An Analysis Of A Dump Heat Exchanger For The Versatile Test Reactor's Secondary Loop

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Abstract

The VTR is a new research reactor that uses a Dump Heat Exchanger (DHX) to transfer heat from sodium to the surrounding air. A DHX is used in place of a power cycle for a testing reactor to displace the heat from the secondary loop. An analysis of the existing heat exchanger, a cross-flow design, was completed. Possible heat exchanger options, a shell-and-tube and an annulus heat exchanger, were investigated. Using Aspen HYSYS several iterations of analysis were completed. Sodium data from Argonne National Laboratory (ANL) was inputted into HYSYS to be used with all the models. It was found that having a slower flow rate for air passing through the heat exchanger was instrumental to improving the initial cross-flow design. Upon comparing the other design types with the initial cross-flow design based on footprint, volume of material, and weight, the shell and tube heat exchangers were the best option followed by the annulus heat exchangers and finally the original cross-flow design. Out of two possible shell and tube heat exchanger designs investigated the one that contained 100 tubes was the better option.

ACKNOWLEDGEMENTS

The completion of this work would not have been possible without Dr. McKellar, my advisor. He has been super helpful and pushed me the entire way.

DEDICATION

This thesis is dedicated to my wife Monica who has supported me through my education.

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LIST OF ACRONYMS

ATR	Advanced Test Reactor
ANL	Argonne National Laboratory
DHX	Dump Heat Exchanger
EM2	Energy Multiplier Module
FFTF	Fast Flux Testing Facility
INL	Idaho National Laboratory
JHR	Jules Horowitz Reactor
MBIR	Multipurpose fast-neutron research reactor
PRISM	Power Reactor Innovative Small Module
VTR	Versatile Test Reactor

Chapter 1: Introduction

1.1 Background

The United States has primarily used nuclear reactors, for energy and research that operate in the Thermal Energy range. New instrumentation, fuels, and other advancements need to be tested before they can be implemented into commercial reactors. Currently, they are tested at the Advanced Test Reactor (ATR), at the Idaho National Laboratory (INL). However, there is a lack of ability to test these new advancements in the fast neutron range. Without this ability, companies such as TerraPower, Westinghouse, and General Atomics Energy Multiplier Module (EM2) cannot test their newest ideas for the fast reactor technology. Thus, a versatile testing facility is needed. There are currently two facilities being built outside of the US, the Jules Horowitz Reactor (JHR) in France, and Multipurpose fast-neutron research reactor (MBIR) in Russia, see Figure 1.1.[1]

Figure 1.1: Render of what the MBIR could look like.

The ATR is capable of testing within the thermal range. However, it might not be able to fulfill all of the thermal testing needs in the future [1]. For example, TerraPower is developing molten salt cooled reactors, Figure 1.2, and testing components in the ATR may be difficult.

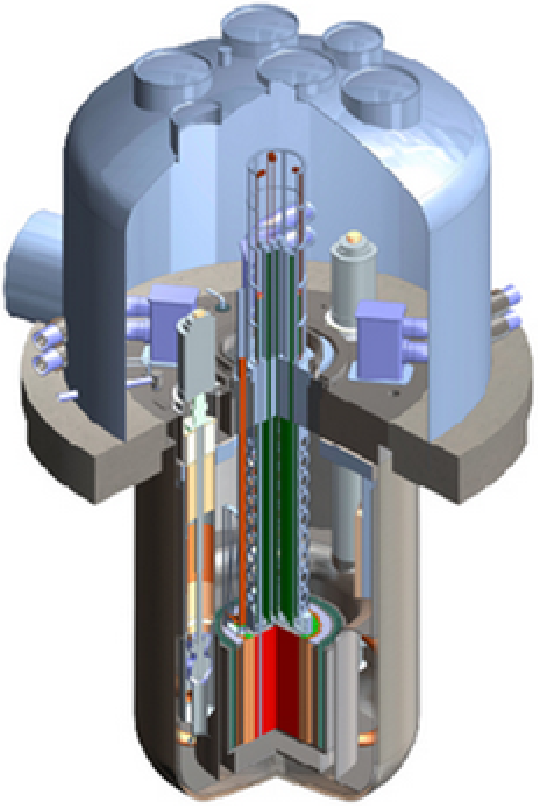


Figure 1.2: TerraPower's newest design of a sodium cooled reactor that uses depleted uranium as its fuel.

Designing a test facility to operate for several decades is costly. This test reactor will need to be highly reconfigurable to test in the Fast and Thermal neutron ranges. The INL said, "A domestic versatile neutron irradiation facility will be a critical tool to enable rapid innovation in the US: it will serve to do performance testing of new fuels and materials, and it will provide the data needed for establishing a science based accelerating testing capability that will give our industry a strong competitive advantage." [1]

1.1.1 What is the Versatile Test Reactor?

The DOE-NE established the following requirements for a Versatile Test Reactor (VTR): [1]

1. The reactor will provide a fast flux irradiation environment prototypical of potential

fast reactor designs:

   (a) The fast flux level will be equivalent to that of existing fast test reactors
      i. At least $4x10^{15} n/cm^2 * s$
   (b) The irradiation environment should be able to change, and accommodate several potential reactor coolants
   (c) The irradiation volume will be able to accommodate a volume equivalent to a fuel assembly
   (d) Several different irradiation vehicles will be allowed:
      i. Loops
      ii. Instrumented assemblies
      iii. Test samples
   (e) Experimental capabilities should enable both integral "traditional" testing, and science-based testing

2. The reactor will provide thermal and epithermal flux irradiation environments complementary of those of ATR and HFIR:
   (a) The thermal flux level will be equivalent to that of ATR
      i. At least $5x10^{14} n/cm^2 * s$
   (b) The irradiation volume will be equivalent to that of ATR
   (c) The irradiation environment should allow for irradiations that are not possible today in ATR and HFIR, inluding loops with various coolants.

3. Other possibilities, including beam tubes for scientific experiments, irradiation vehicles for isotope production, support for code validation, and support for reactor technology demonstration will need to be studied during the pre-conceptual design phase.

The VTR is at its basic rendering, a coupled reactor. A coupled reactor works within the thermal neutron energy range as well as in the fast neutron energy range. Figure 1.3 gives a diagram of a coupled reactor operating in both the thermal and fast ranges. The draft core layout of the VTR, Figure 1.4, will use the fast neutron flux in the center test

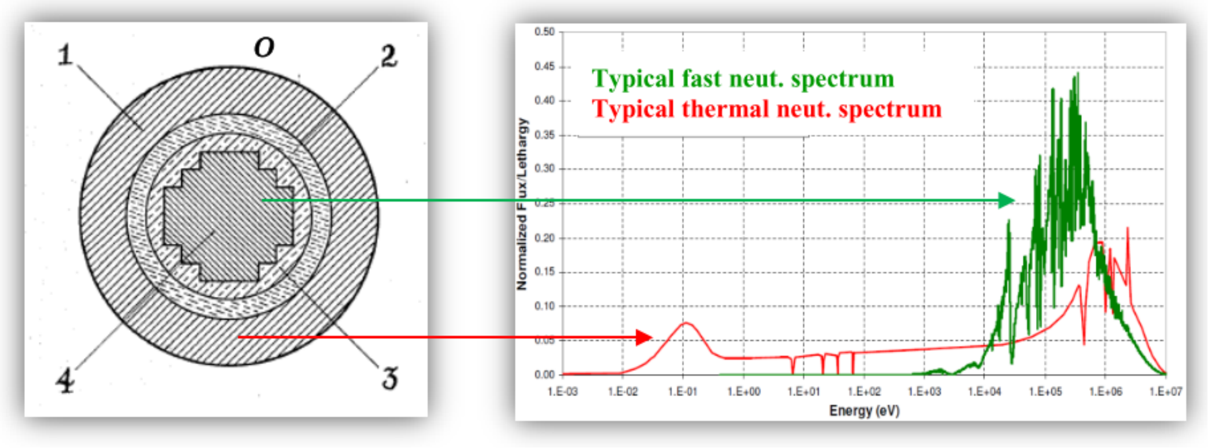


Figure 1.3: Illustration of a coupled reactor (0- outer reflector; 1- thermal annular core; 2- inner reflector; 3- thermal neutron filter; 4- fast core)

locations and the thermal flux in the outer locations. This is characterized by the neutron multiplicity of each zone and there are four parameters that help define what happens.

1. k_F: average number of next generation neutrons in fast zone resulting from a single fission neutron in fast zone
2. k_T: average number of next generation neutrons in thermal zone resulting from a single fission neutron in thermal zone
3. k_{FT}: average number of next generation fission neutrons in thermal zone resulting from a single fission neutron in fast zone
4. k_{TF}: average number of next generation fission neutrons in fast zone resulting from a single fission neutron in thermal zone

If the two zones are far enough apart, then each zone needs to be critical by itself, ie the zones are critical if $k_F = 1$ and $k_T = 1$. However, if they are neutronically coupled, then each zone individually would be subcritical, $k_F < 1$ and $k_T < 1$, and the coupled system is critical only when their coupling coefficients when multiplied together are equal to the product of their local subcriticality's $(1 - k)$.[2]

$$k_{FT}k_{TF} = (1 - k_F)(1 - k_T) \tag{1.1}$$

The power of the coupled system would then be a ratio of how each zone reacts to the changes within it.

$$\frac{P_F}{P_T} = \frac{k_{TF}}{(1 - k_F)} = \frac{(1 - k_T)}{k_{FT}} \tag{1.2}$$

Based on this relation it can be said that the further the values of k_F and k_T are from 1 and the closer the values of k_{FT} and k_{TF} are to 1 the system is more stable. This has great importance to the design process about the operation and the safety of the reactor.

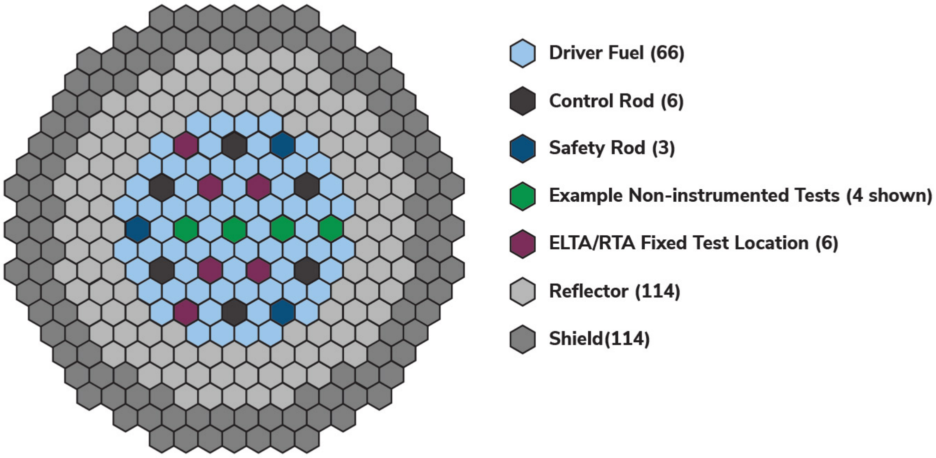


Figure 1.4: VTR draft core layout. The fast neutron region will be at the center and the thermal neutron region will be towards the outside of the driver fuel area.[3]

In 2018, the US decided to have General Electric's Power Reactor Innovative Small Module (PRISM) reactor to be used for the VTR. It is a liquid-metal reactor that is cooled by sodium. GE's initial design was developed during the 1980s.In 2006, the reactor was redesigned to recycle spent fuel and could be connect to more than one reactor. [4]

The PRISM is a liquid-metal, pool type of reactor. It is rated at 840 MWth and 311 MWe. Table 1 shows the basic thermal information about the reactor. Each PRISM transfers heat via an intermediate heat exchanger from the primary sodium loop to a secondary loop of sodium [4]. If the reactor was to be used for commercial use, the secondary loop would then transfer heat to a water/steam loop that would go through a generator and a conventional turbine to create electricity, as seen in Figure 1.5. However, the VTR is a test facility, therefore the secondary loop will pass through a set of Sodium to Air Dump Heat Exchangers. Figures 1.6 and 1.7 show the two thermal loops of the testing facility.

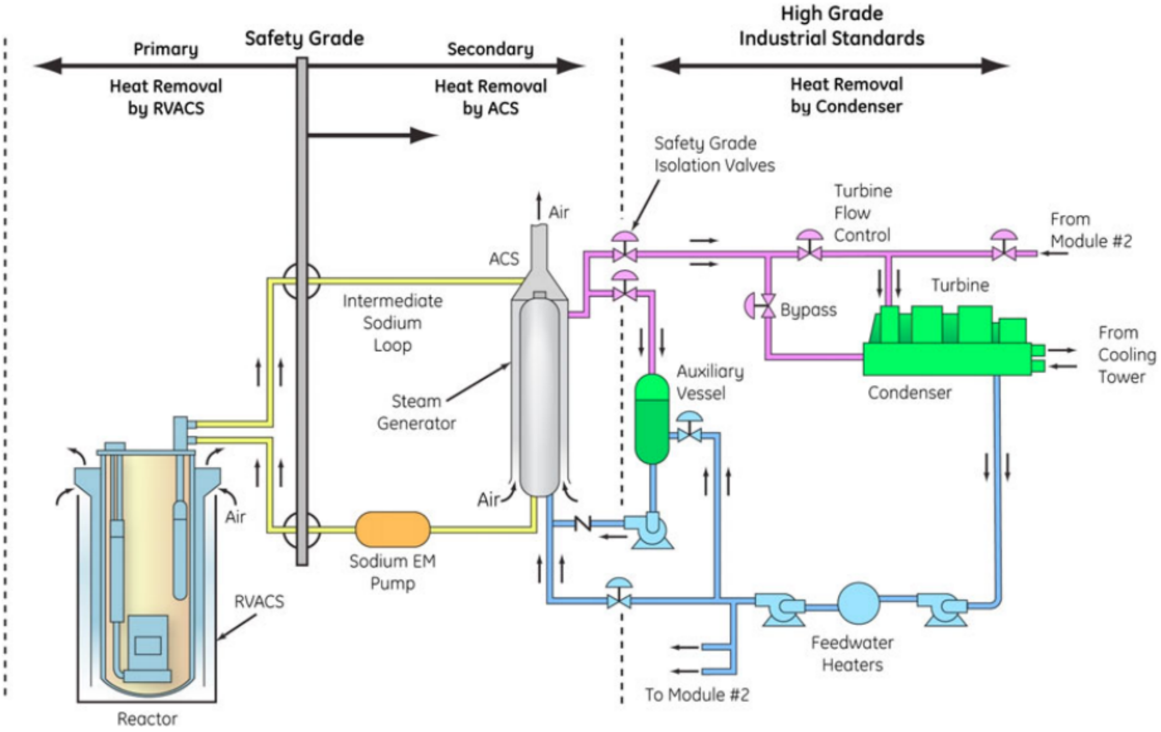


Figure 1.5: Schematic of the Thermal Loop of the PRISM reactor.[4]

Table 1.1: PRISM's specifications.[4]

Thermal Power	840 MW
Primary Sodium Inlet/Outlet Temperatures	360°C (680°F) / 499°C (930°F)
Primary Sodium Flow Rate	5.4 m^3/s (86000 gal/min)
Secondary Sodium Inlet/Outlet Temperatures	326°C (619°F) / 477°C (890°F)
Secondary Sodium Flow Rate	5.1 m^3/s (80180 gal/min)

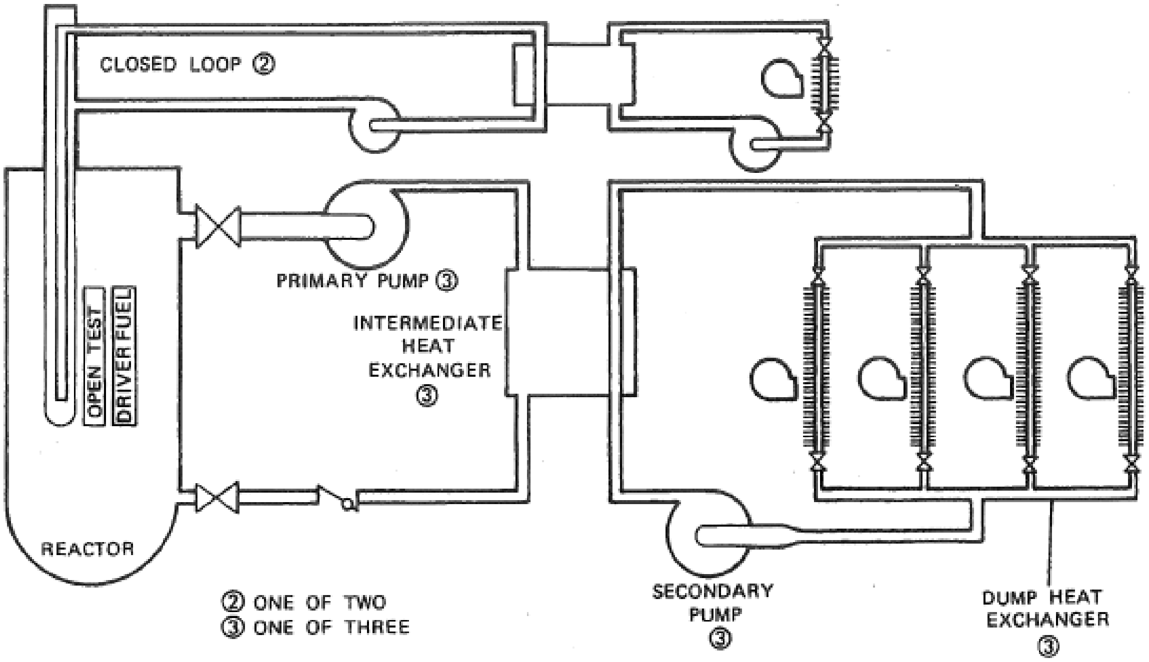


Figure 1.6: Schematic of Heat Removal Facilities. [5]

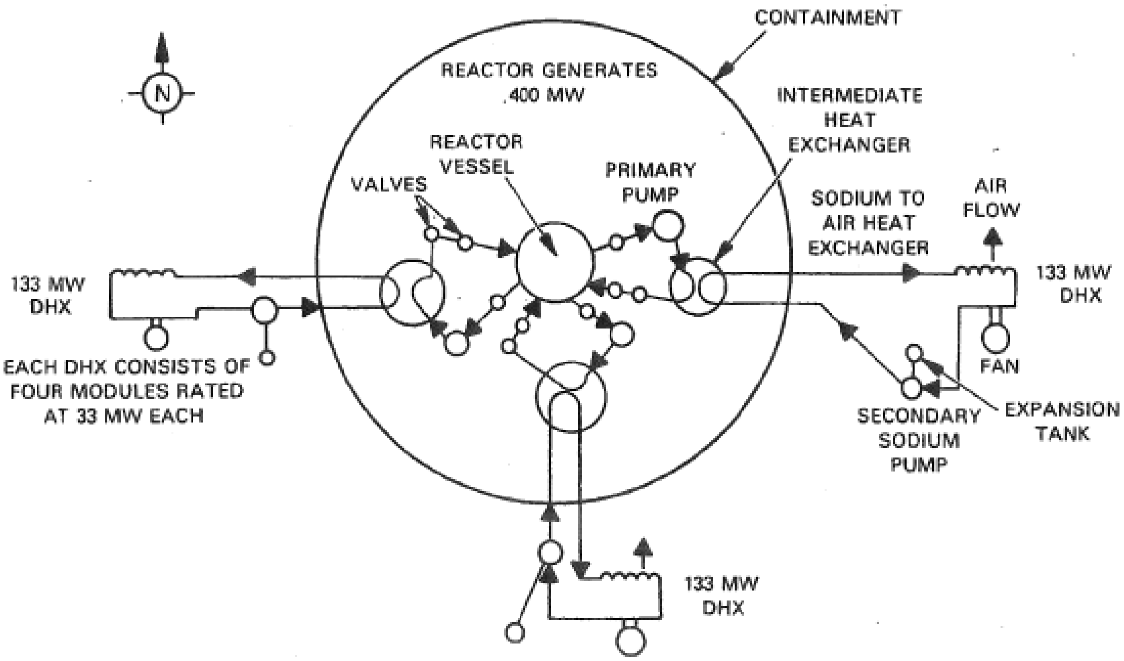


Figure 1.7: Plan View of Heat Transport System. [5]

CHAPTER 2: THEORY

2.1 HEAT EXCHANGERS

2.1.1 TYPES

There are three types of flow arrangements that heat exchangers utilize: parallel flow, Figure 2.1, counterflow, Figure 2.2, and cross-flow, Figure 2.3. Parallel flow is when the flow of hot and cold fluids flow in the same direction. Counterflow is when the hot and cold fluids flow in opposite directions. Finally, the cross-flow is when the cold fluid flows perpendicular to the hot fluid.

