Design of a Packed Distillation Column for a Unit Operations Laboratory

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Abstract

The design for a new packed distillation column for consideration as a new experiment for the University Of Florida Department Of Chemical Engineering Unit Operations Laboratory was created to demonstrate the separation of water and isopropanol (i-Pr) and to evaluate a parallel applied multi-correlation approach to creating a high accuracy process model based on correlations with known margins of error. The final design produced features a core distillation unit, capable of batch, semi-batch, and continuous operation, and a surrounding recycle and waste management system, which is not covered in this paper. The nominal core system configuration was continuous operation with 20 mol% i-Pr, 10 mol% i-Pr, and 60 mol% i-Pr compositions and 10.4 USGPH, 6.6 USGPH, and 3.9 USGPH flow rates for the feed, bottoms, and distillate material streams, respectively. This configuration had a 6.65 inch tall HTU, requires 3.42 NTU, and a minimum required height of 1.89 ft. The final column design used a 6 ft high packing of ¼ in. Raschig Rings and had a 23.1% nominal “average tray efficiency,” which was an expectedly low value due to the presence of an azeotrope at 67 mol% i-Pr.
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Purpose of the Design
The author’s research was spurred by his mentor’s proposition of comparing the performance and design of a packed column distillation unit with an azeotrope to the tray columns the author had prior experienced in operation in the lab. This further evolved into developing a full design to be proposed for construction in the lab for eventual student use.

Chemical System Definition
The chemical system central to the design is a binary mixture of water and isopropanol (i-Pr). This system has a characteristic azeotrope and wildly varying relative volatility. The high degree of variance in the relative volatility at lower concentrations of isopropanol is to be expected as the isopropyl group causes significant steric hindrance to potential hydrogen bonds with the hydroxyl group\textsuperscript{[1]}. This behavior is depicted in Figure 1 in the section on thermodynamic models.

Overview of Design Process
The design process was largely heuristics based with guidance from the research mentor. Along the way, several constraints on the design were encountered which may be summarized prior to the design method for sake of simplicity.

Pedagogical Considerations
Given that the eventual purpose of the design was to function as a working unit operation for student use in the senior laboratory course as well as to test the utility of the chosen modeling scheme, practical pedagogical constraints and the concerns of students taking their laboratory courses using current equipment were taken into consideration. Chief amongst those concerned was the physical capacity to operate the system in a wide enough range of desired conditions to gather characterizable data. To address this issue, the system’s size was bounded by the desire to allow for more experimental operations in the same amount of time, which meant the system would be more sensitive to control manipulations, but would converge in a timely manner. Second was the desire to reduce downtime between experimental operations. This was a broad concern but not as prevalent as many students were not able to achieve multiple runs during the normally allotted time. This was addressed by surrounding the core system with a recycle and waste management system. The pedagogical advantage of this was allowance for a larger degree of measurability since the recycle system would avail the relevant data to students during the recycle procedure.

Nominal Design Constraints and Initial Parameters
Several constraints were placed on the nominal design to satisfy physical and practical constraints inherent to its proposed eventual construction in the Unit Operations Laboratory of the University Of Florida Department Of Chemical Engineering. The design was limited to using a reasonable amount of electrical power and/or steam, fitting within the Unit Operations Laboratory, and reducing costs where possible such that eventual construction was a viable project.

Reduction of costs was applied systematically by determining the utility of spare materials and parts in the lab to the design and by scaling down the system to the optimal configurations with lower associated costs.

Reasonable electrical power was determined based upon peak use of 90% of the maximum current available from a standard wall socket at with approximately 10% loss of potential due to circuit efficiency. A standard wall socket is regulated by circuit breaker and building voltage to provide up to 15 amperes rms at 115 volts rms\textsuperscript{[2]}. As is shown below, this translates to roughly 1.4KW of available power for the entire system.
Equation 1

Assuming that any process controls used are manual or pneumatic and removing from the system’s electrical power limit the sufficient power to operate a computer of minimalist design (to be used for process control and data recording), which was poorly estimated at an arbitrary 400W, leaves a reasonable limit of 1KW for the maximum operating power of an electrically powered design.

\[ P_{\text{available, system}} = (0.90 \times 15 A_{\text{rms}}) \times ((1 - 0.10) \times 115 V_{\text{rms}}) = 1397.25 \text{ Watts} \]

Equation 2

In the course of designing the system, this created an operational pinch point that was later used as the selection criteria for the means of heating the reboiler after the requisite power was determined.

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The physical constraints of the Unit Operations Laboratory itself limited the system height, and therefore the column height, to the height of the first floor of the lab, which was conveniently the largest available space and approximately 20 feet high. Upon inspection of the first floor of the lab, it was discovered that the frame from a previously dismantled double effect evaporator was available to house the design. The frame was 54 inches wide, 48 inches deep and 108 inches high. This effectively limited the core system diameter to roughly 4 ft.

Given the electrical power limit of 1KW, an initial arbitrary column diameter of 3 inches was chosen as a basis. The packing material chosen was ¼ inch ceramic Raschig Rings as there was a surplus supply in the lab at the time and using it would reduce costs. The nominal compositions for the material streams at the core system boundaries were 20mol% i-Pr for the feed, 10mol% i-Pr for the bottoms, and 60mol% i-Pr for the distillate. The internal conditions of the system were specified as being at VLE with a system pressure of 1 atm.

Model Selection Criteria

Models were selected based primarily on a balance of the global expected inherent uncertainty and the closeness of fit to the specific physical system being modeled. This general strategy was used to select the majority of the pure component models used in the final design. However, some cases required a more in depth exploration into the research that went into the formulation of the respective model. Accuracy became a concern when selecting meta-correlations or correlations built upon the results of subordinate correlations. As may be expected, this was most encountered when selecting multicomponent models to describe the various physical subsystems involved in the overall design.

