 1.73 \text{ m/s} \)
\[ A = \frac{V}{3600} \left( \frac{\rho_G u}{\rho_L} \right) = 113 \text{ m}^2 \]
if 75\% active area, \( A = 151 \text{ m}^2 \)
\[ D = 13.8 \text{ m} \text{ – too large} \]

calculations for bottom of column:
\[ \frac{(L/G)(\rho_G/\rho_L)}{0.5} = 0.054 \]
from flooding graph
\[ K_v = 0.21 \]
\[ u_f = 5.29 \text{ ft/s} = 1.61 \text{ m/s} \]
at 75\% of flooding, \( u = 1.21 \text{ m/s} \)
\[ A = \frac{V}{3600} \left( \frac{\rho_G u}{\rho_L} \right) = 94.9 \text{ m}^2 \]
if 75\% active area, \( A = 127 \text{ m}^2 \)
\[ D = 12.7 \text{ m} \text{ – too large} \]

88 ideal stages

top and bottom \( \alpha = 1.15 \)
\[ \mu \alpha = 0.27 \text{ cp} (1.15) = 0.3 \]
from O’Connell correlation, 0.70 overall column efficiency
⇒ 115 stages (so column about 115 ft tall)

feed at 115(25/80) = 36

\[ \Delta P = \rho g h N \]
\[ 20000 \text{ kg m/m}^2 \text{s}^2 = (800 \text{ kg/m}^3)(9.8 \text{ m/s}^2)(h_{weir})(115) \]
\[ h_{weir} = 0.022 \text{ m} = 0.87 \text{ in} \]

try packed distillation column
structured packing, low pressure drop, high flooding capacity (choose packing so that \( G_f = 1.0 \))

top of column
\[ \frac{(L/V)(\rho_G/\rho_L)}{0.5} = 0.04 \]
\[ (G' - C_f \mu_L) \frac{0.1}{(\rho_G/\rho_L)} = 0.3 \]
\[ \rho_G = 0.00027 \text{ kg/m s} \]
solve for \( G' = 27.1 \text{ kg/m}^2 \text{s} \)
at 75% of flooding
\[ A = \frac{V}{3600}/[(0.75)(27.1)] = 12.98 \text{ m}^2 \]
\[ D = 4.06 \text{ m} \]

bottom of column
\[ \frac{L}{V}(\rho_G/(\rho_L - \rho_G))^{0.5} = 0.054 \]
\[ (G' \mu^2 C_f \mu_L)^{0.1}/(\rho_G(\rho_L - \rho_G)) = 0.29 \]
\[ \mu_L = 0.00027 \text{ kg/m s} \]
solve for \( G' = 34.93 \text{ kg/m}^2\text{s} \)
at 75% of flooding
\[ A = \frac{V}{3600}/[(0.75)(34.93)] = 10.17 \text{ m}^2 \]
\[ D = 3.49 \text{ m} \]

make diameter 4.06 m
packing HETP = 0.3 m
column height = 0.3(115) = 34.5 m
feed at 34.5(36/115) = 10.8 m from top
column will be 5 m taller to allow room for distributors at feed location and throughout column
total column height = 39.5 m