There are different construction designs that are used. The very basic and the one that all other heat exchangers are compared to is a concentric tube, or double-pipe, design. This design allows for either parallel or counterflow. Another type is the shell-and-tube construction. This is where many tubes are surrounded by a single shell and the tubes can pass back and forth several times within the shell. This construction type only allows for counter and parallel flow arrangements. Finally, the cross-flow design. These designs are tubular heat exchangers that either have fins or no fins. The use of fins determines how the flow looks, either mixed or unmixed.

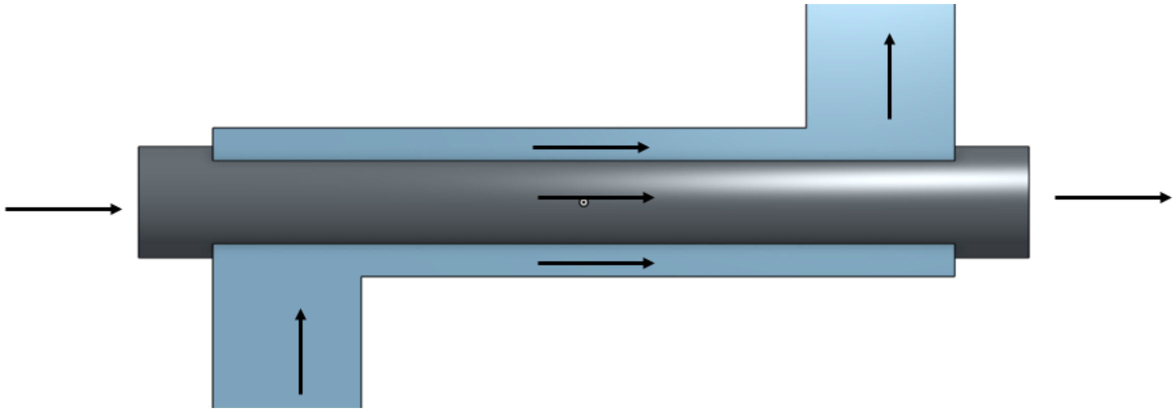


Figure 2.1: Parallel-flow concentric tube heat exchanger. Arrows denote the flow path.

2.1.2 OVERALL HEAT TRANSFER COEFFICIENT

The overall heat transfer coefficient is related to the total thermal resistance between two fluids. During normal operation, the heat exchanger surfaces experience fouling, such

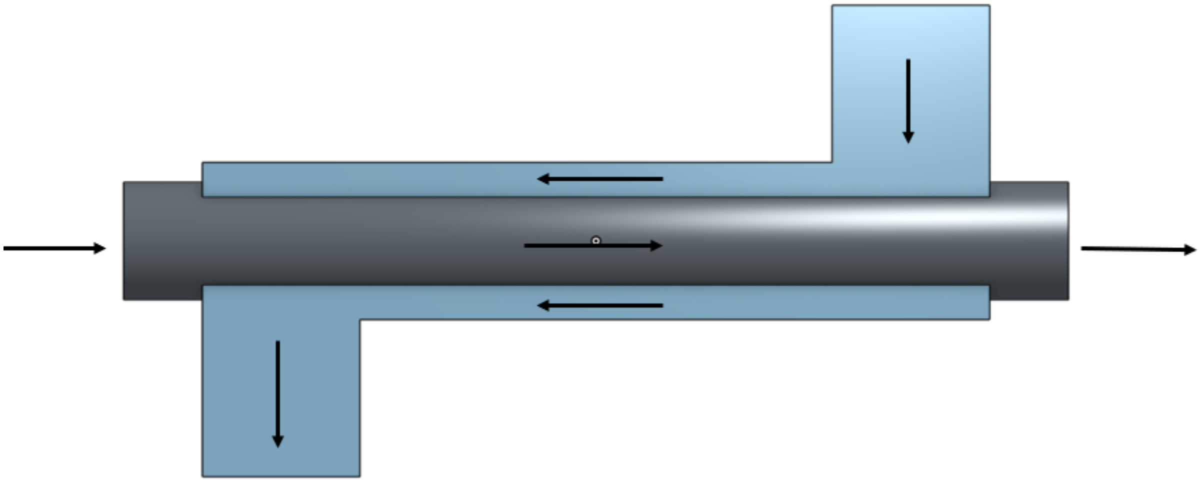


Figure 2.2: Counter-flow concentric tube heat exchanger. Arrows denote the flow path.

as fluid impurities, rust formation, or other reactions between the fluid and the wall. To account for this, the overall heat transfer coefficient includes the parameter R_f, or the fouling factor. Fouling increases the resistance. In addition, if there is more surface area exposed to the fluid, by adding fins, it will decrease the overall resistance. The overall heat transfer coefficient can be expressed in the following equation

$$\frac{1}{UA} = \frac{1}{U_c A_c} = \frac{1}{U_h A_h} = \frac{1}{(\eta_0 A)_c} + \frac{R"_{f,c}}{(\eta_0 A)_c} + R_w + \frac{R"_{f,h}}{(\eta_0 A)_h} + \frac{1}{(\eta_0 A)_h} \tag{2.1}$$

where c and h refer to the cold and hot fluids. This generalized equation also includes the overall surface efficiency, η_0. If fouling can be neglected, the heat transfer rate would look like

$$Q = \eta_0 h A (T_b - T_\infty) \tag{2.2}$$

where T_b is the base surface temperature and A is the total exposed surface area. To calculate η_0, the following equation can be used.

$$\eta_0 = 1 - \frac{A_f}{A}(1 - \eta_f) \tag{2.3}$$

where the subscript f are fin parameters. If the assumption is made that there are no fins for a tubular heat exchanger, Equation 2.1 simplifies to

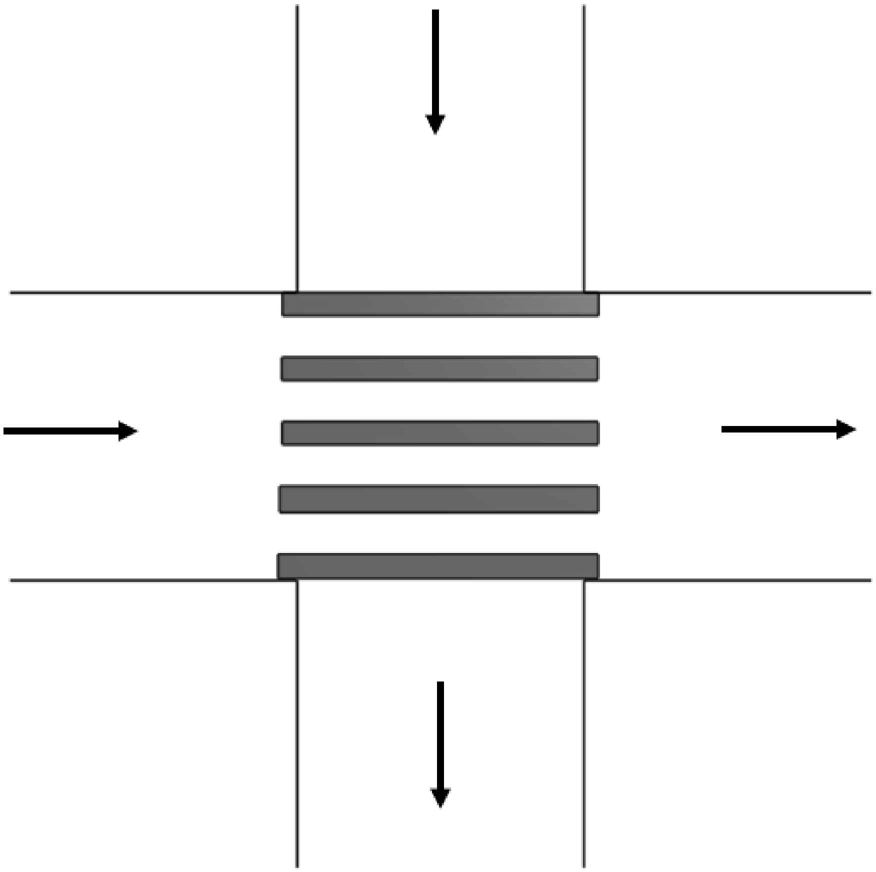


Figure 2.3: A cross section of a cross-flow heat exchanger. Arrows denote the flow path.

$$\frac{1}{UA} = \frac{1}{U_iA_i} = \frac{1}{U_oA_o} = \frac{1}{h_iA_i} + \frac{R"_{f,i}}{A_i} + \frac{ln(D_o/D_i)}{2\pi kL} + \frac{R"_{f,o}}{A_o} + \frac{1}{(h_oA_o)} \tag{2.4}$$

This simplification comes from an assumption that it is 1-Dimensional and at steady-state. Figure 2.4, shows the 1-D, Steady-State drawing for a pipe that uses the resistance method to find UA. Each resistance, R_1, R_2, and R_3, depict a different mode of heat transfer. R_1 is the heat transfer mode of convection from the fluid to the surface of the pipe and is defined as Equation 2.5. R_2 is the conduction between the walls of the pipe, see Equation 2.6, and Equation 2.7, or R_3 is the convection from the pipe surface to the outside fluid.

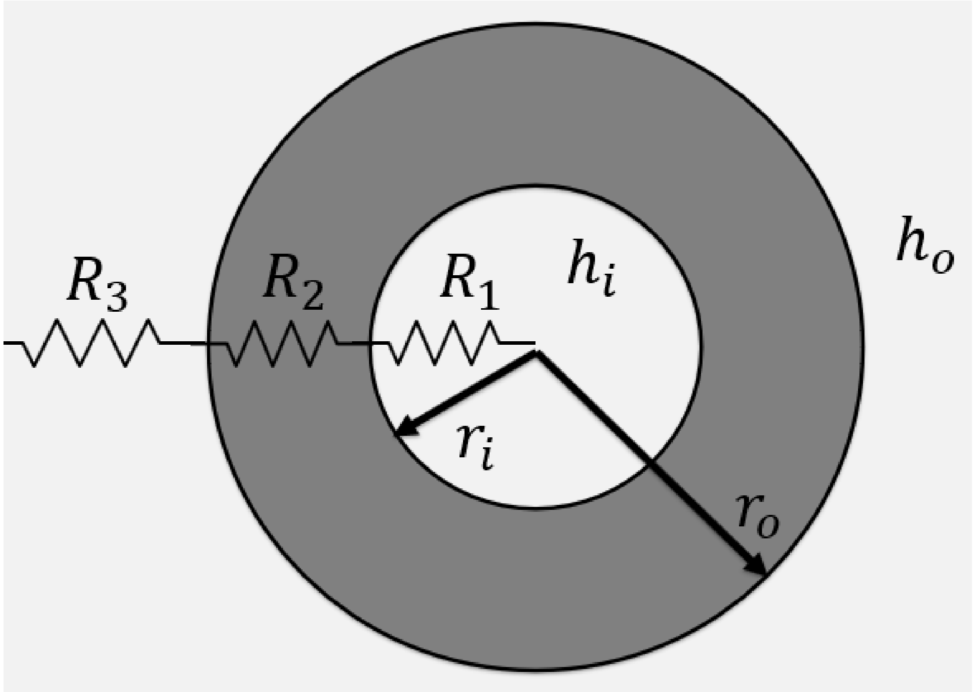


Figure 2.4: Use of the electric resistance method to find UA for a 1-D, steady-state pipe.

$$R_1 = \frac{1}{h_i A_i} \tag{2.5}$$

$$R_2 = \frac{ln(r_0/r_i)}{2\pi kL} = \frac{ln(D_0/D_i)}{2\pi kL} \tag{2.6}$$

$$R_3 = \frac{1}{h_o A_o} \tag{2.7}$$

Using the resistance method, the UA is just the addition of all the resistance terms

$$\frac{1}{UA} = R_{Total} = R_1 + R_2 + T_3 + \frac{R"_{f,i}}{A_i} + \frac{R"_{f,o}}{A_o} \tag{2.8}$$

Adding in the resistance equations from above, Equation 2.4 comes out. For the rest of the thesis, the assumption that no fouling takes place is made; therefore, the $R"_f$ terms drop out of the equation for UA and leaves the equation as

$$\frac{1}{UA} = \frac{1}{U_i A_i} = \frac{1}{U_o A_o} = \frac{1}{h_i A_i} + \frac{ln(D_o/D_i)}{2\pi kL} + \frac{1}{(h_o A_o)} \tag{2.9}$$

2.1.3 Effectiveness-NTU Method

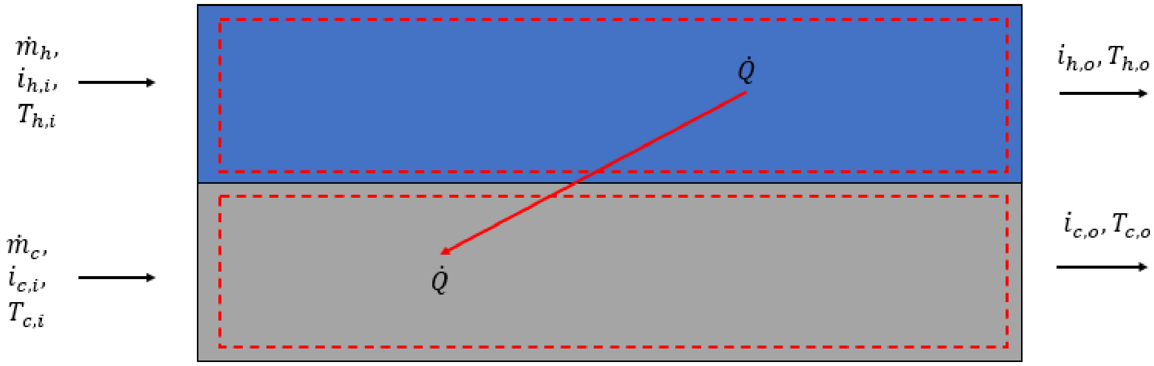


Figure 2.5: Overall energy balances for the hot and cold fluids of a two-fluid heat exchanger.

To figure out the effectiveness of a heat exchanger, it is necessary to know the maximum possible heat transfer, $\dot{Q}_{max}$. To find out what $\dot{Q}_{max}$ is, we must first define what the heat transfer equation is, $\dot{Q}$. This can be found by using the following equations and Figure 2.5.

$$\dot{Q} = \dot{m}_h(i_i - i_o)_h \tag{2.10}$$

and

$$\dot{Q} = \dot{m}_c(i_o - i_i)_c \tag{2.11}$$

where i is the fluid enthalpy and h and c refer to hot and cold fluids. The subscripts "i" and "o" refer to inlet and outlet conditions. With the assumption that the specific heats are constant, the equations become

$$\dot{Q} = \dot{m}_h c_{p,h}(T_i - T_o)_h \tag{2.12}$$

and

$$\dot{Q} = \dot{m}_c c_{p,c}(T_o - T_i)_c \tag{2.13}$$

these equations can be further simplified if the mass flow rate and the specific heat are combined to form heat capacity rates

$$Q = C_h(T_i - T_o)_h \tag{2.14}$$

and

$$Q = C_c(T_o - T_i)_c \tag{2.15}$$

Now that we have defined the equations for Q, we can now look at what Q_{max} is. From the equations above, there is a temperature difference. For Q_{max} the temperature difference is the maximum difference, and it so happens that the max happens between the two inlets, or $T_{h,i} - T_{c,i}$. With the use of two fluids, there could be two different combinations to make the max heat transfer.

$$Q_{max} = C_c(T_{h,i} - T_{c,i}) \tag{2.16}$$

This equation is used when $C_c < C_h$. However, when the hot fluid's heat capacity is less than the cold fluid, $C_c > C_h$, we can use

$$Q_{max} = C_h(T_{h,i} - T_{c,i}) \tag{2.17}$$

So, it can be said that

$$Q_{max} = C_{min}(T_{h,i} - T_{c,i}) \tag{2.18}$$

where C_{min} is equal to which ever heat capacity is smaller. The smallest heat capacity, C_{min}, is used primarily because the fluid that has the smallest C values will have the maximum heat transfer. The maximum heat transfer occurs when the minimum capacity fluid has the maximum temperature difference. If the maximum capacity fluid were used it would calculate a duty that the minimum side could never achieve. Seeing as a fluid will not experience the max heat transfer, it is necessary to define how effective the heat transfer was. This can be done by dividing the heat transfer done by the max that could be done.

$$\epsilon \equiv \frac{Q}{Q_{max}} \tag{2.19}$$

If we then expand the equations for both Q and Q_{max}, we get

$$\epsilon = \frac{C_c(T_o - T_i)_c}{C_{min}(T_{h,i} - T_{c,i})} \tag{2.20}$$

or

$$\epsilon = \frac{C_h(T_i - T_o)_h}{C_{min}(T_{h,i} - T_{c,i})} \tag{2.21}$$

Based on the definition of effectiveness above, the effectiveness, ϵ, is between the values of 0 to 1. It can also be said that the heat transfer can be found using effectiveness and the maximum heat transfer.

From Kays and London's Compact Heat Exchanger book [6], they use a definition for effectiveness that follows

$$\epsilon = f\Big(NTU, \frac{C_{min}}{C_{max}}\Big) \tag{2.22}$$

where C_{min}/C_{max} is either C_h/C_c or C_c/C_h, depending on their respective magnitudes. NTU stands for the number of transfer units and is a dimensionless parameter that is defined as

$$NTU = \frac{UA}{C_{min}} \tag{2.23}$$

NTU signifies how much "number of units" of heat the given heat exchanger is capable of transferring from one fluid to another. The larger the NTU value, the bigger the heat exchanger.

The NTU-ϵ method is primarily used when the outlet temperatures are not known. When those temperatures are known, the method known as the Log Mean Temperature Difference (LMTD) is used. The LMTD is the mean temperature between the hot and cold fluids and is found by using the following equation for a counterflow heat exchanger design.

$$\Delta T_{lm} = \frac{\Delta T_2 - \Delta T_1}{ln(\Delta T_2/\Delta T_1)} \tag{2.24}$$

where

$$\Delta T_2 = T_{h,i} - T_{c,o} \tag{2.25}$$

$$\Delta T_1 = T_{h,o} - T_{c,i} \tag{2.26}$$

To use the LMTD method, the heat transfer equation used is

$$\dot{Q} = UA\Delta T_{lm} * F \tag{2.27}$$

where the F is a correction factor based on the design and is found in figures in most heat transfer books.