Many of the models chosen to describe multicomponent behavior were abstract mixing rules, meta-correlations constructed to be agnostic of the pure component subordinate correlations chosen as a basis. For example, the Van der Waals and Wong-Sandler mixing rules are constructed such that their pure component basis is simply restricted to the general type of correlation construction. For the Van der Waals mixing rule, any equation of state may be used\(^3\), whereas the Wong-Sandler mixing rule can use any model for the excess Gibbs energy of mixing model\(^4\) or excess Helmholtz energy of mixing at infinite pressure, as was its original formulation\(^5\). This appears to be a generally constructive strategy\(^6\), but it is the author’s opinion that blindly accepting a meta-correlation without consideration of the subordinate correlations used tends to misrepresent the multicomponent model’s accuracy. Given this reasonable constraint that the generalized meta-correlations selected for this design be previously tested, the author consulted several works when selecting the multicomponent models and chose those that had been tested using multiple subordinate correlations when possible. When the author could not locate a suitably tested multicomponent correlation, the previous general heuristic was applied and the subordinate correlations specified were employed when possible.
Selection of Thermodynamic Properties Models

Several thermodynamic models were considered for this design. Since some degree of quantitative accuracy was a desired goal, more complex models were chosen in lieu of those which may have been qualitatively sufficient. The general calculation procedure used was to calculate the fugacity coefficient for each phase using a combination of pure component models and mixing rules, then to use the $\phi - \phi$ method to determine the properties of the equilibrium states of the vapor and liquid phases\(^3\)\(^7\)\(^8\).

Vapor Phase Model

The thermodynamic model used for the vapor phase was the Peng-Robinson-Stryjek-Vera-2 (PRSV-2) model with literature binary coefficients used for the binary interaction parameters\(^9\)\(^10\). This method affords a significant increase in accuracy for VLE calculations over even the Peng-Robinson (PR) model. This was found to be due to the extreme degree of non-linearity present in the equations governing VLE and the numerical method requisite in determining stable VLE states\(^9\)\(^10\).

Liquid Phase Model

The thermodynamic model used for the liquid phase was based in the General NRTL activity model\(^11\), with binary coefficients estimated by UNIFAC\(^12\). While this may seem counterintuitive as activity models are typically used for the $\gamma - \phi$ method\(^3\), the careful choice of mixing rule allows for use of the much less complicated $\phi - \phi$ method\(^5\). The UNIFAC estimated binary interaction parameters were sufficient for describing the chemical system’s behavior upon comparison of the nominal system predictions with literature data\(^1\)\(^13\)\(^16\).

Mixing Rules

Two mixing rules were used to obtain mixture thermodynamic properties, one for each respective phase. The Van der Waals mixing rule was used to predict the vapor phase state and the Wong-Sandler model was used for the liquid phase.

Van der Waals

This mixing rule was chosen for its relative simplicity over newer models which sacrifice significant computation time for relatively small gains in accuracy\(^14\). It was sufficient that the choice of the PRSV-2 model over the PR model brought the system behavior into a reasonably quantitative range of accuracy\(^15\). The Van der Waals mixing rule is also thermodynamically consistent as it satisfies the quadratic second Virial coefficient condition (QSVC)\(^13\).

Wong-Sandler

This mixing rule was chosen for its significant improvements in accuracy over previous models as well as its general versatility\(^5\). It is independent of the chosen activity model used\(^8\), which provided flexibility in how the thermodynamic models were evaluated against the reference data. When used in combination with the General NRTL model, it satisfies the QSVC condition\(^8\). This thermodynamic consistency was a characteristic the author desired to maintain as a governing threshold during VLE calculations.

Evaluation of Thermodynamic Properties

As was previously mentioned, the $\phi - \phi$ method, allowed by the Wong-Sandler mixing rule, was used to calculate the VLE states of the nominal system\(^16\). The VLE conditions were calculated for 1000 evenly spaced compositions including the pure components. This was accomplished using the UniSim Design software\(^16\). This data set formed one of two components comprising the basis dataset used for all further calculations. The other half of the basis dataset was the transport properties data calculated for each of the mentioned compositions. As may be seen in Figure 1, the nominal design compositions are constrained by an azeotrope at roughly 67mol% i-Pr. As all nominal compositions are below this limit, none were changed at this stage of the design. The T-XY diagram, Figure 2, was revealing as at the entire system is specified as being at or below the normal boiling temperature of water with no significant pressure drop across vessel walls.
Figure 1: Water-Isopropanol Vapor-Liquid Equilibrium Plot

Figure 2: Water-Isopropanol System T-X Diagram
Selection of Transport Properties Models

Transport properties models were similarly chosen for their relative accuracy, but this constraint was allowed to relax some as the transport properties were not involved in the VLE calculations [7]. The key distinction between the regimes of accuracy tolerance is the degree of uncertainty introduced through feedback in iterative calculations. The transport properties were involved primarily in feedforward calculations, which carry significantly less risk of solution instability due to objective function uncertainty.

This change in how uncertainty is propagated may be seen by carrying out the systematic uncertainty analysis when recursively evaluating a continued fractions expression to an arbitrary degree and then comparing the result with the uncertainty propagated by evaluating the analytically derived solution that requires a single evaluation. This example is sufficient to suggest the necessity of a higher standard of accuracy for thermodynamic equilibria calculations as VLE solution techniques employ equations of a non-linearity well beyond that of a simple continued fractions statement [17] [18].

As such, the default models present in UniSim [16] were consulted first and replaced or modified if needed.

Viscosity Model

The default modified Letsou-Stiel model present in UniSim was used for the viscosity model [16]. The data produced by the modified Letsou-Stiel model qualitatively agreed very well with the reference data [1] [13] [20] [21] [25]. The resulting plot of liquid viscosity as a function of composition is given below in Figure 3.

![C3H7OH-H2O System Liquid Viscosity vs X Diagram](image)

Figure 3: Plot of Liquid Viscosity vs Composition
Surface Tension Models
As was done with the viscosity, the surface tension model was left up to UniSim to compute and was then checked against reference data for qualitative agreement\textsuperscript{[16]}. The surface tension model had similarly good agreement with the reference data\textsuperscript{[1][13]}. The plot of surface tension as a function of composition is given below in Figure 4.

![C3H7OH-H2O System Surface Tension vs X Diagram](image)

\textbf{Figure 4: Plot of Surface Tension vs Composition}

Thermal Conductivity and Dielectric Coefficient Models
The thermal conductivity and dielectric coefficient models were also allowed to be governed by UniSim\textsuperscript{[16]}. They had good qualitative agreement with the reference data\textsuperscript{[1][13]}.