2.1.3.1 Example of Effectiveness-NTU Method

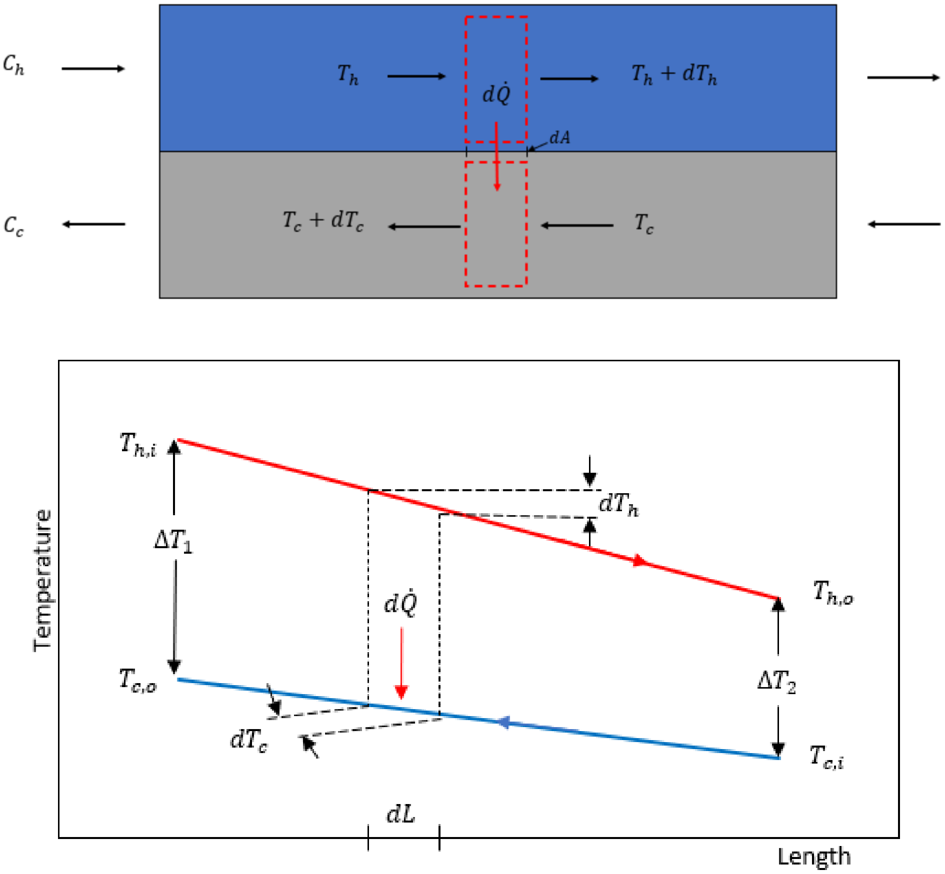


Figure 2.6: Temperature distributions for a counterflow heat exchanger

To determine a specific form of the effectiveness-NTU relation, consider a counter-flow heat exchanger for which $C_{min} = C_c$.

We start off with the following equations

$$d\dot{Q} = U \Delta T dA \tag{2.28}$$

and

$$\Delta T \equiv T_h - T_c \tag{2.29}$$

change the above equation to look at a small change versus a large change

$$d(\Delta T) = dT_h - dT_c \tag{2.30}$$

To find dT_h and dT_c we use

$$d\dot{Q} = \dot{m} c_p dT \tag{2.31}$$

Apply this equation for the hot fluid

$$d\dot{Q} = \dot{m}_h c_{p,h}(-dT_h) = C_h(-dT_h) \tag{2.32}$$

the dT_h is negative, due to the slope found in figure 2.6. Now solving for dT_h we get

$$dT_h = -\frac{d\dot{Q}}{C_h} \tag{2.33}$$

Similarly, we now look at the cold fluid

$$d\dot{Q} = \dot{m}_c c_{p,c}(-dT_c) = C_c(-dT_c) \tag{2.34}$$

$$dT_c = -\frac{d\dot{Q}}{C_c} \tag{2.35}$$

Imputing dT_h and dT_c back into the original equation we now get

$$d(\Delta T) = -\frac{d\dot{Q}}{C_h} + \frac{d\dot{Q}}{C_c} = -\frac{d\dot{Q}}{C_c}\Big[\frac{C_c}{C_h} - 1\Big] \tag{2.36}$$

We now make four assumptions.

1. $C_c = C_{min}$

2. $C_h = C_{max}$
3. $C_r = C_{min}/C_{max}$
4. $dQ = UdA\Delta T = U\Delta TPdL$
5. Assume Steady-State and 1-Dimensional

where P is the perimeter.

Adding our assumptions to the equation we get

$$d(\Delta T) = -\frac{UdA\Delta T}{C_{min}}\Big[C_r - 1\Big] \tag{2.37}$$

Collect similar terms to each side then integrate

$$\int_{\Delta T_1}^{\Delta T_2} \frac{1}{\Delta T} d(\Delta T) = -\frac{U}{C_{min}}\Big[C_r - 1\Big] * \int dA \tag{2.38}$$

$$ln\Big(\frac{\Delta T_2}{\Delta T_1}\Big) = \frac{UA}{C_{min}}\Big[1 - C_r\Big] = NTU\Big[1 - C_r\Big] \tag{2.39}$$

Now using algebra we get rid of the natural log. We also want to multiply both sides by a -1.

$$\frac{\Delta T_1}{\Delta T_2} = EXP(-NTU(1 - C_r)) \tag{2.40}$$

From Figure 2.6 we get the values for ΔT_1 and ΔT_2 by looking at the differences at the right and left of the temperature profiles.

$$\frac{T_{h,i} - T_{c,o}}{T_{h,o} - T_{c,i}} = EXP(-NTU(1 - C_r)) \tag{2.41}$$

To find the values for the outlet conditions, we go back to the equation

$$\epsilon = \frac{q}{q_{max}} = \frac{C_h(T_{h,i} - T_{h,o})}{C_{min}(T_{h,i} - T_{c,i})} = \frac{C_c(T_{c,o} - T_{c,i})}{C_{min}(T_{h,i} - T_{c,i})} \tag{2.42}$$

Working with the hot fluid first we can solve for $T_{h,o}$

$$
\begin{aligned}
\epsilon &= \frac{C_h(T_{h,i} - T_{h,o})}{C_{min}(T_{h,i} - T_{c,i})} \\
\epsilon &= \frac{C_{max}}{C_{min}} \frac{T_{h,i} - T_{h,o}}{T_{h,i} - T_{c,i}} \\
\epsilon &= \frac{1}{C_r} \frac{T_{h,i} - T_{h,o}}{T_{h,i} - T_{c,i}} \\
\epsilon C_r(T_{h,i} - T_{c,i}) &= T_{h,i} - T_{h,o} \\
T_{h,o} &= T_{h,i} - \epsilon C_r(T_{h,i} - T_{c,i})
\end{aligned}
\tag{2.43}
$$

Similarly we do this to find $T_{c,o}$

$$
\begin{aligned}
\epsilon &= \frac{C_c(T_{c,o} - T_{c,i})}{C_{min}(T_{h,i} - T_{c,i})} \\
\epsilon &= \frac{C_{min}}{C_{min}} \frac{T_{c,o} - T_{c,i}}{T_{h,i} - T_{c,i}} \\
\epsilon &= \frac{T_{c,o} - T_{c,i}}{T_{h,i} - T_{c,i}} \\
\epsilon(T_{h,i} - T_{c,i}) &= T_{c,o} - T_{c,i} \\
T_{c,o} &= T_{c,i} + \epsilon(T_{h,i} - T_{c,i})
\end{aligned}
\tag{2.44}
$$

Putting the values for the outlet conditions back into equation 2.32,

$$
\frac{T_{h,i} - (T_{c,i} + \epsilon(T_{h,i} - T_{c,i}))}{(T_{h,i} - \epsilon C_r(T_{h,i} - T_{c,i})) - T_{c,i}} = EXP(-NTU(1 - C_r)) \tag{2.45}
$$

It simplifies down to

$$
\frac{T_{h,i} - T_{c,i} - \epsilon(T_{h,i} - T_{c,i})}{T_{h,i} - T_{c,i} - \epsilon C_r(T_{h,i} - T_{c,i})} = EXP(-NTU(1 - C_r)) \tag{2.46}
$$

Pull out like terms

$$
\frac{(T_{h,i} - T_{c,i})(1 - \epsilon)}{(T_{h,i} - T_{c,i})(1 - \epsilon C_r)} = EXP(-NTU(1 - C_r)) \tag{2.47}
$$

The new equation becomes

$$\frac{1-\epsilon}{1-\epsilon C_r} = EXP(-NTU(1-C_r)) \tag{2.48}$$

Solving for ϵ

$$1-\epsilon = EXP(-NTU(1-C_r)) - \epsilon C_r EXP(-NTU(1-C_r)) \tag{2.49}$$

$$1-EXP(-NTU(1-C_r)) = \epsilon - \epsilon C_r EXP(-NTU(1-C_r)) \tag{2.50}$$

$$1-EXP(-NTU(1-C_r)) = \epsilon(1 - C_r EXP(-NTU(1-C_r))) \tag{2.51}$$

$$\epsilon = \frac{1-EXP(-NTU(1-C_r))}{1-C_r EXP(-NTU(1-C_r))} \tag{2.52}$$

Similarly, we could perform this same process for any orientation of heat exchanger. However, for simplicity, these effectiveness equations can be found in any undergraduate heat transfer book, for example in Incropera and Dewit's Introduction to Heat Transfer book, in Table 11.3 [7]. The equations of note from this table are for the shell-and-tube and cross-flow heat exchangers.

The shell-and-tube equation that has one pass and several tube passes is

$$\epsilon = 2\left[1 + C_r + (1+C_r^2)^{1/2} * \frac{1+EXP[-NTU(1+C_r^2)^{1/2}]}{1-EXP[-NTU(1+C_r^2)^{1/2}]}\right]^{-1} \tag{2.53}$$

The cross-flow heat exchanger has three different equations based upon how the fluids are behaving. For the work done with this thesis, it was assumed that one side was mixed and the other unmixed. Seeing as there were two equations that could work, a back of the envelope calculation was done to determine which equation was going to be used. It was found that the equation where C_{max} was mixed and C_{min} was unmixed was to be chosen.

$$\epsilon = \left(\frac{1}{C_r}\right)(1 - exp[-C_r(1-EXP(-NTU))]) \tag{2.54}$$

2.2 VERIFICATION OF SODIUM PROPERTIES

One of the main concerns of using any simulation software, are the properties for the fluid. Within HYSYS there is a property bank; however, sodium is not part of the that bank. So properties were put into HYSYS then verification studies were done to make sure that the properties were usable. ASPEN, the company that owns HYSYS, also owns a program called ASPEN PLUS. This program is more centered on chemical processes and does include a sodium property option. Because both programs were available, HYSYS can use the properties from ASPEN PLUS. The verification studies are a comparison between Argonne National Laboratory (ANL), data, the ASPEN PLUS, and what is called a Hypothetical property in HYSYS. A Hypothetical is a way of creating properties in HYSYS.

To create a Hypothetical, property information must be known for the following: boiling point, molecular weight, and the critical temperature and pressure. These values were found in an ANL document, [8]. Once these values are specified, HYSYS can then estimate the equations to use for property information. After the estimation is complete, a fluid package is chosen. For the hypothetical of sodium, NRTL was chosen. Once chosen, data from ANL was used to correct each property.

The properties that were chosen to enhance the accuracy of the hypothetical, were liquid density, liquid viscosity, heat capacity, thermal conductivity, liquid enthalpy, and surface tension. A temperature range from 400 kelvin to 2400 kelvin was chosen for the properties. This range was chosen because the ANL provided data for all necessary properties at these temperature. Once the data was inputted, HYSYS fit the said data by using pre-programmed equations.. Using a polynomial trendline, each of the equations were found; each of the trendlines had a correlation coefficient or R^2 value of at least 0.999.

$$\rho = -6E - 11 * T^4 + 3E - 07 * T^3 - 0.0005 * T^2 + 0.1479 * T + 922.06 \tag{2.55}$$

Equation 2.55 shows the equation for the density, where T is the temperature in kelvin.

$$\begin{aligned} C_p =& 2.3E - 26 * T^9 - 2.8E - 22 * T^8 + 1.5E - 18 * T^7 - 4.3E - 15 * T^6 \\ & + 7.7E - 12 * T^5 - 8.8E - 9 * T^4 + 6.4E - 6 * T^3 - 2.8E - 3 * T^2 \\ & + 0.6967 * T - 70.142 \end{aligned} \tag{2.56}$$

$$k = -1.2E - 8 * T^3 + 5.5E - 5 * T^2 - 0.114 * T + 124.757 \tag{2.57}$$

Equation 2.56 is the equation for the specific heat capacity, equation 2.57 is for the thermal conductivity.

$$\begin{aligned}\mu =& -1.9E-22*T^6-1.9E-18*T^5+7.4E-15*T^4\\ &-1.5E-11*T^3+1.7E-8*T^2-1.006E-5*T+0.0027\end{aligned} \tag{2.58}$$

$$s=-1.04E-6*T^2+0.00555*T+1.5096 \tag{2.59}$$

$$h=1.13E-9*T^4-5.42E-6*T^3+8.68E-3*T^2-3.8997*T-2131.2 \tag{2.60}$$

Similarly, equations 2.58, 2.59, and 2.60 are for the viscosity, mass entropy, and mass enthalpy, respectively. To show how these properties comapred to the original ANL data as well as the properties found in ASPEN PLUS, the specific heat capacity, density, viscosity, and thermal conductivity were compared. Figures 2.7, 2.8, 2.9, and 2.10 show the results of these comparisons. As seen in these figures, the hypothetical was more accurate to the ANL data than that of the ASPEN PLUS. Thus, for the rest of the modeling, the hypothetical will be used for all sodium properties.

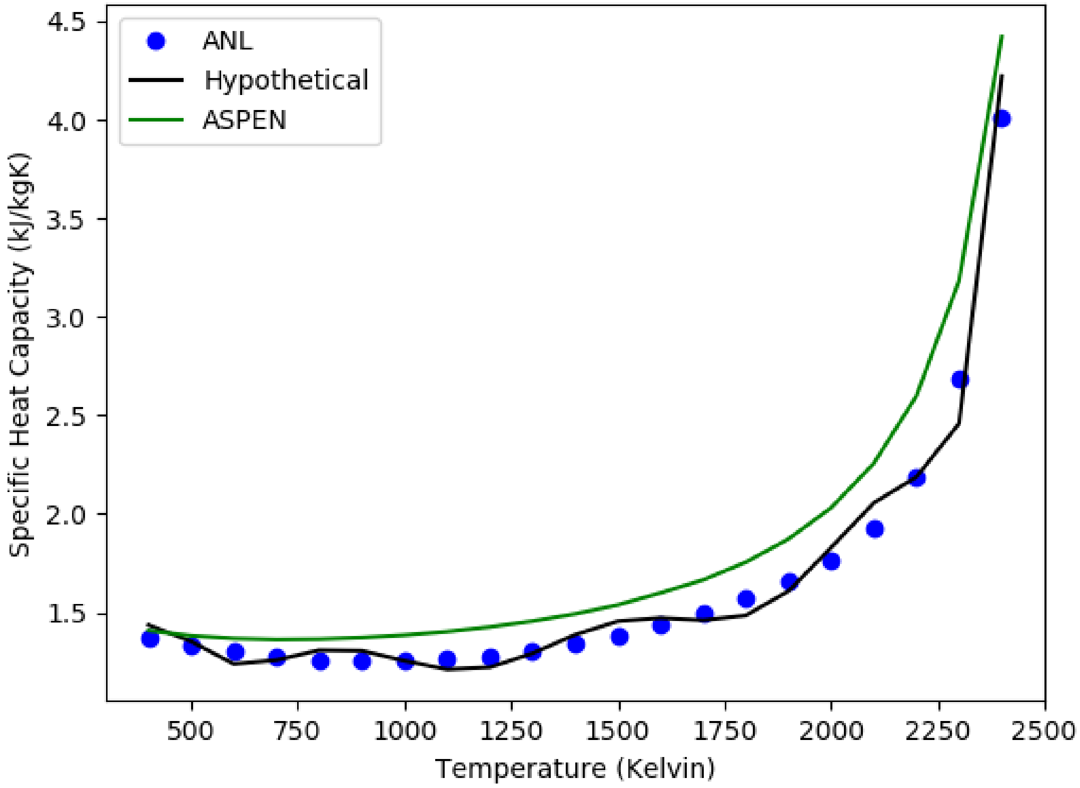


Figure 2.7: Comparison of data from ANL, ASPEN PLUS, and a Hypothetical in HYSYS for the specific heat capacity of sodium

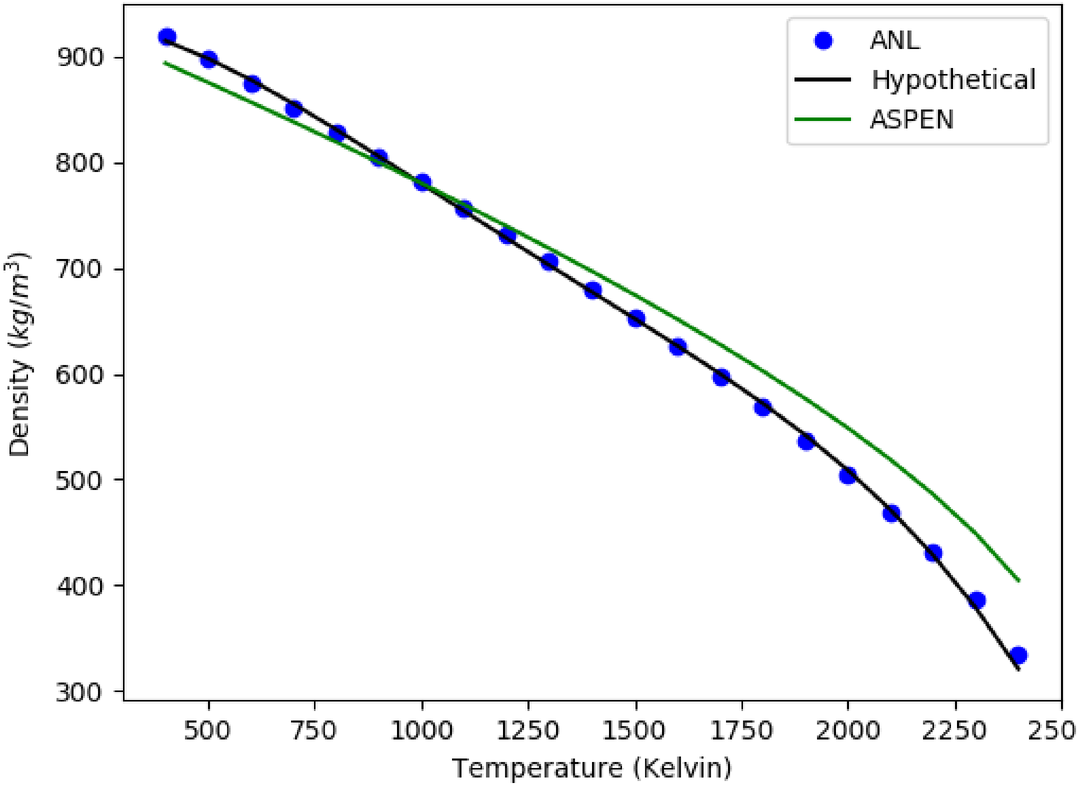


Figure 2.8: Comparison of data from ANL, ASPEN PLUS, and a Hypothetical in HYSYS for the density of sodium