Diffusivity Models
The diffusivity models were selected based on ease of use and applicability to the system being studied.

\textbf{Gilliland Correlation}
The Gilliland correlation describes the effective diffusivities of gasses and was used to determine the diffusivities of the vapor phase\textsuperscript{[19]}.

\textbf{Wilke and Chang Correlation}
Since the liquid phase cannot be treated in the same ideal manner as the vapor phase (for which most models begin with the classical Stokes-Einstein relationship), the infinite dilution diffusivities are calculated and combined using a mixing rule much the same way as the thermodynamics models are constructed. The Wilke and Change correlation is used for non-polar to moderately polar substances. It is a good model for weakly polar substances dissolved in polar substances, and was therefore used for the infinitely dilute isopropanol in bulk water\textsuperscript{[19]}.

\textbf{Sitaraman et al. Correlation}
This correlation is specifically recommended for infinitely dilute water in a bulk substance of weaker polarity, therefore it was used for the infinitely dilute water in bulk isopropanol\textsuperscript{[19]}.
Leffler and Cullinan Correlation
This correlation acts as the mixing rule that combines the pure substances’ behavior to describe the mixture. The high degree of non-linearity relative to other available models was a concern, but was it was discovered upon inspection that the uncertainty propagated would not likely be of concern to the final model [19]. This model did correlate well with literature data within the range of conditions in the nominal design [27].

Selection of Flooding Model
While there were many good models to choose from, the model that made the most sense to use in the final design was the definitive Sherwood et al. model. This model was constructed from experiments performed on a steam rectification unit with the same nominal packing and internal conditions range as those chosen for the design being discussed [20].

The alternate model used for qualitative analysis of system behavior was the far more general correlation by Piché et al. [20]. This model was based on the use of an artificial neural network to correlate the behavior of a randomly packed column over a wide range of conditions using a wide variety of packings. It is the author’s opinion that the correlation produced may not have had enough subunits to satisfactorily capture the fully generalized nature of packed systems in quantitative detail [21] and that there was sufficient accuracy within the validation data set to warrant qualitative use prior to final selection of a nominal packing material [20].

Selection of Loading Model
The correlation by Piché et al. for loading point prediction was used in the same manner as the corresponding flooding point model [22]. Since the loading behavior of a packed column does not quantitatively impact the maximum power requirement of the reboiler, a qualitative description of the behavior is satisfactory for use in locating reasonable limits of operation [23].
Determination of Power Requirements

The power requirements for the core system were based on the calculated vapor rate at the flood point. This is simply determined as the product of the flow rate and latent heat of vaporization.

\[ P_f = \lambda_{vap} \times V_{2,fl} \]

Equation 3

The flooding power requirement as a function of column height was determined using the generalized correlation of Piché et al. [20] and is shown in Figure 5 below.

As may be seen in Figure 5, the power scales roughly as a function of column diameter squared and has a value of approximately 7.2KW for a column with a 3 inch diameter. Projecting along the trend line, the column would have to be 1 inch (at the nearest 1/16 inch) in diameter to reach the electrical power limit. This ruled out the use of electrical power at the desired system size. There was also the accuracy of the models being used to predict the flood point to consider when selecting a column diameter. Most flooding models are correlated such that the predictions deviate significantly from observed system behavior when the ratio of the column diameter to packing diameter falls below 30 [23]. Specifically, the model used for this preliminary power requirement estimate tends to over predict the power required for random packings with a diameter less than ½ inch [20], but the qualitative conclusions as to which power source should be used for heating were quite clear: steam heating.

Final determination of the required power for the reboiler was based on the correlation by Sherwood et al., which was included in the final design model [20].
Selection of Heat Transfer Models

Heat transfer models were chosen for their applicability to the various physical and chemical regimes in the core system and then by the accuracy of the model with respect to said application.

Nusselt Model

The Nusselt model for condensation in a horizontal pipe was chosen to describe the condensation occurring in both the reboiler (steam) and condenser (distillate) for its applicability to a wide range of conditions and its general accuracy.[3][31].

Mostinski Model

The Mostinski model was chosen for its general applicability to the heat transfer occurring in the nucleate pool boiling regime for pure fluids [24][25][33]. As will be explained further, the model chosen for describing the heat transfer for the nucleate pool boiling regime in a multicomponent mixture requires pure component heat transfer coefficients to work.

Modified Thöme and Shakir Model

The modified Thöme and Shakir model was originally considered for use due to its generally superior performance relative to other correlations when considering the water isopropanol system [24]. However, a relatively small modification allowed for a worthwhile increase in accuracy and was used in tandem [7].

Combined Model Evaluation and Heat Exchanger Sizing

The models for the reboiler and condenser were assembled using the series resistances paradigm shown below

\[ Q_{RB} = \sum_j \Delta T_j / \sum_j R_j = \frac{T_i - T_o}{h_i A_i + \Delta \frac{\Delta}{k_w A_w} + \frac{1}{h_o A_o}} \]

Equation 4

where \( T \) is temperature, \( r \) is pipe radius, \( A \) is area, \( h \) is heat transfer coefficient, and \( k \) is thermal conductivity [3][7][26]. The respective correlations were substituted into Equation 4 for both the reboiler and condenser, which were then rearranged to produce the following respective non-linear objective functions of the length of pipe [3][7]

\[ f_{obj}(L) = \alpha + \beta L^{-\frac{1}{3}} - \gamma L + \delta L^{0.7} \left( 1 + e \left( 1 - \exp \left( \frac{\xi}{L} \right) \right) \right) \]

Equation 5

\[ f_{obj}(L) = L^{\frac{4}{3}} + \alpha L^{\frac{31}{30}} + \beta L^{\frac{1}{3}} + \gamma \]

Equation 6

where all variables other than \( L \) are compound expressions of other physical variables. Given the reasonably smooth nature of these objective functions within the range of physically possible values for length (positive real numbers), Newton’s method and successive substitution with physically plausible initial values were used to find the respective solutions [3]. This approach produced consistent and reasonable results, as there were neither situations calling for impractically sized heat exchangers encountered nor non-physical results produced. Evaluation of the size of the required heat exchanging surface using the solutions from Equation 5 and Equation 6 is the first step in determining the size of both the reboiler and the condenser.
Initial Sizing of the Reboiler