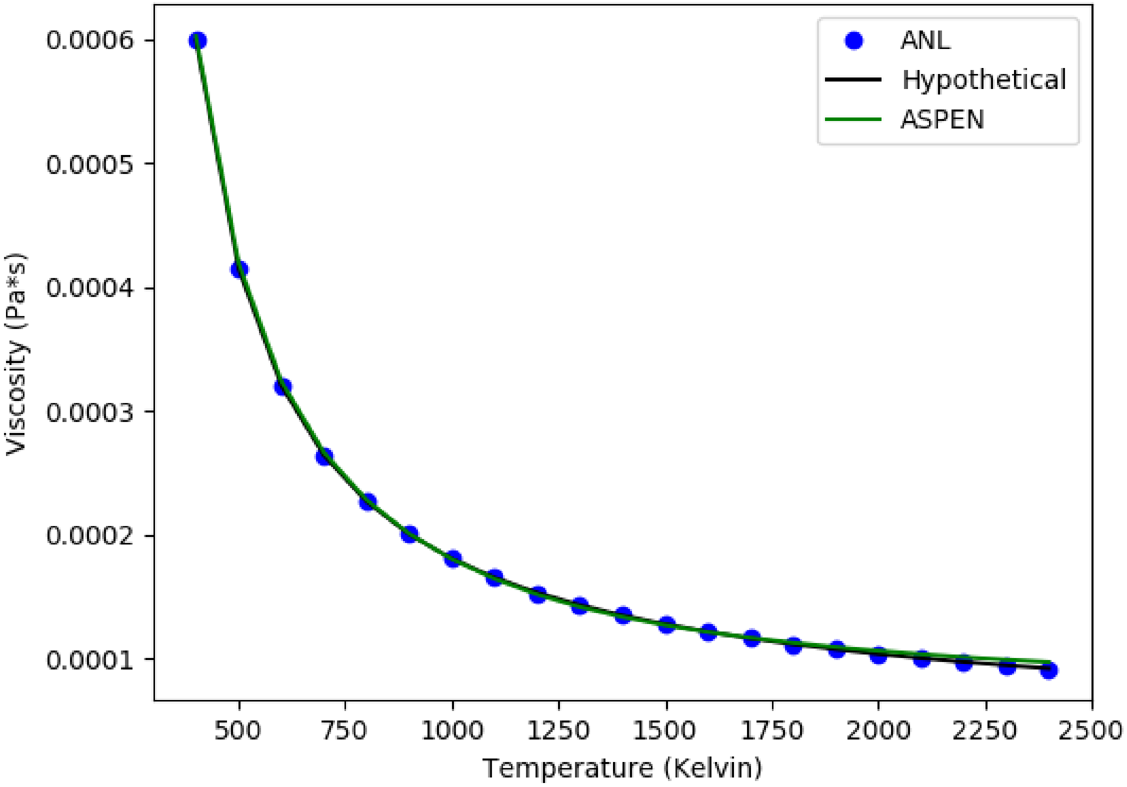


Figure 2.9: Comparison of data from ANL, ASPEN PLUS, and a Hypothetical in HYSYS for the dynamic viscosity of sodium

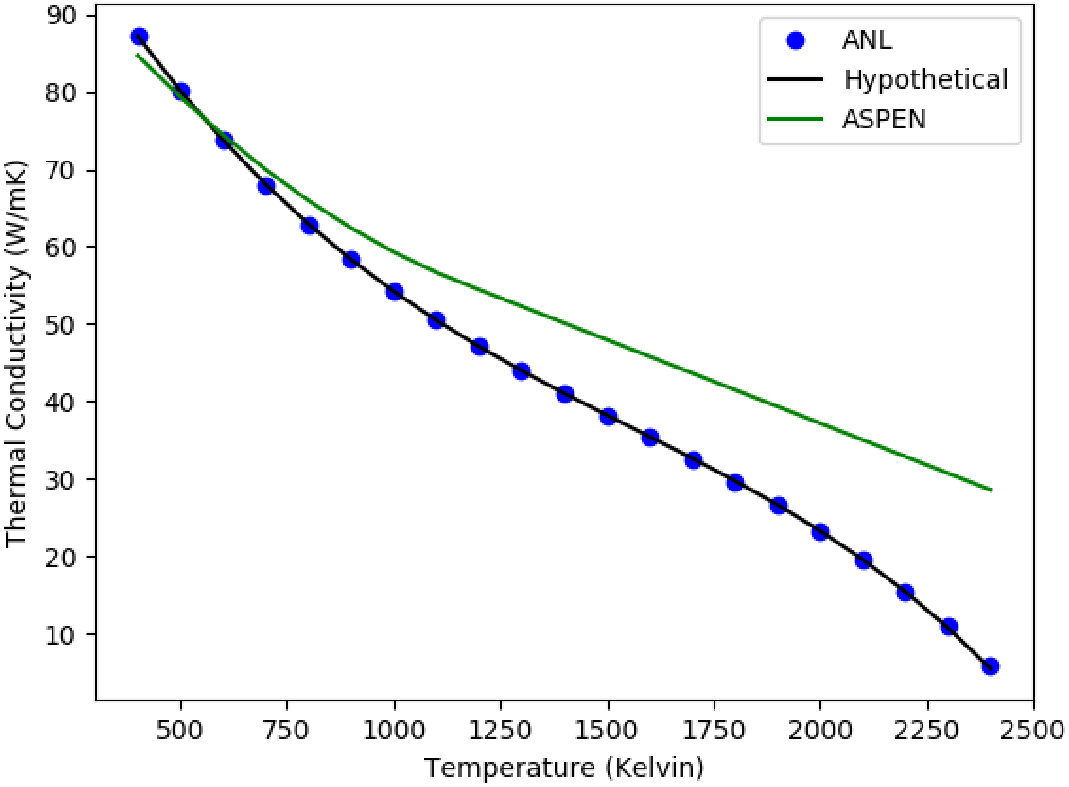


Figure 2.10: Comparison of data from ANL, ASPEN PLUS, and a Hypothetical in HYSYS for the thermal conductivity of sodium

Chapter 3: Fast Flux Testing Facility's Heat Exchanger Analysis

3.1 Introduction

The focus of this document will be to analyze the dump heat exchanger found on Figure 1.7. This heat exchanger type is a cross-flow heat exchanger that will have the sodium going through the tubes and air being forced over them with a fan. This dump heat exchanger has been previously designed to look like Figure 3.1. This heat exchanger is very similar to the heat exchanger on Monju in Japan, Figure 3.2.

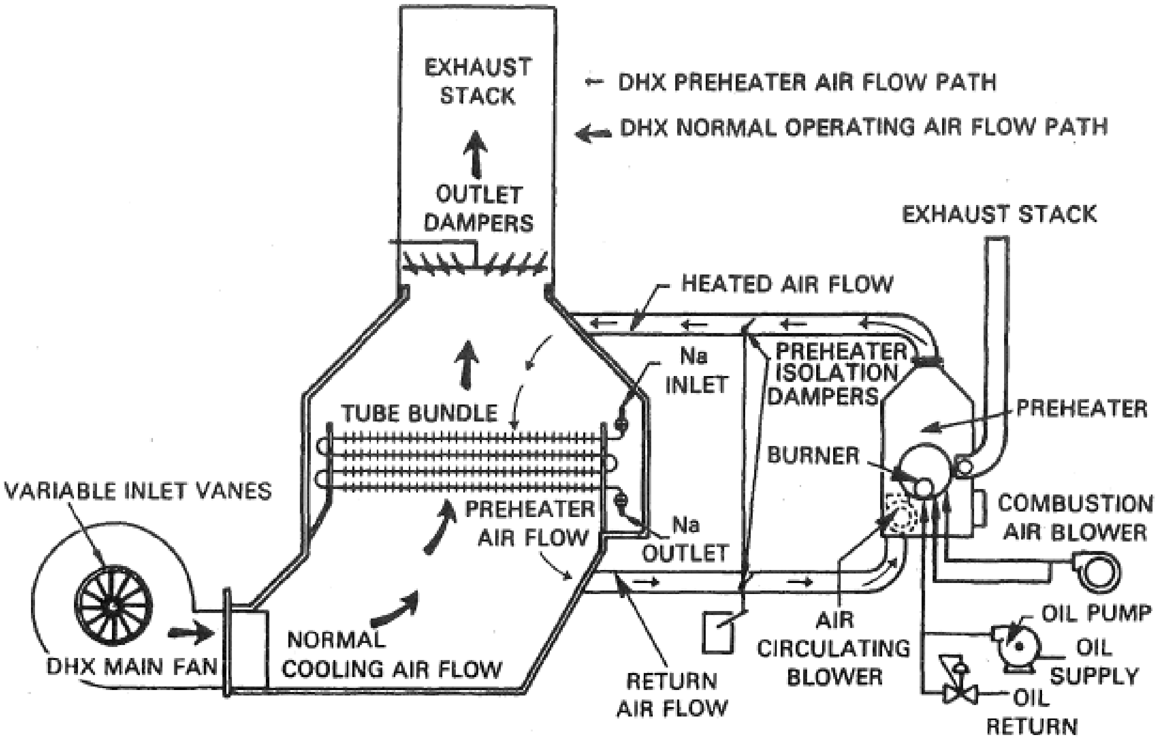


Figure 3.1: Dump Heat Exchanger for the FastFlux Testing Facitlity.[5]

The heat exchanger is used to cool the hot coolant, sodium, with a forced flow of air. The sodium will enter the heat exchanger via a tube with four-passes that are 30 ft long each and are connected by 180-degree returns and contains fins around the tube [5]. Figure 3.1 shows how this exchanger was designed. There are 66 of these tubes that are in the tube bank. The size of the fins nor the arrangement of the heat exchanger was

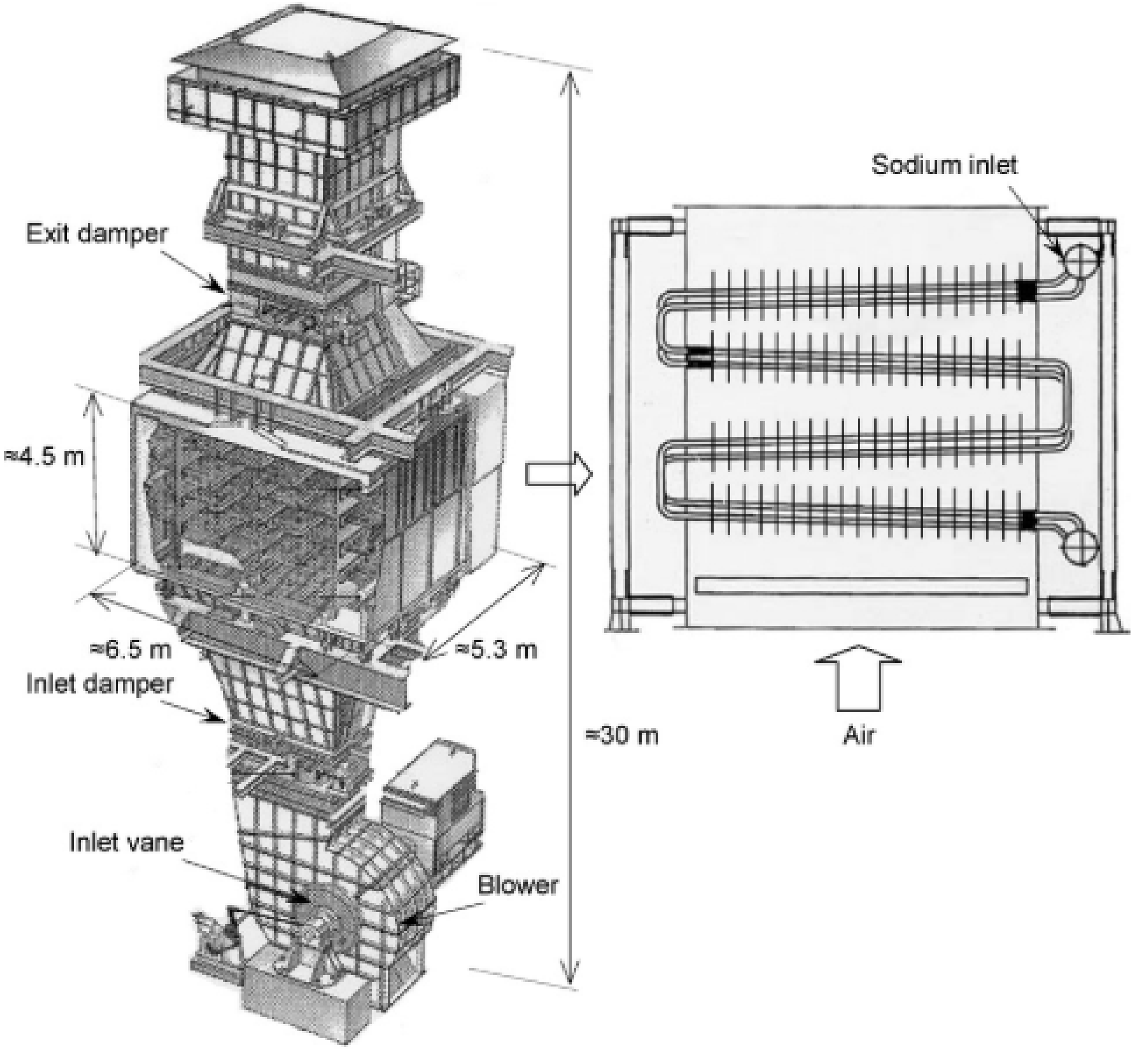


Figure 3.2: Schematic of the Dump Heat Exchanger on Monju. [9]

given, the tubes were simplified to have no fins as shown in Figure 3.3. Within the same report that the design of the tubes was found, there were initial conditions of the heat exchanger. These values are found in Table 3.1.

3.2 Methods and Materials

To view the design to its full extent, the primary and secondary loop of this test reactor set-up was modeled in ASPEN HYSYS, as shown in Figure 3.4. HYSYS has parameters that need to be modified to make sure that everything is modeled correctly. First, HYSYS does not contain the thermal and fluid properties of sodium. Thus, one had to be made. ANL published a document of the properties of sodium [8]. Next, using the ANL sodium

Table 3.1: Initial Conditions of the Dump Heat Exchanger found on the FFTF.[5]

Duty	33 MW
Air Inlet Temp	90°F
Air Mass Flow	$2.25x10^6$ lb/hr
Air Fan Motor	1250 hp
Δ P Air	11 in of H20
Sodium Inlet Temp	1000°F
Sodium Volume Flow	3625 USGal/min

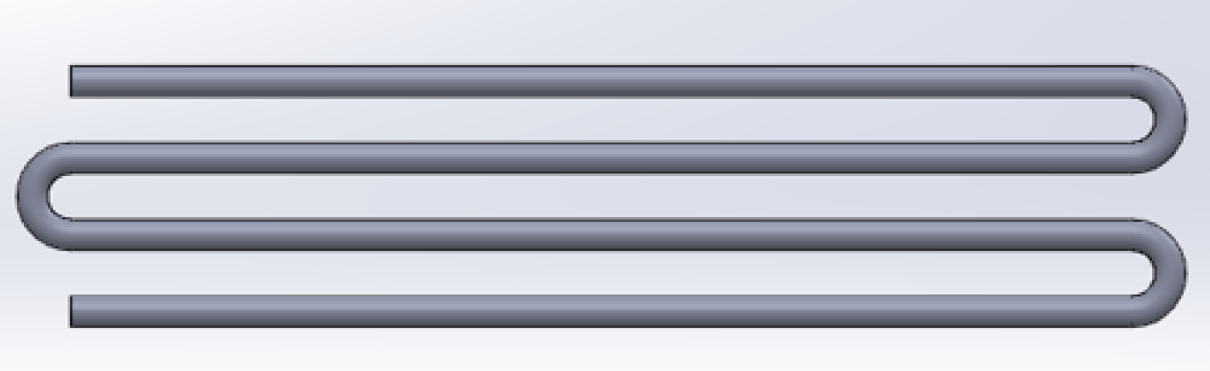


Figure 3.3: Simplified version of a single tube within the tube bank.

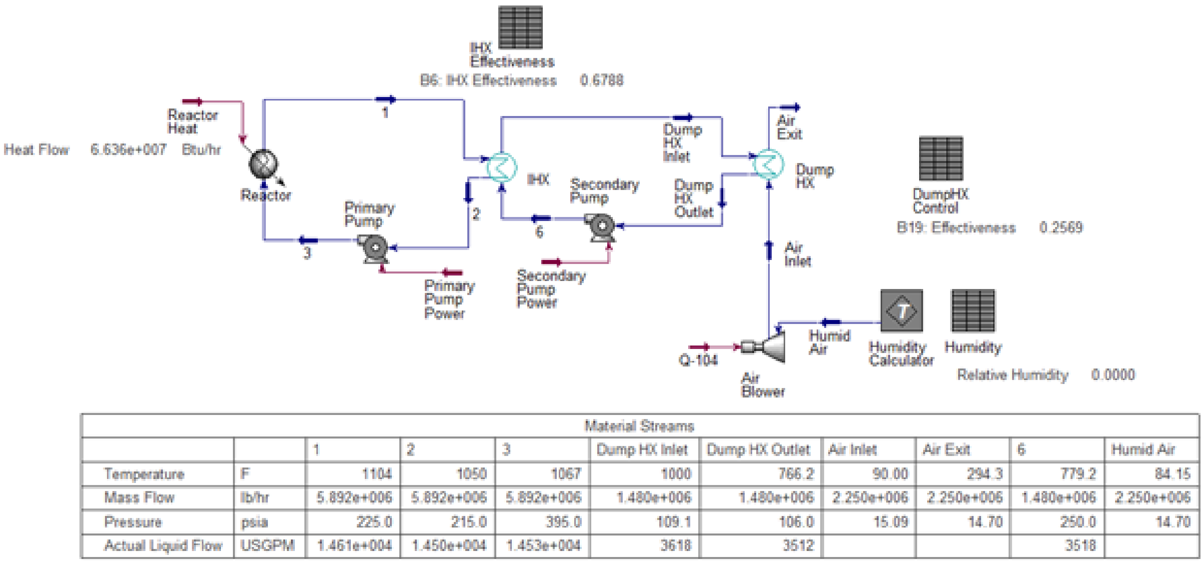
properties within HYSYS, the pressure drop across a single tube was calculated using HYSYS' pipe module, see Figure 3.5. The given the geometric parameters, material of the pipe, and the heat transfer conditions, the module can estimate the pressure drop.

The default heat exchanger within HYSYS is a counter flow heat exchanger and therefore parameters such UA, NTU, and mean temperature difference are evaluated. The DHX is a cross-flow heat exchanger. To obtain the correct values for UA, NTU and ΔT, equation 3.1 found in Incropera and DeWitt's heat transfer book was used [7]. This is equation 2.45 rearranged to solve for NTU.

$$NTU = -ln(1 + \Big(\frac{1}{C_r}\Big)ln(1 - \epsilon C_r) \tag{3.1}$$

The comparison of what HYSYS calculated with the heat exchanger module and what the true values should be are in Table 3.2.

To try and match the UA value that HYSYS calculated, a design approach was used in an embedded spreadsheet. An embedded spreadsheet is like an Excel spreadsheet but has the ability to use the thermal and fluid properties in HYSYS. First thing that had to



Material Streams										
		1	2	3	Dump HX Inlet	Dump HX Outlet	Air Inlet	Air Exit	6	Humid Air
Temperature	F	1104	1050	1067	1000	766.2	90.00	294.3	779.2	84.15
Mass Flow	lb/hr	5.892e+006	5.892e+006	5.892e+006	1.480e+006	1.480e+006	2.250e+006	2.250e+006	1.480e+006	2.250e+006
Pressure	psia	225.0	215.0	395.0	109.1	106.0	15.09	14.70	250.0	14.70
Actual Liquid Flow	USGPM	1.461e+004	1.450e+004	1.453e+004	3618	3512			3518	

Figure 3.4: Primary and Secondary loop of reactor with a single IHX and a single DHX. Model created in HYSYS.