With the length of the pipe to be used for heat exchange numerically solvable as a function of pipe radius, the next step was to size the shell and to determine the pipe’s geometry relative to the shell. A minimum reboiler diameter was determined by using a dual coil design for the pipe geometry with a single pipe diameter spacing maintained within the coil. This design was chosen because it allowed for completely planar coil geometry and featured counter current flow of the heat source in a cylindrical geometry. The planar geometry allows for greater flexibility in vertical placement of the coil as it is only one pipe diameter thick, and the dual coil design also allows for placement of the steam inlet and outlet in any position along the outside of the reboiler in the plane of the coil. The vertical placement is important as nucleate pool boiling is theoretically based upon low or zero bulk flow conditions in most treatments \[7\][26]. The cylindrically oriented counter current flow of condensing steam provides for even heating of the reboiler contents. The reboiler was initially sized for continuous operation of the core system. This meant that the volume of the reboiler was irrelevant to the method used to predict the mass transfer behavior of the system.

Selection of Mass Transfer Models

Models for mass transfer were chosen to determine the effective specific area of the packing and the mass transfer coefficients of the column. Determination of these values was discovered to be the most heavily involved step in determining how the column would behave and how to size the final system \[37\][38].

Onda et al. Correlations

The correlation for effective specific area by Onda et al. was chosen because the original research behind it was performed on the same packing material being used for the nominal system design and because the correlation is satisfactorily accurate for quantitative prediction \[27\]. The correlation for the interface mass transfer coefficients, both $k_G$ and $k_L$, by Onda et al. were similarly chosen for the same similarity in physical systems involved \[27\]. Follow up work by Piché et al. attempting to generalize the prediction of packed column mass transfer was used to confirm the quantitative utility of these models \[28\] and a review of mass transfer correlations by Wang et al. confirmed the general qualitative accuracy of the chosen correlations relative to other possible choices in the context of the intended nominal design \[29\].

Mass Transfer Behavior and Column Sizing

The overall mass transfer behavior was determined by translating from the interfacial mass transfer regime to the overall mass transfer regime and then using the design integral for packed columns to size the column itself.

Translation from Interfacial to Overall Mass Transfer

Conversion of interfacial coefficients to overall coefficients was accomplished by taking advantage of the relationship between the interfacial and overall transfer coefficients as may be seen in the following equation

\[
\frac{1}{K_Y} = \frac{1}{k_G} + \frac{m'}{k_L}
\]

Equation 7

where $K_Y$ is the vapor phase overall mass transfer coefficient, $m'$ is the slope of the equilibrium line on the XY diagram shown in Figure 1, and $k_G$ and $k_L$ are the interfacial mass transfer coefficients as were previously defined \[3\][19][23][27][29][30]. The overall mass transfer coefficient was only necessary for one phase to continue, though the correlated value for both phases would be necessary to perform an internal check on the model’s accuracy. Only the overall mass transfer coefficient for the vapor phase was calculated in the interest of time constraints.
Design Integral
The design integral was subsequently used to determine the required height of packing material to yield the desired nominal mass transfer. The equation for this is

$$z = \int_{x_B}^{x_D} H_{oy} \frac{dy}{y' - y} = \int_{x_B}^{x_D} H_{oy} dN_{oy} \approx H_{oy} \int_{x_B}^{x_D} dN_{oy} \approx H_{oy} N_{oy}$$

where $z$ is packing height, $x_B$ is reboiler composition, $x_D$ is distillate composition, $H_{oy}$ is the vapor phase height of a transfer unit (HTU), $N_{oy}$ is the vapor phase number of transfer units (NTU), $y$ is the equilibrium vapor phase composition, and $y'$ is the vapor phase composition outside of the column in pseudo-equilibrium with the equilibrium vapor phase composition. The HTU for the vapor phase is based on the correlation by Onda et al. [27].

Column Sizing and Calculated Mass Transfer Behavior
The design integral was evaluated in several different ways, in part, to investigate the variance in accuracy based upon the methods expected to be known and used by students. The full integral was evaluated numerically to get the most accurate results for the required height. This set the benchmark for all further analysis of the expected effective mass transfer. Subsequently, the value for $N_{oy}$ was calculated by integrating over the same interval and used with Equation 8 to solve for the true average value for $H_{oy}$. After this, the integrated value for $H_{oy}$ was evaluated for comparison to the previous value by both integration and summation based averages. Finally, the height of an equivalent theoretical plate (HETP) was calculated using

$$\text{HETP} = H_{oy} \frac{\ln \left( \frac{m'V}{L} \right)}{\frac{m'V}{L} - 1}$$

where $V$ is the vapor phase molar flow rate and $L$ is the liquid phase molar flow rate. The HETP may be further used for comparison with tray columns operating under comparable constraints to evaluate their relative effective mass transfer efficiencies.

Final Selection of Column
The column chosen to be used was already present in the lab and was selected because it has the same packing material and the same diameter as the nominal design. The height was slightly different, but the model was constructed such that this form of variation was easily compensated for.

Sizing the Condenser
With the mass transfer behavior determined, the condenser was sized to match or exceed the power entering at the reboiler using the previously defined heat exchanger sizing equation (Equation 6) and the designated nominal composition of the distillate, which was confirmed as feasible by the corresponding predictions for mass transfer behavior. This safety consideration was well exceeded as the size called for by the nominal design was exceeded by a factor of three in the smallest available unit present in the lab. It was decided that sub-cooling would be an interesting pedagogical twist so the spare shell and tube heat exchanger was selected as the candidate condenser for the final design.
Final Sizing of the Reboiler
As the system was designed from the beginning with an external means of recycling and waste management, the column was operable in continuous, semi-batch, and batch modes. With the condenser sized, reboiler heat exchanger sized, and mass transfer behavior determined, the final sizing of the reboiler was considered based on batch operation. The volume of the reboiler was sized to contain enough fluid to operate for the entirety of a single lab session, approximately four hours. To maximize boil off and thereby maximize possible separation, the reboiler was designed in several flanged segments. The bottom section was set at a slightly larger diameter than was determined by the initial sizing. This slightly oversized the heat exchanger, which consequently would challenge students to properly control the system without flooding it. The middle section was set at a diameter that would contain the required volume for a full lab session while fitting within the frame to be used for the system. Since the liquid level in the reboiler was to be set to never fall below the interface of these two sections for normal operation, the minimized boil off ratio for the given volume was achieved, which allowed for a maximum of possible separation. The middle section was also tall enough to provide good resolution, and therefore a high resolving power, on a calibrated sight glass spanning the height of the total reboiler. The top section acted simply as a cap to the reboiler and interfaced with the column itself. This design was chosen such that the middle section could be removed to inspect and service the heat exchanger. A schematic diagram of the final reboiler design is given in Appendix C.

Assembling the Completed Model
The final model was constructed within a Microsoft Office Excel 2010 workbook and setup such that many of the design constraints and nominal values were variable user inputs. This provided significant flexibility in selecting components and in determining the final nominal design. A static copy of the final design is given in Appendix A and the file is available upon request from the author.

Description of Nominal System Design and Behavior

Column and Packing Material
The final nominal design is center around a core unit with a 6 ft tall, 3 inch inner diameter borosilicate glass column randomly packed with ¼ inch Raschig Rings.

Reboiler
The reboiler has a nominal volume of 110 USGal. Its heating section is 12 inches in diameter and is 8 inches tall. The middle section is 3 ft in diameter and is 2 ft tall. The top section has a 3 inch diameter flanged attachment and the bottom section has a 1 inch diameter outlet. The heat exchanger is made of type K, ½ inch NPS copper pipe. The minimum exchanger length is 1.05 ft which provides 0.172 sqr ft of exchanger area. The minimum diameter of the reboiler is 8.2 inches.

Condenser
The condenser is a shell and tube design with an 8.33 inch ID aluminum shell and 15 l inch ID steel tubes. The minimum length required is 10.2 inches which produces a minimum exchange area of 32 square inches.

Nominal Operation
The nominal core system operates continuously at 50% of the flooding power. The feed is 20 mol% i-Pr flowing at 10.4 USGPH into the reboiler. The bottoms is 10 mol% i-Pr flowing at 6.6 USGPH from the reboiler recycle return line. The Distillate is 60 mol% i-Pr flowing at 3.9 USGPH from the reflux return line. The column has a 23.1% overall “average tray efficiency,” 6.65 inch HTU, and 3.42 NTU corresponding to a 1.89 ft minimum required height.
Nominal Lab Session
The nominal lab session is predicted to include up to five continuous runs or 3 batch runs, and can accommodate
runs lasting the entirety of the lab session. The recycle and waste management system was designed such that a
downtime of as little as 8 minutes is expected between runs to pump from a pre-mixer to the supplying feed tank.

Concluding Remarks
The final design includes significant predicted improvements over the tray columns present in the lab. The design is
based upon sound correlations as verified by the literature data consulted but still suffers from the cumulative
propagation of small but significant error. While this was minimized by the careful selection of the correlations
chosen, the authors confidence in the numbers produced is cautiously estimated as ±20% and guessed to be as low
as ±10%. The author feels the experience was very rewarding as the process of synthesizing a full design and
performing each of the concomitant steps was particularly illuminating of the challenges involved in accurate
process design.

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Dr. Spyros Svoronos for his encouragement and advice. The author would also like to acknowledge the University of
Florida and its Department of Chemical Engineering.
References


# Appendix A: Static Description of the Nominal Core System Description

The following is a static copy of the model as was constructed in the Excel workbook.

<table>
<thead>
<tr>
<th>Manual Inputs</th>
</tr>
</thead>
</table>

## Physical Consts

<table>
<thead>
<tr>
<th>Physical Data</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>g</strong></td>
<td>9.81 m/s^2</td>
</tr>
<tr>
<td><strong>sigma_crit</strong></td>
<td>0.061 N/m</td>
</tr>
<tr>
<td><strong>dP @ Flood</strong></td>
<td></td>
</tr>
<tr>
<td><strong>FW_PrOH</strong></td>
<td>60.1 Kg/Kgmol</td>
</tr>
<tr>
<td><strong>FW_H2O</strong></td>
<td>18.02 Kg/Kgmol</td>
</tr>
<tr>
<td><strong>P_c_PrOH</strong></td>
<td>47.6 bar-abs</td>
</tr>
<tr>
<td><strong>P_c_H2O</strong></td>
<td>221.2 bar-abs</td>
</tr>
</tbody>
</table>

## Packing Data

<table>
<thead>
<tr>
<th>Packing Data</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type</strong></td>
<td>Raschig Ring</td>
</tr>
<tr>
<td><strong>Material</strong></td>
<td>Ceramic</td>
</tr>
<tr>
<td><strong>d_p</strong></td>
<td>0.25 in.</td>
</tr>
<tr>
<td><strong>a_p</strong></td>
<td>330 m^2/m^3</td>
</tr>
<tr>
<td><strong>N_p</strong></td>
<td>50000 m^-3</td>
</tr>
</tbody>
</table>

## NRTL-PR VLE Data

<table>
<thead>
<tr>
<th>NRTL-PR VLE Data</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>alpha_12</strong></td>
<td>0.326</td>
</tr>
<tr>
<td><strong>beta_12</strong></td>
<td>833.168</td>
</tr>
</tbody>
</table>

## Pure Fluid Data @ Normal BP

<table>
<thead>
<tr>
<th>Pure Fluid Data</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PrOH dHvap</strong></td>
<td>659200 J/Kg</td>
</tr>
<tr>
<td><strong>H2O dHvap</strong></td>
<td>2213000 J/Kg</td>
</tr>
</tbody>
</table>

## Mass Transfer Data

<table>
<thead>
<tr>
<th>Mass Transfer Data</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>D_AB_inf</strong></td>
<td>1.1328E-10 m^2/s</td>
</tr>
<tr>
<td><strong>D_BA_inf</strong></td>
<td>1.81888E-07 m^2/s</td>
</tr>
</tbody>
</table>