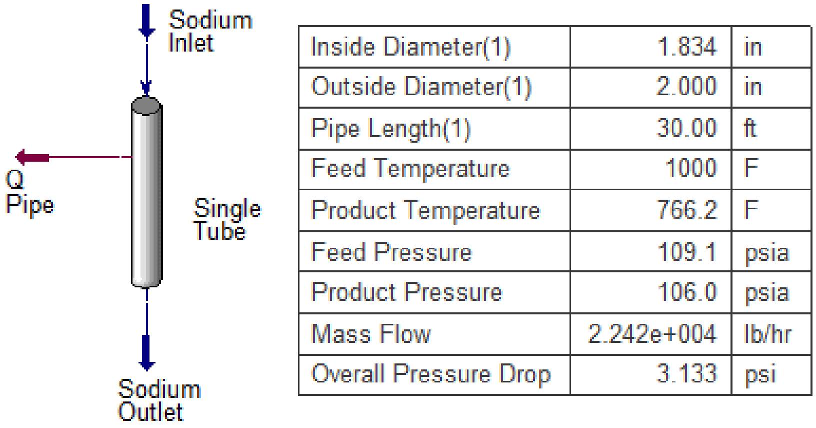
Table 3.2: Values of UA, NTU, and ΔT for the heat exchanger calculated from HYSYS and correcting the values to accommodate for it being a cross-flow heat exchanger.

Variable	HYSYS Calculated	Cross-flow Value
UA	86.0 kJ/C-s	92.18 kJ/C-s
NTU	-	0.3626
ΔT	383.6°C	358°C

be looked at was the tube arrangement. Figure 3.6 shows the two arrangements of the tube bundle. Upon further research, most tube bundles that have a high number of tubes are staggered, therefore, it will be assumed that the bundle is staggered. Furthermore, due to the large number of tubes, 66, we can use the following equation for finding the average Nusselt number [10]

$$Nu_f = C * Re_{D,max}^m * Pr_f^{0.36} * (Pr_f/Pr_w)^{0.25} \tag{3.2}$$

where C and m are constants that are found in the Table 3.3. Also note that Pr_w is the Prandtl number found using the properties found with the wall temperature. The Nusselt number is the measure of convection heat transfer at the surface of where the heat transfer is taking place.



Inside Diameter(1)	1.834	in
Outside Diameter(1)	2.000	in
Pipe Length(1)	30.00	ft
Feed Temperature	1000	F
Product Temperature	766.2	F
Feed Pressure	109.1	psia
Product Pressure	106.0	psia
Mass Flow	2.242e+004	lb/hr
Overall Pressure Drop	3.133	psi

Figure 3.5: Specification of pipe to solve within HYSYS.

The Reynolds number here is found at the maximum fluid velocity. However, there are two places where the maximum velocity can happen on a staggered bundle, at the transverse plane, A_1, or the diagonal plain, A_2 [10]. The equation for the transverse plain is

$$V_{max} = \frac{S_T}{S_T - D} V \tag{3.3}$$

Whereas the diagonal plain maximum velocity can be found by

$$V_{max} = \frac{S_T}{2(S_D - D)} V \tag{3.4}$$

Using the maximum velocity, it is put into the Reynolds number equation

$$Re_{D,max} = \frac{\rho V_{max} D}{\mu} \tag{3.5}$$

The Reynolds number is the ratio of the inertia and viscous forces. This means that the lower the number, the calmer the flow. The higher the number, the more turbulent.

It is also known that the Prandtl number can be found by

$$Pr_f = \frac{\mu c_p}{k} = \frac{\nu}{\alpha} \tag{3.6}$$

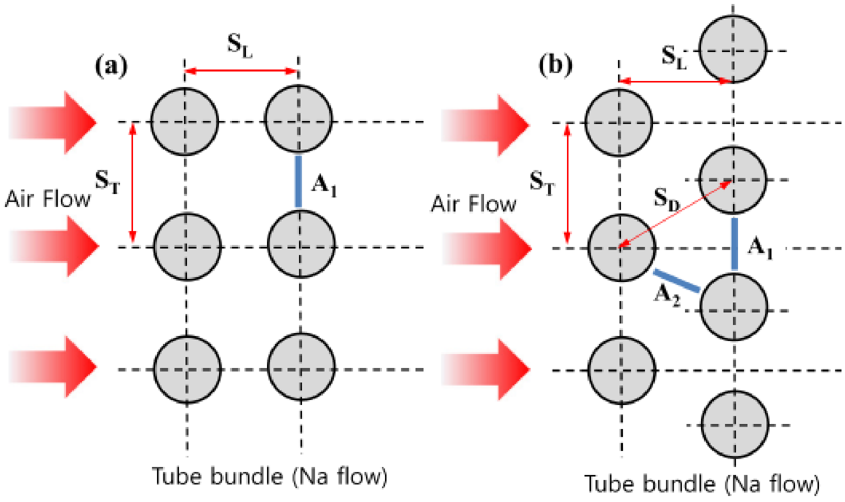


Figure 3.6: Tube bundle alignment a) Aligned b) Staggered [11]

The Prandtl number is the ratio of the momentum and thermal diffusivities. The smaller the number means that the temperature boundary layer will develop first, while the velocity boundary layer will develop slower. Similarly, as the Prandtl number increases in values the boundary layers develop opposite, the velocity boundary layer develops first and is followed by the temperature boundary layer.

Table 3.3: Constants for the average Nusselt number for air.

Configeration	Reynold's Number	C	m
Staggered	1.6 - 40	1.04	0.4
	40 - 1000	0.71	0.5
	1000 - 200000**	$0.35 * (S_T/S_L)^{0.2}$	0.6
	1000 - 200000	0.4	0.6
	200000 - 2000000	$0.031 * (S_T/S_L)^{0.2}$	0.8
In-line	1.6 - 100	0.9	0.4
	100 - 1000	0.52	0.5
	1000 - 200000	0.27	0.63
	200000 - 2000000	0.033	0.8

**$S_T/S_L < 2$

Once we calculate the Nusselt number, the heat transfer coefficient can be calculated by

$$h_o = \frac{Nu * k}{D_o} \tag{3.7}$$

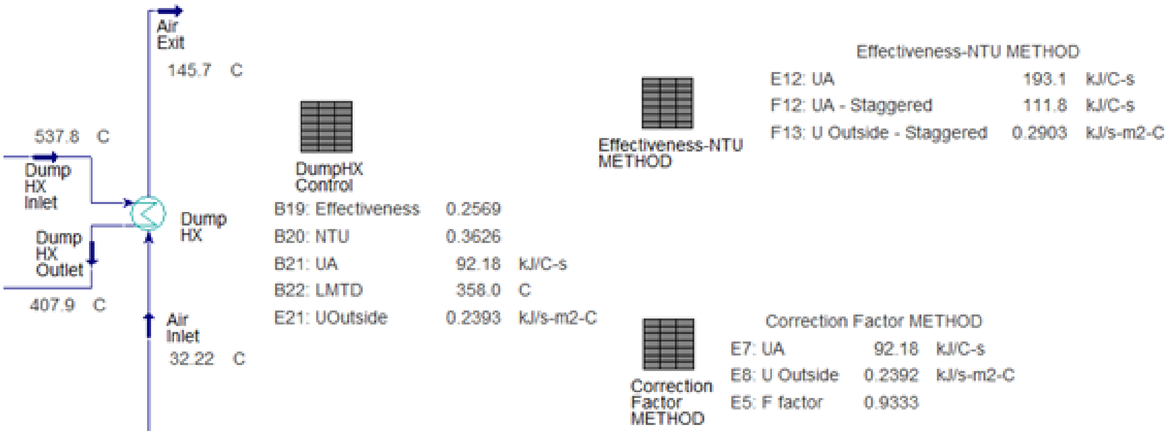
For the inside of the tubes, to find the average Nusselt number the following equation was used.

$$Nu = 4.82 + 0.185Pe^{0.827} \tag{3.8}$$

where $Pe = RePr$. We then use the same relationship found in Equation 11 to find the heat transfer coefficient for the inside of the tubes. From here, the UA can be found by using the following

$$U_oA_o = \Big(\frac{1}{h_oA_o} + \frac{ln(D_o/D_i)}{2\pi kL} + \frac{1}{h_iA_i}\Big)^{-1} \tag{3.9}$$

where the $A = 2\pi D$.



DumpHX Control

B19: Effectiveness	0.2569	
B20: NTU	0.3626	
B21: UA	92.18	kJ/C-s
B22: LMTD	358.0	C
E21: UOutside	0.2393	kJ/s-m2-C

Effectiveness-NTU METHOD

E12: UA	193.1	kJ/C-s
F12: UA - Staggered	111.8	kJ/C-s
F13: U Outside - Staggered	0.2903	kJ/s-m2-C

Correction Factor METHOD

E7: UA	92.18	kJ/C-s
E8: U Outside	0.2392	kJ/s-m2-C
E5: F factor	0.9333	

Figure 3.7: Calculated values for UA using two different methods to confirm initial look.

Figure 3.7 shows the values that were obtained using this method. From this calculation, the values for $Uoutside$ do not match. Thus, the correction factor method was used to try and confirm the numbers. These numbers seemed to match up; however, further investigation into the Effectiveness-NTU method will be done later on. From here, work will be made to look for improvements of the DHX.

Upon finishing the cross-flow heat exchanger in HYSYS, a discrepancy was found with the heat exchanger itself. Using the simple relationship of duty and the change of temperature, I was able to find the correct values, either for mass flow rate or for the duty. The equation for duty is as follows

$$\dot{Q} = \dot{m}c_p\Delta T \tag{3.10}$$

If the Duty is correct and the inlet and outlet temperatures of the sodium side are achieved, we get a corrected mass flow rate of

$$\begin{aligned} 33MW &= \dot{m} * 1.361\frac{kJ}{kgC} * (1000°F - 830°F) \\ \dot{m} &= 253\frac{kg}{s} \end{aligned} \tag{3.11}$$

If the mass flow rate is correct and the inlet and outlet temperatures of the sodium side are achieved, we get a corrected duty of

$$\begin{aligned} \dot{Q} &= 186.5\frac{kg}{s} * 1.361\frac{kJ}{kgC} * (1000°F - 830°F) \\ &= 24.32MW \end{aligned} \tag{3.12}$$

3.3 PARAMETRIC STUDIES - HUMID AIR

Once the heat exchanger was modeled in HYSYS, some parametric studies were done on the air side. There were three different parametric studies: the air mass flow rate, the humidity, and the temperature at which the air enters.

The first study was to see how the humidity of the air would effect the NTU and efficiency of the heat exchanger. To run this study, humidity was taken from 0 to 100% humid at increments of 10%. This would allow for the effects of air from a desert to that of air from a jungle. Figure 3.8, shows the results of this parametric study. As the humidity increased, the NTU increased but the efficiency decreased. Looking at the values of NTU and effectiveness in Figure 3.8, it can be seen that the changes to both the effectiveness and the NTU happen in the fourth decimal place. This means that humidity doesn't affect performance of the heat exchanger; therefore changing the humidity becomes negligible.

The second study looked at the temperature effect on the air. The range of temperature that was looked at was from 10°C to 60°C. This can be seen in Figure 3.9. As seen in the figure, the higher the temperature is, the more advantageous it is to the heat exchanger's operation. It both increases the efficiency and the NTU value. From this

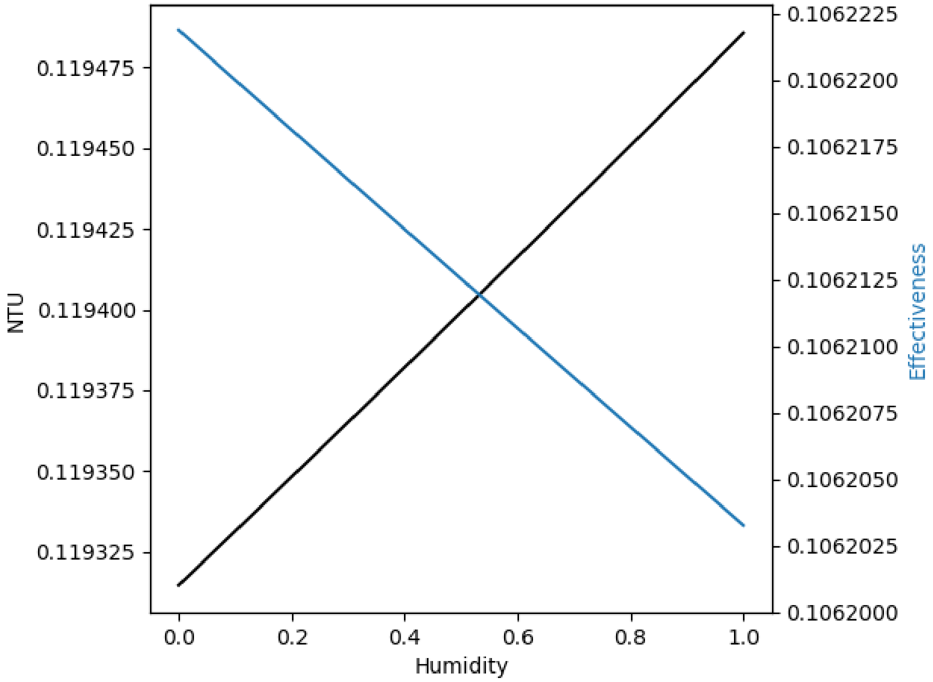


Figure 3.8: Changing the humidity of the air on the Dump Heat Exchanger and comparing the NTU and Effectiveness.

study, changing the temperature has a negligible effect seeing as the change to the NTU and the effectiveness both take place in the fourth decimal place.

Finally, the flow rate of the air was studied. It was determined that the range of the study would be from 200 kg/s to 340 kg/s. This would encompass the original value as well as going below and above to get some idea of what would happen. Figure 3.10, shows the results of the study. The slower the speed the better the values of efficiency and NTU are. This is because it allows for more heat to be transferred to the air as it travels through the heat exchanger. Based on these results slowing down the flow rate would greatly increase how well the heat exhanger performed.

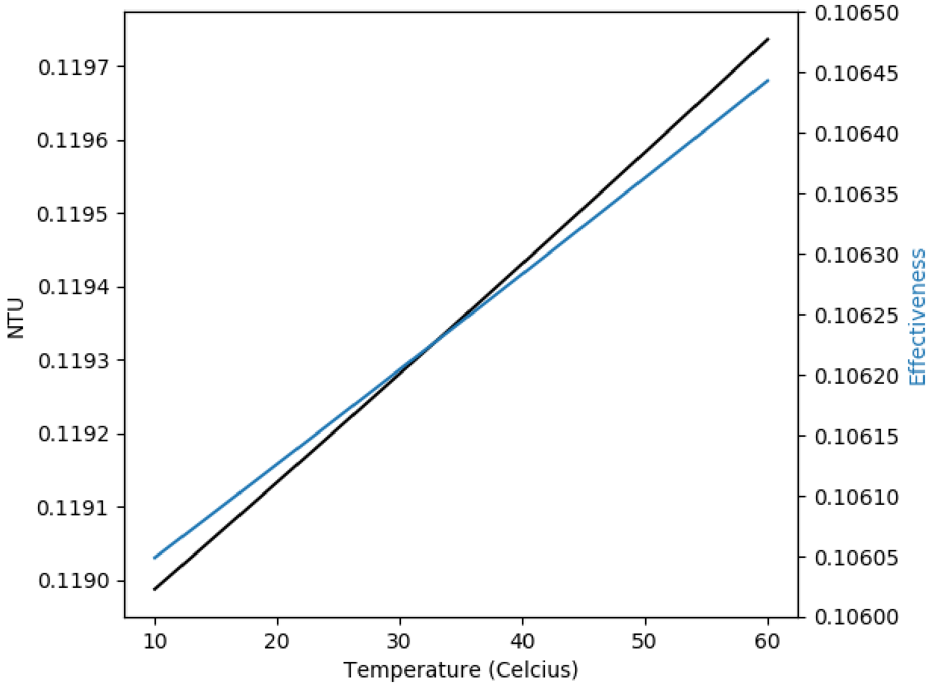


Figure 3.9: Changing the temperature of the air on the Dump Heat Exchanger and comparing the NTU and Effectiveness.

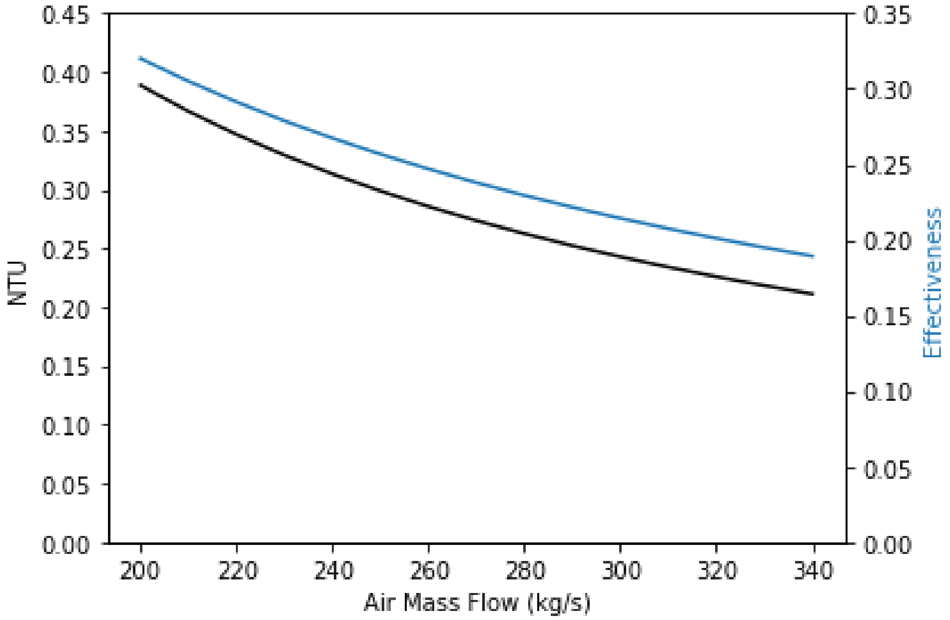


Figure 3.10: Changing the flow rate of the air on the Dump Heat Exchanger and comparing the NTU and Effectiveness.

Chapter 4: Potential Heat Exchangers

After this analysis was done, work was started from a design point of view for an annulus heat exchanger that was based on the results of the cross-flow heat exchanger. First it was determined to look at a single annulus. In William S. Jenna's book, Design of Fluid Thermal Systems, [11], he gives the steps on how to design an annulus heat exchanger. This process can be found in Appendix A. Following the single annulus heat exchanger, another analysis was performed to include a group of annulus exchangers that had a duty of 40 MW. Finally, a brief look into shell and tube heat exchangers was done to compare to the original cross-flow heat exchanger.

4.1 Annulus Heat Exchanger Design

After going through the design process for a single annulus, tube-in-tube heat exchanger, a case study was done to determine possible inner diameters of the sodium pipe and the length of the heat exchanger that would work with reasonable pressure drops. Originally, it was determined that only pressure drops below 500 kPa would be investigated first. Figure 4.1 shows the results of the case study. In terms of mass flow rate in the annulus, it was varied from 100 kg/s to 300 kg/s and the results only varied the pressure drop in the second to third decimal place. Table 4.1 contains all possible variations of Annulus heat exchangers that have a pressure drop under 500 kPa. The table also values highlighted that match the duty of 33 MW.

After collecting all this data, a further look into allowable pressure was done. It was found that for water in residential piping, [12], a drop of 3 psi over 100 ft is the maximum allowed pressure. When water in residential piping is assumed to be at atmospheric pressure, the 3 psi drop comes out to be about a 20% drop. Taking this approach and applying it to the heat exchangers in this section, the max allowable drop comes out to 21.8 psi (150 kPa). Comparing the annulus heat exchangers with the Fast Flux Testing Facility (FFTF)'s cross-flow design there are four annulus heat exchangers that would work as shown in Table 4.3. Each annulus that came up with a Duty of 33 MW were 5 meters long. When comparing the designs, there was only one option that was below the max allowable pressure of 150 kPa, the annulus that had an inner diameter for the pipe of 30 cm. However, the others still matched the duty of the cross-flow heat exchanger so they were left on the table.

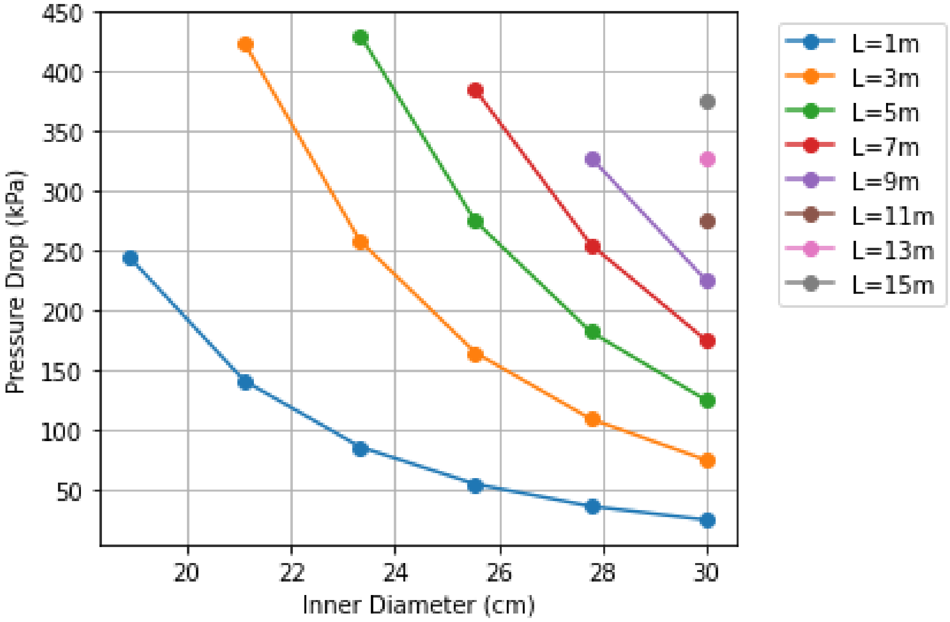


Figure 4.1: Pressure drop as a function of the inner diameter of the pipe, which contains sodium, and length in meters of a single annulus.

After matching the 33MW duty of the cross-flow heat exchanger, it was determined to investigate the addition of multiple annuli. When 25 annuli were looked at, every combination of flowrate, length, and diameter of the sodium pipe gave reasonable pressure drops. When looking at either the single annulus or the 25 annuli, the duty varied greatly. It ranged from 5 to 50 MW, these values can be seen in Table 4.1. The combinations of inner diameter and length that give 33 MW or close to it are highlighted.

Now, it has been decided to investigate a shell-and-tube heat exchanger. This will be done by using the heat exchanger module, which is already built into HYSYS. By using the HYSYS operations manual, a design of the heat exchanger will be made which will work for the project.

Within HYSYS, there is a heat exchanger module that can be used for design. This module can be used to create many types of heat exchangers, mainly shell-and-tube, double pipe, and cross-flow. To verify the calculations that were done with the double pipe heat exchanger above, The heat exchanger module that is built into HYSYS was used. The first heat exchanger that was made, had an inner pipe outer diameter of 0.2 m and an annulus inner diameter of 0.25 m. The length of each double pipe was 10 m and the number of pipes required to match the design parameter of 33 MW, was 22. However,

Table 4.1: Possible inner diameter of sodium, length, pressure drop, and duty found through the design process of the Annulus Heat Exchanger. The highlighted rows are viable choices for the heat exchanger that work.

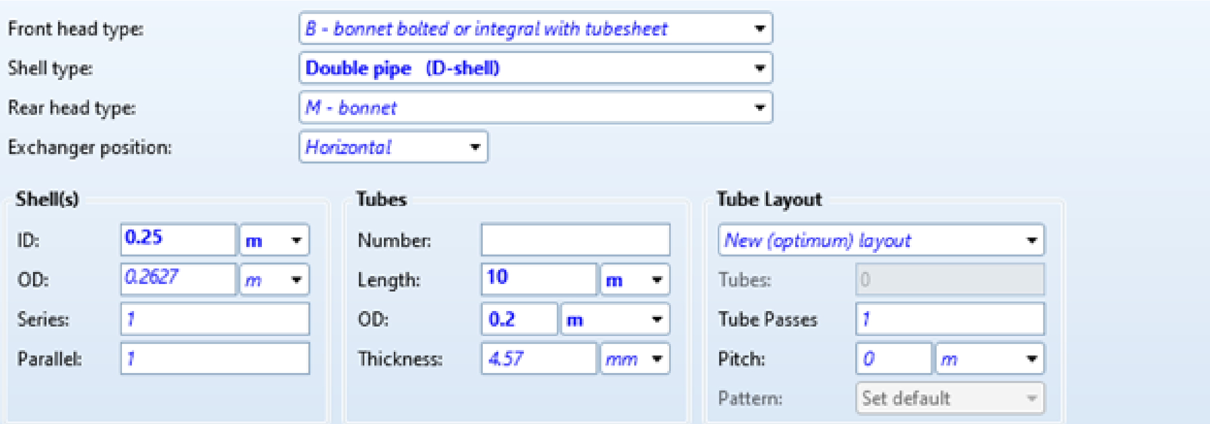
IDp (cm)	L (m)	Delta P (kPa)	Duty (MW)
18.889	1	245.06	6-7
21.111	1	141.21	6-8
21.111	3	423.64	19-20
23.333	1	86.111	7.5-8.7
23.333	3	258.33	20.9-21.3
23.333	5	430.555	29.7-32.6
25.55	1	54.987	8.2-9.4
25.55	3	164.961	22.7-23.4
25.55	5	274.935	31.4-35
25.55	7	384.9095	37.2-45.2
27.77	1	36.481	4.9-10
27.77	3	109.444	24-25
27.77	5	182.407	32.7-37.4
27.77	7	255.37	38.5-48.3
27.77	9	328.333	42.4-57.7
30	1	24.9969	9.6-10.8
30	3	74.9909	25.2-26.5
30	5	124.9849	34-39.7
30	7	174.9788	39.7-51
30	9	224.9728	43.4-60.7
30	11	274.9668	45.8-69
30	13	324.9607	47.5-76.1
30	15	374.955	48.6-82.5

to come up with this many pipes, each heat exchanger was designed to have a total of 25 pipes. Figure 4.2 shows the portion of the HYSYS module that was used to specify the geometry of one double pipe exchanger. However, to make sure that there would be enough duty, to remove the required heat from the sodium, it was decided to design to a duty of 40 MW.

Table 4.2: Cross-Flow heat exchanger compared to different Annulus heat exchangers all having a length of 5 meters.

Heat Exchanger	**Number of Tubes**	**Inner Diameter Pipe (cm)**	**Inner Diameter Annulus (m)**	**Mass Flow Rate Air (kg/s)**	**Total Duty (MW)**	**Pressure Drop (kPa)**
Cross-Flow	66			283.5	33	20.685
Annulus 1	1	23.33	3.6	300	32.6	430.555
Annulus 1	1	25.55	2.3-2.5	120-140	32.8-33.7	274.935
Annulus 1	1	27.77	2.1-2.2	100-110	32.7-33.7	182.407
Annulus 1	1	30	2.105	100	34.07	124.985

To compare these results, a case study was done where the outer diameter of the inner pipe was made smaller, 0.1 m and 0.05 m. To do this study, the length of the tubes was kept constant. When the diameter was decreased, the amount of annulus pipes increased. Figure 4.3 shows the annulus dimensions for one pipe for the diameter 0.1 m. When the diameter was changed, the outer pipe diameter was changed until the duty came out to be 0.4 MW. Which led to needing 100 annulus heat exchanger tubes to get to the 40 MW. Likewise, when the diameter was decreased to 0.05 m, it took 200 pipes to reach the 40 MW. Figure 4.4 shows the dimensions of the 0.05 m outer diameter annulus pipe.


Front head type: B - bonnet bolted or integral with tubesheet
Shell type: Double pipe (D-shell)
Rear head type: M - bonnet
Exchanger position: Horizontal

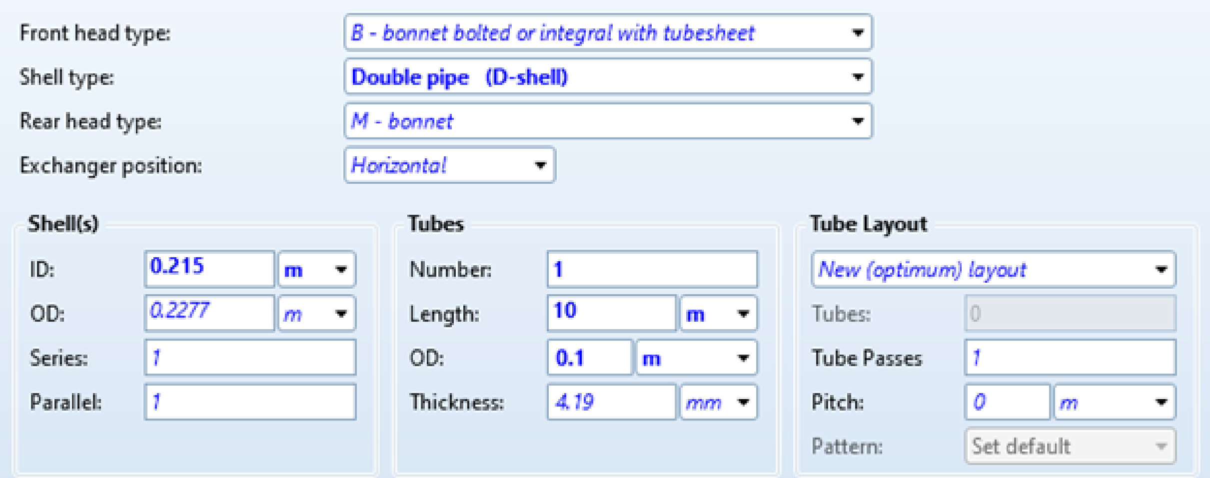
Shell(s)
ID: 0.25 m
OD: 0.2627 m
Series: 1
Parallel: 1

Tubes
Number:
Length: 10 m
OD: 0.2 m
Thickness: 4.57 mm

Tube Layout
New (optimum) layout
Tubes: 0
Tube Passes: 1
Pitch: 0 m
Pattern: Set default

Figure 4.2: Double pipe, Annulus, heat exchanger that is 10 m in length and has a duty of 1.641 MW. The total number of double pipe heat exchanges would be around 25.

To gain a better understanding of how these designs compared to the original cross-flow heat exchanger, Table 4.3 was created. In this table, there are not any pressure drops for the Annulus 25, 100, and 200 heat exchangers due to that data not being pulled from the studies. However, they all reached a convergence of under the allowable pressure drop



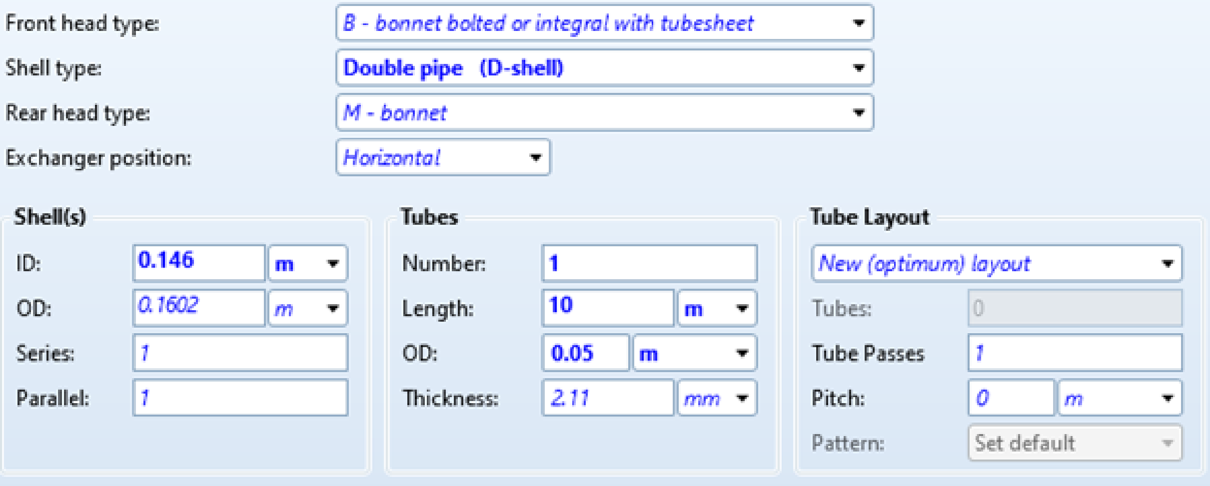
Front head type: B - bonnet bolted or integral with tubesheet
Shell type: Double pipe (D-shell)
Rear head type: M - bonnet
Exchanger position: Horizontal

Shell(s)
ID: 0.215 m
OD: 0.2277 m
Series: 1
Parallel: 1

Tubes
Number: 1
Length: 10 m
OD: 0.1 m
Thickness: 4.19 mm

Tube Layout
New (optimum) layout
Tubes: 0
Tube Passes: 1
Pitch: 0 m
Pattern: Set default

Figure 4.3: Double pipe, Annulus, heat exchanger that is 10 m in length and has a duty of 0.4 MW. The total number of double pipe heat exchangers would be around 100.



Front head type: B - bonnet bolted or integral with tubesheet
Shell type: Double pipe (D-shell)
Rear head type: M - bonnet
Exchanger position: Horizontal

Shell(s)
ID: 0.146 m
OD: 0.1602 m
Series: 1
Parallel: 1

Tubes
Number: 1
Length: 10 m
OD: 0.05 m
Thickness: 2.11 mm

Tube Layout
New (optimum) layout
Tubes: 0
Tube Passes: 1
Pitch: 0 m
Pattern: Set default

Figure 4.4: Double pipe, Annulus, heat exchanger that is 10 m in length and has a duty of 0.2 MW. The total number of double pipe heat exchangers would be around 200.

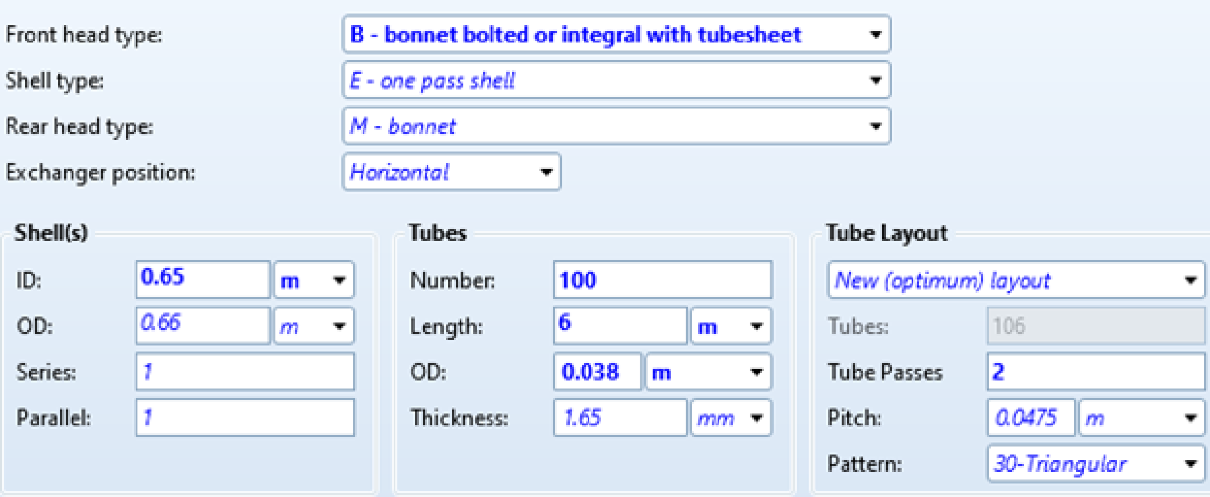
of 150 kPa. Also on Table 4.3, there are three variations of a single annulus heat exhanger that met the design parameter of 40 MW. These all had a length of 7 meters, with mass flow rates around 100 kg/s of air, and needed to have a Annulus Inner Diameter of over 2 meters to accomplish the 40 MW of duty. None of these annulus heat exchangers gave pressure drops under 150 kPa, but they were included because the pressure drop is what would be expected if the duty of 40 MW was achieved.

Table 4.3: Initial Cross-Flow HX vs Annulus HX.

Heat Exchanger	**Inner Diameter Pipe (cm)**	**Inner Diameter Annulus (m)**	**Mass Flow Rate Air (kg/s)**	**Individual Duty (MW)**	**Number of Tubes**	**Total Duty (MW)**	**Pressure Drop (kPa)**
Cross-Flow			283.5		66	33	20.685
Annulus 25 (L=10m)	19.54	0.25	11.34	1.641	25	40	
Annulus 100 (L=10m)	5.81	0.215	2.835	0.4	100	40	
Annulus 200 (L=10m)	2.89	0.146	1.142	0.2	200	40	
Annulus 1 (L=7m)	25.55	2.3-2.4	120-130	39.7-40.7	1	39.7-40.7	384.909
Annulus 1 (L=7m)	27.77	2.2	110	40.1	1	40.1	255.370
Annulus 1 (L=7m)	30	2.1	100	39.7	1	39.7	174.979

4.2 shell-and-tube Heat Exchanger

After reaching the design parameters with using annulus heat exchangers, shell-and-tube heat exchangers were looked at. This was done using the same HYSYS module from up above. There were two different cases run for the shell-and-tube heat exchangers. First, one with 100 tubes and the second with 150 tubes. The goal was to have each heat exchanger have a duty around 40 MW and have a reasonable temperature of air exiting the shell side. Figure 4.5 shows the geometry of the first module that has 100 tubes. For each tube containing the sodium, the outer diameter was set to 0.038 m (1.5 in). The tubes contained 2 passes and the straight sections were 6 m long. The inner diameter of the shell was then set to 0.65 m (about 25.6 in). With these mechanical properties, the duty of 40 MW was achievable. Figure 4.6 shows the resulting physical states of what surrounds the heat exchanger. The sodium leaves at 446.3°C and the air leaves at 106.5°C. The mass flow rate of the air is what determines the duty of the heat exchanger. For this heat exchanger, the amount of air flow that was needed came out to be 536.8 kg/s. One thing to note, is that the pressure drop across the sodium tubes is quite large. The sodium leaves at 1501 kPa.



Front head type: B - bonnet bolted or integral with tubesheet
Shell type: E - one pass shell
Rear head type: M - bonnet
Exchanger position: Horizontal

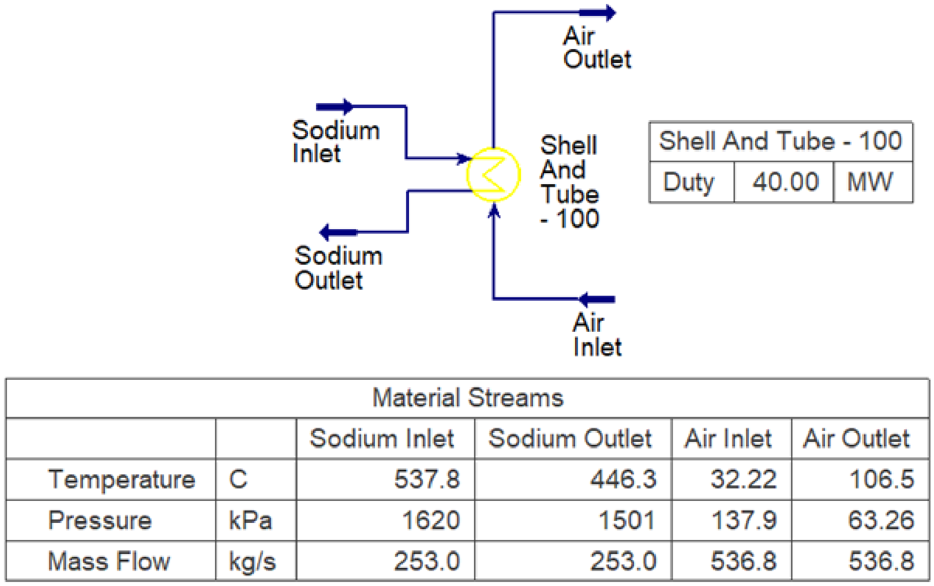
Shell(s)
ID: 0.65 m
OD: 0.66 m
Series: 1
Parallel: 1

Tubes
Number: 100
Length: 6 m
OD: 0.038 m
Thickness: 1.65 mm

Tube Layout
New (optimum) layout
Tubes: 106
Tube Passes: 2
Pitch: 0.0475 m
Pattern: 30-Triangular

Figure 4.5: Geometry of shell-and-tube with 100 tubes.