## Desired Column Specs and Desired Overall Performance (Continuous and Batch)

<table>
<thead>
<tr>
<th>Desired Column Specs and Desired Overall Performance</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>P_RB</strong></td>
<td>1 atm</td>
</tr>
<tr>
<td><strong>R_D</strong></td>
<td>1</td>
</tr>
<tr>
<td><strong>z_desired</strong></td>
<td>0.6</td>
</tr>
<tr>
<td><strong>D_c</strong></td>
<td>3 in.</td>
</tr>
<tr>
<td><strong>% Of Flood</strong></td>
<td>0.1</td>
</tr>
</tbody>
</table>

## Reboiler Physical and Sizing Correlation Parameters

<table>
<thead>
<tr>
<th>Reboiler Physical and Sizing Correlation Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>beta_L</strong></td>
<td>0.0003 m/s</td>
</tr>
<tr>
<td><strong>b</strong></td>
<td>0.1011</td>
</tr>
<tr>
<td><strong>Pipe OD</strong></td>
<td>0.625 in.</td>
</tr>
<tr>
<td><strong>Pipe t</strong></td>
<td>0.049 in.</td>
</tr>
<tr>
<td><strong>Pipe NPS</strong></td>
<td>0.5 in.</td>
</tr>
</tbody>
</table>

## Reboiler Steam Properties

<table>
<thead>
<tr>
<th>Reboiler Steam Properties</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>T_s</strong></td>
<td>150 C</td>
</tr>
<tr>
<td><strong>rho_c</strong></td>
<td>917.06 Kg/m^3</td>
</tr>
<tr>
<td><strong>dHvap</strong></td>
<td>2098.3 KJ/Kg</td>
</tr>
<tr>
<td><strong>K_c</strong></td>
<td>0.6821 W/m*K</td>
</tr>
</tbody>
</table>

## Condenser Physical and Sizing Correlation Parameters

<table>
<thead>
<tr>
<th>Condenser Physical and Sizing Correlation Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pipe OD</strong></td>
<td>1 in.</td>
</tr>
<tr>
<td><strong>Pipe t</strong></td>
<td>0.0625 in.</td>
</tr>
<tr>
<td><strong>Shell ID</strong></td>
<td>8.329 in.</td>
</tr>
<tr>
<td><strong>K_p</strong></td>
<td>12 W/m*K</td>
</tr>
<tr>
<td><strong># of Tubes</strong></td>
<td>15</td>
</tr>
</tbody>
</table>

## Condenser Coolant Properties

<table>
<thead>
<tr>
<th>Condenser Coolant Properties</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>T_c</strong></td>
<td>25 C</td>
</tr>
<tr>
<td><strong>rho_c</strong></td>
<td>997 Kg/m^3</td>
</tr>
<tr>
<td><strong>K_c</strong></td>
<td>0.58 W/m*K</td>
</tr>
</tbody>
</table>

## Lab Session Constraints

<table>
<thead>
<tr>
<th>Lab Session Constraints</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>t_lab</strong></td>
<td>4 hrs</td>
</tr>
<tr>
<td><strong>t_mix</strong></td>
<td>20 min</td>
</tr>
<tr>
<td><strong>t_shutdown</strong></td>
<td>10 min</td>
</tr>
<tr>
<td><strong>t_transition</strong></td>
<td>20 min</td>
</tr>
<tr>
<td><strong># trials desired</strong></td>
<td>4 trials/lab</td>
</tr>
<tr>
<td>Calculated Inputs</td>
<td></td>
</tr>
<tr>
<td>-------------------</td>
<td></td>
</tr>
<tr>
<td><strong>Overall Performance</strong></td>
<td><strong>Column Specs</strong></td>
</tr>
<tr>
<td>L/V</td>
<td>0.5</td>
</tr>
<tr>
<td><strong>Reboiler Heat Exchanger Parameters</strong></td>
<td>r_o</td>
</tr>
<tr>
<td><strong>Condenser Physical Parameters</strong></td>
<td>r_s</td>
</tr>
<tr>
<td></td>
<td>r_i</td>
</tr>
<tr>
<td></td>
<td>D_H</td>
</tr>
<tr>
<td></td>
<td>Pr_o</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Lab Session Constraints (Assuming Equal Length Trials Operating in Steady State or Batch)</strong></td>
<td>t_trial_min</td>
</tr>
</tbody>
</table>
### Physical Data

- **dP @ Flood**: 6.135359619 inH2O
- **Q_RB,op**: 6.336012623 KW

### Average Diffusivity Data

- **avg D_L**: 1.92398E-09 m^2/s
- **avg D_V**: 1.98755E-05 m^2/s

### Numerical Packing Height

- **Z_t**: 0.577007275 m
- **% Z_desired**: 28.85036374
- **% dZ_desired**: -71.14963626

### Transfer Unit Data

- **Noy* (int)**: 3.418178223
- **avg Hoy* (int)**: 0.154451178 m
- **avg Hoy*(sum)**: 0.15480292 m
- **Hoy* (z/Noy*)**: 0.168805497 m
- **avg HETP_y***: 0.20732365 m
- **avgc HETP_y***: m

### Reboiler Heating Requirements Data and Numerical Evaluation Values

- **r_i_RB_min**: A
- **B**: 9.27024E-05
- **C**: 3.38437E-06
- **D**: 9.89475E-05
- **E**: 0.273450087
- **r_o_RB**: L_i
- **L_i**: 0.5 erth
- **1E-12 L_min**: 0
- **L_max**: 100 L_0
- **0.320425218 err**: 9.86838E-13
- **9.86904E-13**:
- **L_RB**: 0.320425218 m
- **= 1.051488597 ft**
- **A_RB**: 0.015980498 m^2
- **CrossA_RB**: 0.03412473 m^2
- **r_i_col**: Condenser Cooling Requirements Data and Numerical Evaluation Values
- **r_o_col**: 0.010458752 A
- **0.000459671 B**: 0.00198224

### Column Insulation Sizing and Associated Power Loss

- **Manual Inputs**
- **B**: 92.52463625 erth
- **a_i**: 4.319689899
- **K_wall_col**: a_max
- **100 a_min**: 1.570796327 dr
- **0.320425218 err**: 9.86838E-13
- **9.86904E-13**:
- **L_RB**: 0.320425218 m
- **= 1.051488597 ft**
- **A_RB**: 0.015980498 m^2
- **CrossA_RB**: 0.03412473 m^2
- **r_i_col**: Condenser Cooling Requirements Data and Numerical Evaluation Values
- **r_o_col**: 0.010458752 A
- **0.000459671 B**: 0.00198224