When looking at the second iteration of the shell-and-tube heat exchanger, more tubes were added to see how much change would happen. The tube size and length all remained the same as the first shell-and-tube module. However, to fit the amount of tubes in it, the shell's inner diameter was changed to 0.8 m (about 31.5 in), see Figure 4.7. When



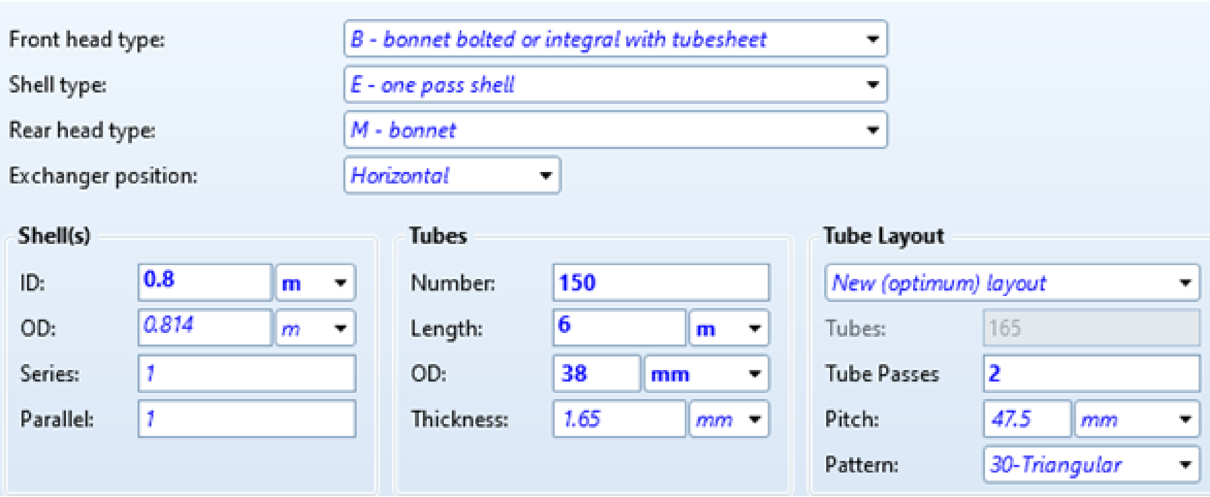
Shell And Tube - 100		
Duty	40.00	MW

Material Streams					
		Sodium Inlet	Sodium Outlet	Air Inlet	Air Outlet
Temperature	C	537.8	446.3	32.22	106.5
Pressure	kPa	1620	1501	137.9	63.26
Mass Flow	kg/s	253.0	253.0	536.8	536.8

Figure 4.6: Temperature, pressure, and mass flow rate for the shell-and-tube that contains 100 tubes.

comparing the results of the shell-and-tube heat exchanger that has only 100 tubes, there are some improvements in going with more tubes. The pressure coming out of the heat exchanger is larger, 1564 kPa vs the 1501 kPa. Also the flow rate of the air has decreased on the order of 20 kg/s. This leads to a higher temperature exiting the shell of 109.8°C, but it would require less equipment to achieve this, see Figure 4.8.

To better compare the shell and tube heat exchangers, these two heat exchangers designs were added to Table 4.3. Table 4.4 has the complete comparison. Both two shell and tube designs both had pressure drops under the allowable pressure drop. However, when looking back at the models form HYSYS, it was found that there are some issues with the models, the modules appear yellow, see Figures 4.6 and 4.8, instead of blue like in Figure 3.4.



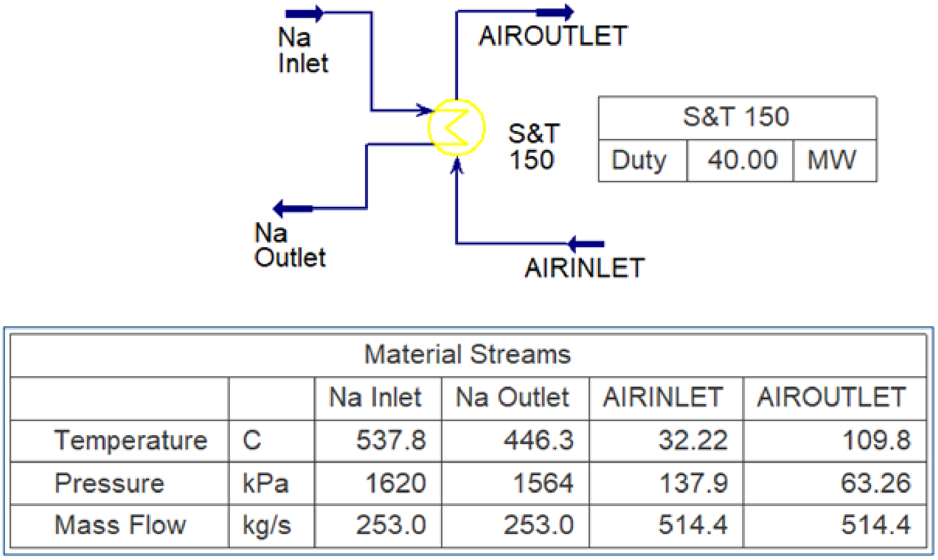
Front head type: B - bonnet bolted or integral with tubesheet
Shell type: E - one pass shell
Rear head type: M - bonnet
Exchanger position: Horizontal

Shell(s)
ID: 0.8 m
OD: 0.814 m
Series: 1
Parallel: 1

Tubes
Number: 150
Length: 6 m
OD: 38 mm
Thickness: 1.65 mm

Tube Layout
New (optimum) layout
Tubes: 165
Tube Passes: 2
Pitch: 47.5 mm
Pattern: 30-Triangular

Figure 4.7: Geometry of shell-and-tube with 150 tubes.



S&T 150		
Duty	40.00	MW

Material Streams					
		Na Inlet	Na Outlet	AIRINLET	AIROUTLET
Temperature	C	537.8	446.3	32.22	109.8
Pressure	kPa	1620	1564	137.9	63.26
Mass Flow	kg/s	253.0	253.0	514.4	514.4

Figure 4.8: Temperature, pressure, and mass flow rate for the shell-and-tube that contains 150 tubes.

Table 4.4: Initial Cross-Flow HX vs Annulus HX vs Shell and Tube HX.

Heat Exchanger	**Inner Diameter Pipe (cm)**	**Inner Diameter Annulus (m)**	**Mass Flow Rate Air (kg/s)**	**Individual Duty (MW)**	**Number of Tubes**	**Total Duty (MW)**	**Pressure Drop (kPa)**
Cross-Flow			283.5		66	33	20.685
Annulus 25 (L=10m)	19.54	0.25	11.34	1.641	25	40	
Annulus 100 (L=10m)	5.81	0.215	2.835	0.4	100	40	
Annulus 200 (L=10m)	2.89	0.146	1.142	0.2	200	40	
Annulus 1 (L=7m)	25.55	2.3-2.4	120-130	39.7-40.7	1	39.7-40.7	384.909
Annulus 1 (L=7m)	27.77	2.2	110	40.1	1	40.1	255.370
Annulus 1 (L=7m)	30	2.1	100	39.7	1	39.7	174.979
Shell and Tube 100	36.45	0.65	536.8		100	40	119
Shell and Tube 150	36.45	0.8	514.4		150	40	56

Chapter 5: Results

One of the crucial portions of this thesis work was creating the hypothetical property package for sodium in HYSYS. ANL data was used to create this hypothetical. The properties that needed to be imported were density, specific heat capacity, thermal conductivity, viscostiy, mass entropy, mass enthalpy. Once equations were created for fitting the data, the resulting hypothetical were compared to the original ANL data, as well as a sodium property found in ASPEN PLUS. These results found that the hypothetical was a better fit to that of the ASPEN PLUS version. Once the sodium property was created and the FFTF heat ecahanger was modeled in HYSYS a parametric study was done on the air side to see how humidity affected it.

There were three studies done on the air side which consisted of changing the humidity, the temperature, and changing the mass flow rate. In each study, only one parameter was changed. The first study consisted of changing the humidity from 0% to 100%. Figure 3.8 shows that as the humidity increased the NTU values increased, but the effectiveness went down. When looking at how much the NTU and effectiveness values were affected, there was not a big difference; thus, humidity did not have a big impact on the heat exchanger. Figure 3.9 shows that as the temperature increased the NTU values and effectiveness values both increased, meaning that it would be beneficial to have higher temperatures for the air going into the heat exchanger. Figure 3.10 shows that has the mass flow rate decreases as the flow rate increases. Thus, having a slower air flow would be beneficial.

Table 5.1: List of mass flow rate, duty, and sodium outlet temperature for the current design and the corrected valued cases.

	Mass Flow Rate	Duty	Sodium Outlet Temperature
Current Design (FFTF)	186.5 kg/s	33 MW	766.2°F
Correct $\dot{m}$	253 kg/s	33 MW	830°F
Corrected Duty	186.5 kg/s	24.32 MW	830°F

When investigating the FFTF's heat exchanger there were some differences with the heat exchanged and the outlet temperature on the sodium side. An analysis was done to compare what was modeled to that of (1) changing the mass flow rate and keeping the heat exchanged, and (2) keeping the mass flow rate and changing the duty. Table 5.1, shows the comparison. The original design mass flow rate and duty are on the first row. When the duty is kept, 33 MW, to get the design outlet temperature of 830°F a mass flow rate of 253 kg/s is needed. However, if the mass flow rate is kept the same as the original, a new lower duty is required to obtain the desired outlet temperature of 24.32 MW.

Potential heat exchangers were looked at. First, a single annulus heat exchanger was used to match the 33 MW duty that the original FFTF's cross-flow heat exchanger. Table 4.2, gives four options all 5 meters in length, but varying in size, that were able to produce 33 MW. Out of the four possible annulus heat exchangers, the last option, with an inner diameter of the pipe of 30 cm and an inner diameter of the annulus of 2.105 meters, is the only design that falls under the allowable pressure drop of 150 kPa. Second, bundles of annuli heat exchangers were investigated. Bundles of 25, 100, and 200 were all designed to have a duty of 40 MW and were compared the existing cross-flow heat exchanger, see Table 4.3. Any of these three heat exchangers would be a viable design. Finally, an initial design on two versions of a shell and tube heat exchangers was also completed. Table 4.4, gives a comparison of all the potential heat exchangers that were designed with a duty 40 MW. It shows that even though the shell and tube heat exchangers were preliminary results, they were still a viable solution because they gave a pressure drop below the allowable pressure.

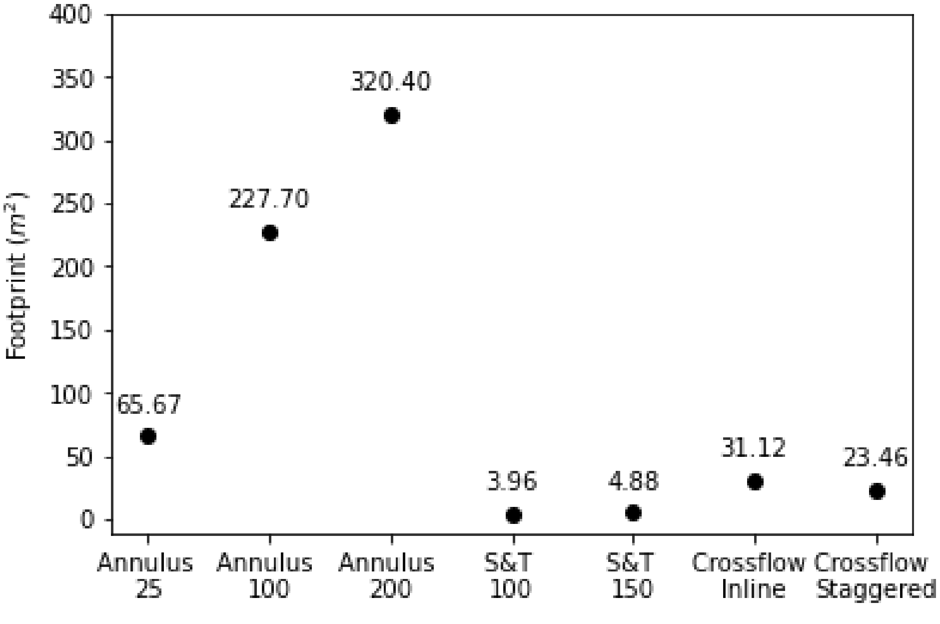


Figure 5.1: Total footprint of the potential heat exchangers in m^2

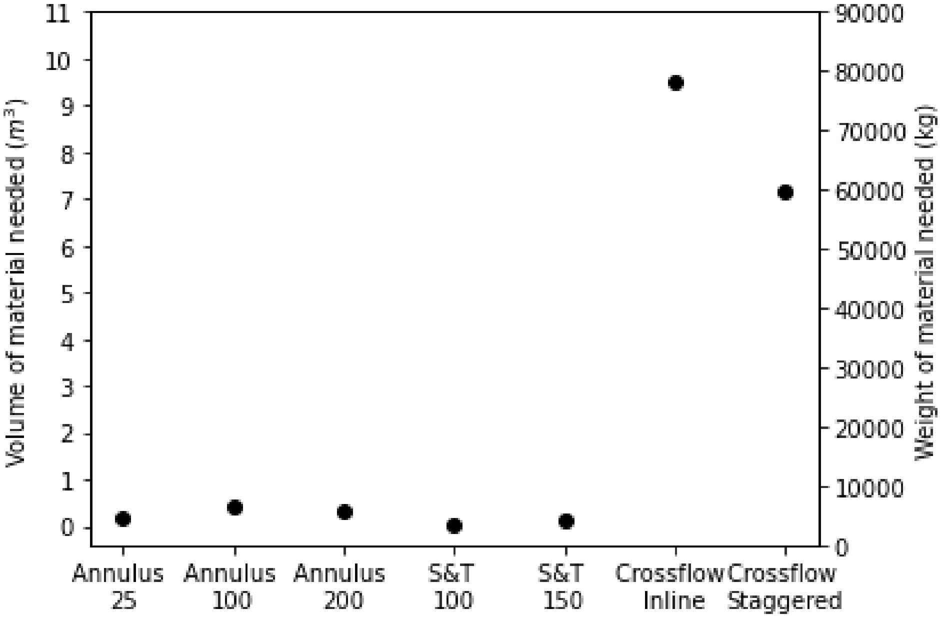


Figure 5.2: Volume of material needed to create each potential heat exchanger.

Chapter 6: Summary and Conclusions

Conclusions:

- Found discrepancies with mass flow rate of sodium and the duty in the existing FFTF's cross-flow heat excahanger. By using the heat transfer equation $\dot{Q} = \dot{m} c_p \Delta T$, corrected values were found, see Table 5.1.
- It was found that humidity and inlet air temperature for the heat exchanger does not affect the performance of the exchanger. However, changing the mass flow rate does effect the performance. The slower the the flow the more efficient the exchanger would be.
- Comparing the possible heat exchangers and the initial cross-flow design the exchangers were ranked based on footprint, volume of material, and weight
    1. Shell and Tube with 100 tubes
    2. Shell and Tube with 200 tubes
    3. Annulus with 25 annuli
    4. Annulus with 100 annuli
    5. Annulus with 200 annuli
    6. Cross-flow design using a staggered tube arrangement
    7. Cross-flow design using an inline tube arrangement

Future Work:

- Validate Shell and Tube heat exchanger models
- Add fins to all potential heat exchangers and compare the results to this study.
- Perform an experiment on a smooth tubed cross-flow heat exchanger to confirm assumptions of model.

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APPENDIX A: SOLVING ANNULUS HEAT EXCHANGER FROM JANNA'S BOOK [11]

Assumptions:

1. $V_a = 30m/s$
   - (a) Engineering toolbox for max velocity through a pipe
   - (b) Setting Velocity, gives IDa
2. Initial Conditions
   - (a) $T_1 = 1000°F$, $\dot{m}_p = 253kg/s$, $P_1 = 752.2kPa$
   - (b) $t_1 = 90°F$, $p_1 = 109.6kPa$
   - (c) Smooth tubes
3. Variables to control design
   - (a) Length, L
   - (b) Inner Diameter of pipe, IDp
   - (c) Outer diameter of pipe, ODp (Assumed thickness of walls till found solutions that work)
   - (d) Mass flow rate of the annulus, $\dot{m}_a$

Design Process:

1. Get fluid properties a the average temperature (inlet of both sides)
2. Set Tubing size (if known)
3. Solve for flow area
   - (a)

$$A_p = \frac{\pi IDp^2}{4} \tag{A.1}$$

   - (b)

$$A_a = \frac{\pi(IDa^2 - ODp^2)}{4} \tag{A.2}$$

4. Find Fluid Velocities

   (a)

$$V_p = \dot{m}_p/\rho A_p \tag{A.3}$$

   (b)

$$V_a = \dot{m}_a/\rho A_a \tag{A.4}$$

5. Find the Annulus Equivalent Diameters

   (a) Friction:

$$D_h = IDa - ODp \tag{A.5}$$

   (b) Heat Transfer:

$$D_e = (IDa^2 - ODp^2)/ODp \tag{A.6}$$

6. Find Reynold's Number

   (a)

$$Re_p = \frac{V_p IDp}{\nu} \tag{A.7}$$

   (b)

$$Re_a = \frac{V_p D_e}{\nu} \tag{A.8}$$

7. Nusselt Numbers

   (a)

$$Nu_p = 0.023(Re_p)^{4/5} Pr^{0.3} \tag{A.9}$$

   (b)

$$Nu_a = 0.023(Re_a)^{4/5} Pr^{0.4} \tag{A.10}$$

8. Convection Coefficients

   (a)

$$h_i = Nu_p k_f/IDp \tag{A.11}$$

   (b)

$$h_p = h_i IDp/ODp \tag{A.12}$$

   (c)
$$h_a = Nu_a k_f / D_e \tag{A.13}$$

9. Exchaner Coefficient

   (a)
$$\frac{1}{U_o} = \frac{1}{h_p} + \frac{1}{h_a} \tag{A.14}$$

10. Outlet Temperature Calculation (Length Needed)

   (a)
$$R = \frac{\dot{m}c_{p,c}}{\dot{m}c_{p,h}} \tag{A.15}$$

   (b)
$$A_o = \pi ODpL \tag{A.16}$$

   (c) Counter-flow

      i.
$$E_{counter} = exp\Big[\frac{U_o A_o (R-1)}{\dot{m}c_{p,c}}\Big] \tag{A.17}$$

      ii.
$$T_2 = \frac{T_1(R-1) - Rt_1(1 - E_{counter})}{RE_{counter} - 1} \tag{A.18}$$

      iii.
$$t_2 = t_1 + \frac{T_1 + T_2}{R} \tag{A.19}$$

11. LMTD

12. Heat Balance

   (a)
$$q_h = \dot{m}c_{p,h}(T_1 - T_2) \tag{A.20}$$

   (b)
$$q_c = \dot{m}c_{p,c}(t_2 - t_1) \tag{A.21}$$

   (c)
$$q = U_o A_o LMTD \tag{A.22}$$

13. Friction Factors

    (a)

$$\begin{aligned} &Re_p = V_p IDp/\nu \\ &\epsilon/IDp \\ &f_p \end{aligned} \tag{A.23}$$