### Reality Check: Re_c <= 2100?

- **m_s**: 0.003019593 Kgm/s
- **= 23.97387983 lb/hr**
- **TRUE**

### Condenser Cooling Requirements Data and Numerical Evaluation Values

- **A**: 0.010458752 B
- **0.000459671 C**: 0.00198224
- **L_i**: 0.5 erth
- **1E-12 L_min**: 0
- **L_max**: 10 L_0
- **0.25852178 err**: 9.43051E-13
- **9.43051E-13**:
- **L_c**: 0.258521782 m
- **UA_c**: 7.629634611 W/K
- **U_c**: 369.8477748 W/m^2*K
- **Reality Check: Re_c <= 2100?**

### Average Continuous Input/Output Flow Rate Data

- **avg V**: 0.13811335 mol/s
- **F-D-B ( ? = 0 )**: 0
- **TRUE**
- **avg L**: 0.069056677 mol/s
- **= 0.064640941 USGPM**: 3.878456459 USGPH
- **avg D**: 0.069056677 mol/s
- **= 0.064640941 USGPM**: 3.878456459 USGPH
- **avg F**: 0.345283387 mol/s
- **= 0.173660125 USGPM**: 10.41960749 USGPH
- **avg B**: 0.27622671 mol/s
- **= 0.109907409 USGPM**: 6.594444556 USGPH
- **avg L/V**: 0.5
- **avg Q_L/Q_D**: 1
- **avg F/D**: 5
- **avg Q_F/Q_D**: 2.686534604
- **avg F/B**: 1.25
- **avg Q_F/Q_B**: 1.580058396
- **avg D/B**: 0.25
- **avg Q_D/Q_B**: 0.588139975
### Lab Session Constraints: Continuous Operation Max Total Volumes

<table>
<thead>
<tr>
<th>Lab Session Constraints: Continuous Operation Max Total Volumes</th>
<th>Vol_max_F</th>
<th>Vol_max_B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>41.67842995 USGal</td>
<td>26.37777822 USGal</td>
</tr>
</tbody>
</table>

### Lab Session Constraints: Continuous Operation Max Trial Volumes per Trial at Steady State

<table>
<thead>
<tr>
<th>Lab Session Constraints: Continuous Operation Max Trial Volumes per Trial at Steady State</th>
<th>Vol_trial_F</th>
<th>Vol_trial_D</th>
<th>Vol_trial_B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6.078104368 USGal</td>
<td>2.487126339 USGal</td>
<td>3.580977212 USGal</td>
</tr>
</tbody>
</table>

### Lab Session Constraints: Continuous Operation Min Trial Volumes per Trial at Steady State

<table>
<thead>
<tr>
<th>Lab Session Constraints: Continuous Operation Min Trial Volumes per Trial at Steady State</th>
<th>Vol_trial_F</th>
<th>Vol_trial_D</th>
<th>Vol_trial_B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3.473202496 USGal</td>
<td>1.29281882 USGal</td>
<td>2.198148185 USGal</td>
</tr>
</tbody>
</table>

### Column Volumetric Physical Values (Desired Dimensions)

<table>
<thead>
<tr>
<th>Column Volumetric Physical Values (Desired Dimensions)</th>
<th>V_col</th>
<th>SA_col_dry</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.009120735 m^3</td>
<td>3.009842426 m^2</td>
</tr>
</tbody>
</table>

### Relative Volatilities and Corresponding Geometric Means

<table>
<thead>
<tr>
<th>Relative Volatilities and Corresponding Geometric Means</th>
<th>alpha_D</th>
<th>alpha_avg</th>
<th>alpha_F</th>
<th>alpha_avg_D</th>
<th>alpha_B</th>
<th>alpha_avg_B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.160258913</td>
<td>3.219020465</td>
<td>4.756859682</td>
<td>2.349295393</td>
<td>8.93084521</td>
<td>6.517881366</td>
</tr>
</tbody>
</table>

### Number of Equivalent Theoretical Plates and Corresponding Min. Values

<table>
<thead>
<tr>
<th>Number of Equivalent Theoretical Plates and Corresponding Min. Values</th>
<th>N_min</th>
<th>N_min_D</th>
<th>N_min_B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.226277175</td>
<td>2.097795407</td>
<td>0.432600083</td>
</tr>
</tbody>
</table>

### Avg. Efficiencies at the Calculated and Desired Column Heights (Fenske Eqn.)

<table>
<thead>
<tr>
<th>Avg. Efficiencies at the Calculated and Desired Column Heights (Fenske Eqn.)</th>
<th>e_a</th>
<th>E_a</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.799920435</td>
<td>0.230779955</td>
</tr>
</tbody>
</table>

### Ratio of Respective Efficiencies (a possible measure of column effectiveness)

<table>
<thead>
<tr>
<th>Ratio of Respective Efficiencies (a possible measure of column effectiveness)</th>
<th>E_a/e_a</th>
<th>E_D/e_D</th>
<th>E_B/e_B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.288503637</td>
<td>0.288503637</td>
<td>1</td>
</tr>
</tbody>
</table>
Reboiler Volume/Insulation Sizing and Associated Power Loss, Assuming Min. Reboiler Cross-Area

### Manual Inputs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{\text{wall}_{\text{RB}}}$</td>
<td>16.5 W/m*K</td>
<td>$K_{\text{ins}_{\text{RB}}}$</td>
<td>0.021 W/m*K</td>
</tr>
<tr>
<td>$h_{\text{i}_{\text{RB}}}$</td>
<td>1000 W/m^2*K</td>
<td>$h_{\text{o}_{\text{RB}}}$</td>
<td>10 W/m^2*K</td>
</tr>
<tr>
<td>$T_{\text{i}_{\text{RB}}}$</td>
<td>100 C</td>
<td>$T_{\text{o}_{\text{RB}}}$</td>
<td>25 C</td>
</tr>
<tr>
<td>$t_{\text{wall}_{\text{RB}}}$</td>
<td>0.005 m</td>
<td>$t_{\text{ins}_{\text{RB}}}$</td>
<td>0.0762 m</td>
</tr>
<tr>
<td>$z_{\text{RB}_{\text{max}}}$</td>
<td>0.5 m</td>
<td>$V_{\text{RB}}/V_{\text{tot}_{F}}$</td>
<td>0.5 v/v</td>
</tr>
</tbody>
</table>

### Calculated Inputs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r_{\text{i}<em>{\text{RB}</em>{\text{min}}}}$</td>
<td>0.104222066 m</td>
</tr>
<tr>
<td>$V_{\text{RB}_{\text{liq}}}$</td>
<td>0.080230978 m^3</td>
</tr>
<tr>
<td>$r_{\text{ins}_{\text{RB}}}$</td>
<td>0.109222066 m</td>
</tr>
<tr>
<td>$r_{\text{o}_{\text{RB}}}$</td>
<td>0.185422066 m</td>
</tr>
</tbody>
</table>

### Calculated Outputs (Assuming Minimized $SA_{\text{RB}}$)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{\text{RB}_{\text{tot}}}$</td>
<td>0.017062365 m^3 = 4.431783135 USGAL</td>
<td>$SA_{\text{i}_{\text{RB}}}$</td>
<td>0.391112369 m^2</td>
</tr>
<tr>
<td>$Q_{\text{i}_{\text{RB}}}$</td>
<td>10.42943256 W</td>
<td>$Q_{\text{i}<em>{\text{RB}}}/Q</em>{\text{RB}}$</td>
<td>0.164605615 %W/W</td>
</tr>
</tbody>
</table>

Column Insulation Sizing and Associated Power Loss

### Manual Inputs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{\text{wall}_{\text{col}}}$</td>
<td>1.05 W/m*K</td>
<td>$K_{\text{ins}_{\text{col}}}$</td>
<td>0.021 W/m*K</td>
</tr>
<tr>
<td>$h_{\text{i}_{\text{col}}}$</td>
<td>1000 W/m^2*K</td>
<td>$h_{\text{o}_{\text{col}}}$</td>
<td>10 W/m^2*K</td>
</tr>
<tr>
<td>$T_{\text{i}_{\text{col}}}$</td>
<td>100 C</td>
<td>$T_{\text{o}_{\text{col}}}$</td>
<td>25 C</td>
</tr>
<tr>
<td>$t_{\text{wall}_{\text{col}}}$</td>
<td>0.00635 m</td>
<td>$t_{\text{ins}_{\text{col}}}$</td>
<td>0.0508 m</td>
</tr>
</tbody>
</table>

### Calculated Inputs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r_{\text{i}_{\text{col}}}$</td>
<td>0.0381 m</td>
</tr>
<tr>
<td>$r_{\text{ins}_{\text{col}}}$</td>
<td>0.04445 m</td>
</tr>
<tr>
<td>$r_{\text{o}_{\text{col}}}$</td>
<td>0.09525 m</td>
</tr>
</tbody>
</table>

### Calculated Outputs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_{\text{i}_{\text{col}}}$</td>
<td>25.12248517 W</td>
<td>$Q_{\text{i}<em>{\text{col}}}/Q</em>{\text{RB}}$</td>
<td>0.39650308 %W/W</td>
</tr>
</tbody>
</table>

Pipeline Insulation Sizing and Associated Power Losses

### Manual Inputs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{\text{wall}_{\text{pipe}}}$</td>
<td>16.5 W/m*K</td>
<td>$K_{\text{ins}_{\text{pipe}}}$</td>
<td>0.04 W/m*K</td>
</tr>
<tr>
<td>$h_{\text{i}_{\text{pipe}}}$</td>
<td>1000 W/m^2*K</td>
<td>$h_{\text{o}_{\text{pipe}}}$</td>
<td>10 W/m^2*K</td>
</tr>
<tr>
<td>$T_{\text{i}_{\text{pipe}}}$</td>
<td>100 C</td>
<td>$T_{\text{o}_{\text{pipe}}}$</td>
<td>25 C</td>
</tr>
<tr>
<td>$t_{\text{wall}_{\text{pipe}}}$</td>
<td>0.00635 m</td>
<td>$t_{\text{ins}_{\text{pipe}}}$</td>
<td>0.0254 m</td>
</tr>
<tr>
<td>$D_{\text{pipe}}$</td>
<td>0.75 in</td>
<td>$L_{\text{pipe}}$</td>
<td>3.6576 m = 12 ft</td>
</tr>
</tbody>
</table>

### Calculated Inputs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r_{\text{i}_{\text{pipe}}}$</td>
<td>0.009525 m</td>
</tr>
<tr>
<td>$r_{\text{ins}_{\text{pipe}}}$</td>
<td>0.015875 m</td>
</tr>
<tr>
<td>$r_{\text{o}_{\text{pipe}}}$</td>
<td>0.041275 m</td>
</tr>
</tbody>
</table>

### Calculated Outputs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_{\text{i}_{\text{pipe}}}$</td>
<td>65.1731983 W</td>
<td>$Q_{\text{i}<em>{\text{pipe}}}/Q</em>{\text{RB}}$</td>
<td>1.028615348 %W/W</td>
</tr>
<tr>
<td>$Q_{\text{i}<em>{\text{p}}}/L</em>{\text{p}}$</td>
<td>17.81856909 W/m</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>--------------------------</td>
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<td></td>
</tr>
<tr>
<td>Total Required Reboiler Power Required (Including all Accounted Losses)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q_tot</td>
<td>6.436737739 KW</td>
<td>Q_RB/Q_tot</td>
<td></td>
</tr>
<tr>
<td>m_s</td>
<td>0.003067597 Kg/s</td>
<td>98.43515271 %W/W</td>
<td></td>
</tr>
<tr>
<td>Re_c</td>
<td>1603.218193</td>
<td>Reality Check: Re_c &lt;= 2100? TRUE</td>
<td></td>
</tr>
</tbody>
</table>

Total Required Reboiler Power Required (Including all Accounted Losses)
Q_tot 6.436737739 KW Q_RB/Q_tot 98.43515271 %W/W
m_s 0.003067597 Kg/s = 24.35499837 lb/hr
Re_c 1603.218193 Reality Check: Re_c <= 2100? TRUE
Appendix B: Diagram of Core System
Appendix C: Reboiler Design Schematic