    (b)

$$\begin{aligned} &Re_a = V_a D_h/\nu \\ &\epsilon/D_h \\ &f_a \end{aligned} \tag{A.24}$$

    (c) Turbulent = Chen or Churchill equation

    (d) Laminar = equations found on pg 420

14. Pressure Drop Calculations

    (a)

$$\Delta p_p = \frac{f_p L}{IDp} \frac{\rho_p V_p^2}{2g_c} \tag{A.25}$$

    (b)

$$\Delta p_p = \Big(\frac{f_a L}{D_h} + 1\Big) \frac{\rho_a V_a^2}{2g_c} \tag{A.26}$$

15. Iterate with new average temperatures for fluid properties

    (a) Hot Side:

$$T_{avg} = \frac{T_1 + T_2}{2} \tag{A.27}$$

    (b) Cold Side:

$$T_{avg} = \frac{t_1 + t_2}{2} \tag{A.28}$$

Appendix B: HYSYS Models and Reports

BATTELLE ENERGY ALLIANCE
Bedford, MA
USA

Case Name: final project.1.hsc
Unit Set: Project Units3s
Date/Time: Sat Aug 7 20:40:45 2021

Workbook: Case (Main)

Heat Exchangers

Fluid Pkg: All

Name	IHX	Dump HX			
Duty (MW)	30.80	33.00			
Tube Side Feed Mass Flow (kg/s)	742.4	186.5			
Shell Side Feed Mass Flow (kg/s)	186.5	283.5 *			
Tube Inlet Temperature (C)	595.8	537.8 *			
Tube Outlet Temperature (C)	565.6 *	407.9			
Shell Inlet Temperature (C)	415.1	32.22 *			
Shell Outlet Temperature (C)	537.8 *	145.7			
UA (kJ/C-s)	317.5	86.03			

Material Streams

Fluid Pkg: All

Name	1	2	3	Dump HX Inlet	Dump HX Outlet
Temperature (C)	595.8	565.6 *	575.0	537.8 *	407.9
Mass Flow (kg/s)	742.4	742.4	742.4	186.5	186.5
Pressure (kPa)	1551 *	1482	2723	752.4	730.8
Actual Liquid Flow (m3/s)	0.9215	0.9148	0.9169	0.2283	0.2216
Name	**Air Inlet**	**Air Exit**	**6**	**Humid Air**	**Air Surface**
Temperature (C)	32.22 *	145.7	415.1	28.97	472.9 *
Mass Flow (kg/s)	283.5 *	283.5	186.5	283.5	283.5
Pressure (kPa)	104.1	101.3 *	1724 *	101.3 *	102.7 *
Actual Liquid Flow (m3/s)	0.0000	0.0000	0.2219	0.0000	0.0000

Compositions

Fluid Pkg: All

Name	1	2	3	Dump HX Inlet	Dump HX Outlet
Comp Mole Frac (Sodium*)	***	***	***	***	***
Comp Mole Frac (Nitrogen)	***	***	***	***	***
Comp Mole Frac (Oxygen)	***	***	***	***	***
Comp Mole Frac (H2O)	***	***	***	***	***
Comp Mole Frac (Sodium)	1.0000 *	1.0000	1.0000	1.0000 *	1.0000
Name	**6**	**Air Exit**	**Air Inlet**	**Sodium Inlet**	**Sodium Outlet**
Comp Mole Frac (Sodium*)	***	***	***	***	***
Comp Mole Frac (Nitrogen)	***	0.7900	0.7900	***	***
Comp Mole Frac (Oxygen)	***	0.2100	0.2100	***	***
Comp Mole Frac (H2O)	***	0.0000	0.0000	***	***
Comp Mole Frac (Sodium)	1.0000	***	***	1.0000 *	1.0000
Name	**Humid Air**	**Air Average**	**HYPO**	**Aspen**	**4**
Comp Mole Frac (Sodium*)	***	***	1.0000 *	***	***
Comp Mole Frac (Nitrogen)	0.7900	0.7744 *	***	***	***
Comp Mole Frac (Oxygen)	0.2100	0.2059 *	***	***	***
Comp Mole Frac (H2O)	0.0000	0.0197 *	***	***	***
Comp Mole Frac (Sodium)	***	***	***	1.0000 *	1.0000 *
Name	**Air Surface**				
Comp Mole Frac (Sodium*)	***				
Comp Mole Frac (Nitrogen)	0.7744 *				
Comp Mole Frac (Oxygen)	0.2059 *				
Comp Mole Frac (H2O)	0.0197 *				
Comp Mole Frac (Sodium)	***				

Energy Streams

Fluid Pkg: All

Name	Secondary Pump Pow	Primary Pump Power	Reactor Heat	Q Pipe	Q-104
Heat Flow (MW)	2.200	11.35	19.45	0.5000 *	0.9321 *

Aspen Technology Inc. Aspen HYSYS Version 11 Page 1 of 2

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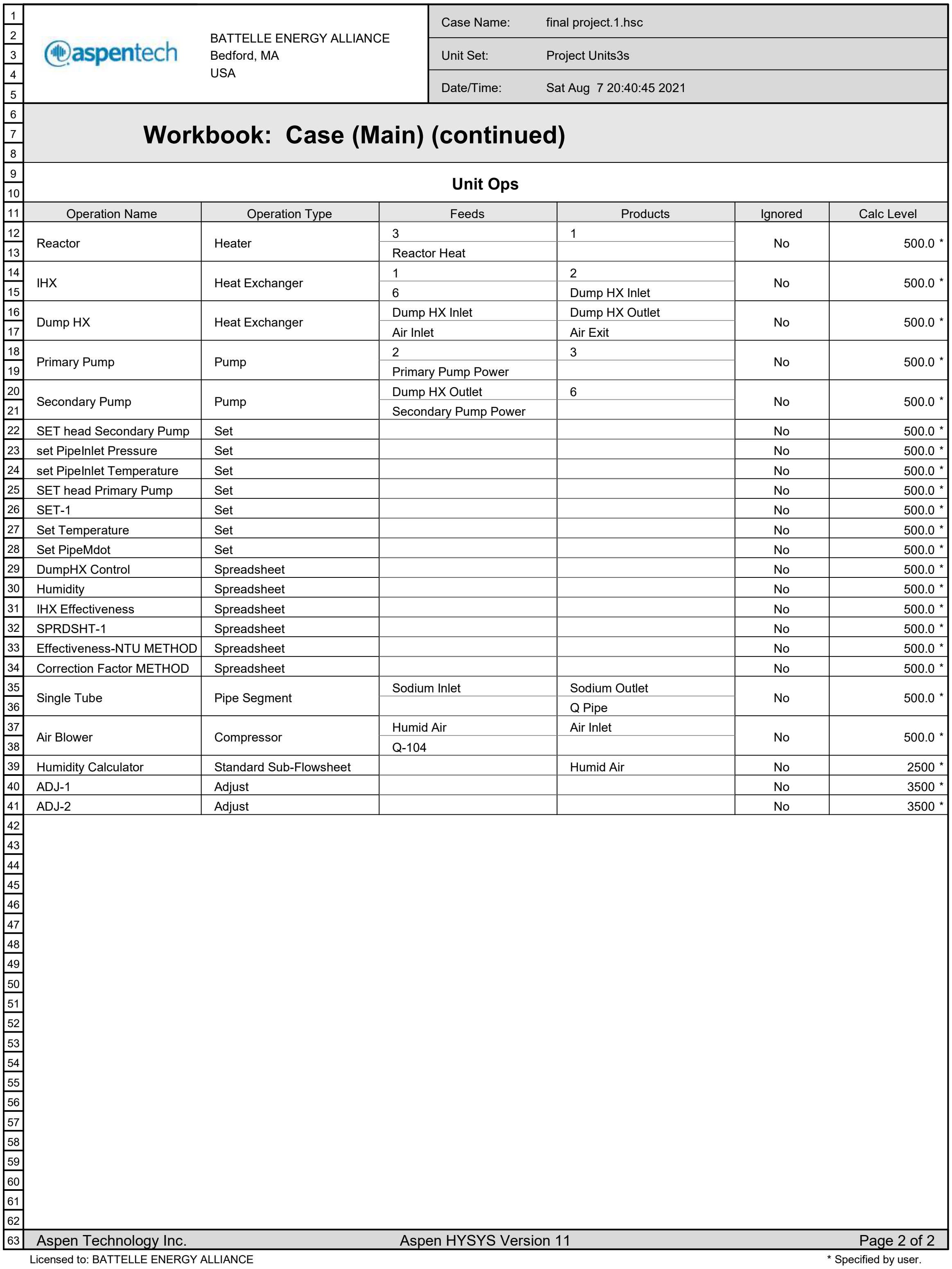

BATTELLE ENERGY ALLIANCE
Bedford, MA
USA

Case Name: final project.1.hsc
Unit Set: Project Units3s
Date/Time: Sat Aug 7 20:40:45 2021

Workbook: Case (Main) (continued)

Unit Ops

Operation Name	Operation Type	Feeds	Products	Ignored	Calc Level
Reactor	Heater	3 Reactor Heat	1	No	500.0 *
IHX	Heat Exchanger	1 6	2 Dump HX Inlet	No	500.0 *
Dump HX	Heat Exchanger	Dump HX Inlet Air Inlet	Dump HX Outlet Air Exit	No	500.0 *
Primary Pump	Pump	2 Primary Pump Power	3	No	500.0 *
Secondary Pump	Pump	Dump HX Outlet Secondary Pump Power	6	No	500.0 *
SET head Secondary Pump	Set			No	500.0 *
set PipeInlet Pressure	Set			No	500.0 *
set PipeInlet Temperature	Set			No	500.0 *
SET head Primary Pump	Set			No	500.0 *
SET-1	Set			No	500.0 *
Set Temperature	Set			No	500.0 *
Set PipeMdot	Set			No	500.0 *
DumpHX Control	Spreadsheet			No	500.0 *
Humidity	Spreadsheet			No	500.0 *
IHX Effectiveness	Spreadsheet			No	500.0 *
SPRDSHT-1	Spreadsheet			No	500.0 *
Effectiveness-NTU METHOD	Spreadsheet			No	500.0 *
Correction Factor METHOD	Spreadsheet			No	500.0 *
Single Tube	Pipe Segment	Sodium Inlet	Sodium Outlet Q Pipe	No	500.0 *
Air Blower	Compressor	Humid Air Q-104	Air Inlet	No	500.0 *
Humidity Calculator	Standard Sub-Flowsheet		Humid Air	No	2500 *
ADJ-1	Adjust			No	3500 *
ADJ-2	Adjust			No	3500 *

Aspen Technology Inc. Aspen HYSYS Version 11 Page 2 of 2

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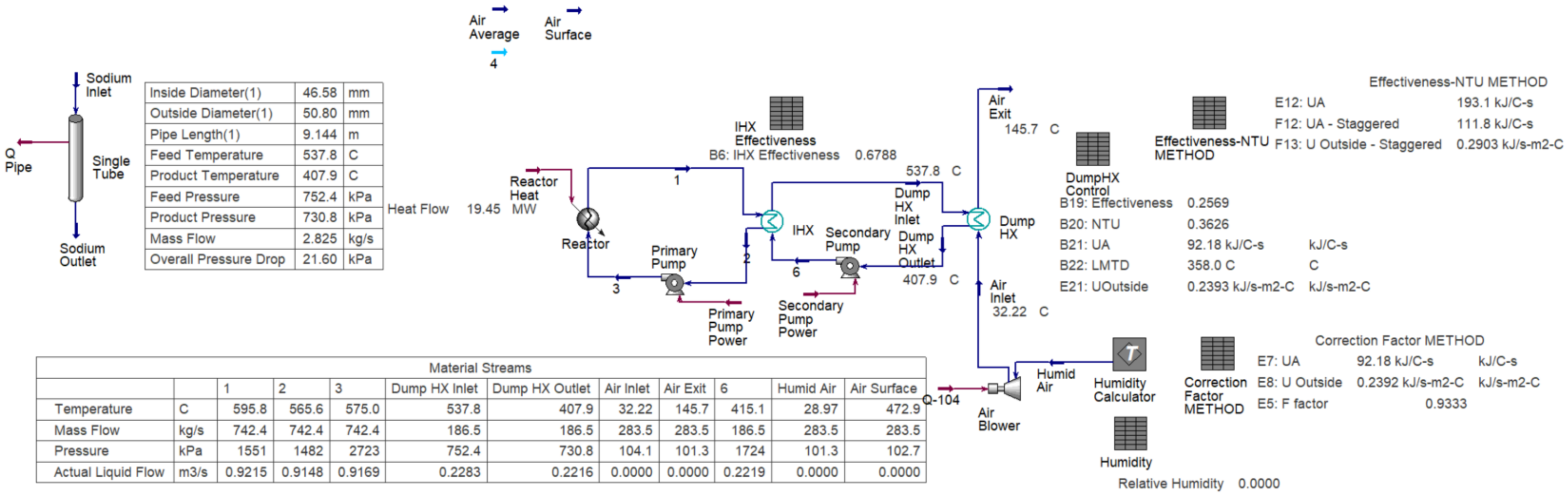
* Specified by user.



Inside Diameter(1)	46.58	mm
Outside Diameter(1)	50.80	mm
Pipe Length(1)	9.144	m
Feed Temperature	537.8	C
Product Temperature	407.9	C
Feed Pressure	752.4	kPa
Product Pressure	730.8	kPa
Mass Flow	2.825	kg/s
Overall Pressure Drop	21.60	kPa

B6: IHX Effectiveness 0.6788

Material Streams											
		1	2	3	Dump HX Inlet	Dump HX Outlet	Air Inlet	Air Exit	6	Humid Air	Air Surface
Temperature	C	595.8	565.6	575.0	537.8	407.9	32.22	145.7	415.1	28.97	472.9
Mass Flow	kg/s	742.4	742.4	742.4	186.5	186.5	283.5	283.5	186.5	283.5	283.5
Pressure	kPa	1551	1482	2723	752.4	730.8	104.1	101.3	1724	101.3	102.7
Actual Liquid Flow	m3/s	0.9215	0.9148	0.9169	0.2283	0.2216	0.0000	0.0000	0.2219	0.0000	0.0000

DumpHX Control

B19: Effectiveness	0.2569	
B20: NTU	0.3626	
B21: UA	92.18 kJ/C-s	kJ/C-s
B22: LMTD	358.0 C	C
E21: UOutside	0.2393 kJ/s-m2-C	kJ/s-m2-C

Effectiveness-NTU METHOD

E12: UA	193.1 kJ/C-s
F12: UA - Staggered	111.8 kJ/C-s
F13: U Outside - Staggered	0.2903 kJ/s-m2-C

Correction Factor METHOD

E7: UA	92.18 kJ/C-s	kJ/C-s
E8: U Outside	0.2392 kJ/s-m2-C	kJ/s-m2-C
E5: F factor	0.9333	

Relative Humidity 0.0000

Figure B.1: Final HYSYS model of 1/12 of the PRISM loop(final project.1)

Spreadsheet: DumpHX Control

Units Set: Project Units

CONNECTIONS

Imported Variables

Cell	Object	Variable Description	Value
B2	Material Stream: Air Inlet	Temperature	32.22 C
C2	Material Stream: Air Exit	Temperature	145.7 C
D2	Material Stream: Dump HX Inlet	Temperature	537.8 C
E2	Material Stream: Dump HX Outlet	Temperature	407.9 C
B4	Material Stream: Air Inlet	Pressure	104.1 kPa
B5	Material Stream: Air Inlet	Mass Heat Capacity	1.014 kJ/kg-K
B6	Material Stream: Air Inlet	Mass Density	1.183 kg/m3
B7	Material Stream: Air Inlet	Mass Enthalpy	7.024 kJ/kg
B8	Material Stream: Air Inlet	Mass Entropy	5.274 kJ/kg-K
B9	Material Stream: Air Inlet	Mass Flow	283.5 kg/s
C4	Material Stream: Air Exit	Pressure	101.3 kPa
C5	Material Stream: Air Exit	Mass Heat Capacity	1.037 kJ/kg-K
C6	Material Stream: Air Exit	Mass Density	0.8392 kg/m3
C7	Material Stream: Air Exit	Mass Enthalpy	123.4 kJ/kg
C8	Material Stream: Air Exit	Mass Entropy	5.606 kJ/kg-K
C9	Material Stream: Air Exit	Mass Flow	283.5 kg/s
D4	Material Stream: Dump HX Inlet	Pressure	752.4 kPa
D5	Material Stream: Dump HX Inlet	Mass Heat Capacity	1.364 kJ/kg-K
D6	Material Stream: Dump HX Inlet	Mass Density	816.9 kg/m3
D7	Material Stream: Dump HX Inlet	Mass Enthalpy	701.1 kJ/kg
D8	Material Stream: Dump HX Inlet	Mass Entropy	1.446 kJ/kg-K
D9	Material Stream: Dump HX Inlet	Mass Flow	186.5 kg/s
E4	Material Stream: Dump HX Outlet	Pressure	730.8 kPa
E5	Material Stream: Dump HX Outlet	Mass Heat Capacity	1.362 kJ/kg-K
E6	Material Stream: Dump HX Outlet	Mass Density	841.6 kg/m3
E7	Material Stream: Dump HX Outlet	Mass Enthalpy	524.1 kJ/kg
E8	Material Stream: Dump HX Outlet	Mass Entropy	1.208 kJ/kg-K
E9	Material Stream: Dump HX Outlet	Mass Flow	186.5 kg/s
B16	Heat Exchanger: Dump HX	Exchanger Cold Duty	33.00 MW
B17	Heat Exchanger: Dump HX	Exchanger Hot Duty	-33.00 MW

Exported Variables' Formula Results

Cell	Object	Variable Description	Value

PARAMETERS

Exportable Variables

Cell	Visible Name	Variable Description	Variable Type	Value
B3	B3:		---	305.4
B11	B11:		---	290.7
B12	B12:		---	254.2
B13	B13:		---	1.025
B14	B14:		---	1.363
B18	B18: Max Duty	Max Duty	Power	128.5 MW
B19	B19: Effectiveness	Effectiveness	---	0.2569
B20	B20: NTU	NTU	---	0.3626
B21	B21: UA	UA	UA	92.18 kJ/C-s
B22	B22: LMTD	LMTD	Temperature	358.0 C
C3	C3:		---	418.9

Spreadsheet: DumpHX Control (continued)

Units Set: Project Units

PARAMETERS

Exportable Variables

Cell	Visible Name	Variable Description	Variable Type	Value
D3	D3:		---	810.9
E3	E3:		---	681.1
E11	E11:		---	1.144
E16	E16:		Length	36.58 m
E17	E17: Pipe Length (Pipe Length_1)	Pipe Length (Pipe Length_1)	Length	5.080e-002 m
E18	E18: nn tubes	nn tubes	---	66.00
E21	E21: UOutside	UOutside	Ht. Tran. Coeff	0.2393 kJ/s-m2-C

User Variables

FORMULAS

Cell	Formula	Result
B3	=b2+273.15	305.4
B11	=b9*(b5+c5)/2	290.7
B12	=d9*(d5+e5)/2	254.2
B13	=(c7-b7)/(c2-b2)	1.025
B14	=(e7-d7)/(e2-d2)	1.363
B18	=B16/B19	128.5 MW
B19	=@if(b12<b11,(d2-e2)/(d2-b2),(c2-b2)/(d2-b2))	0.2569
B20	=@IF(B11<B12, -(1/E11)*@LN(E11*@LN(1-B19)+1),-@LN(1+(1/E11)*@LN(1-E11*B19)))	0.3626
B21	=@IF(B11<B12,B11*B20,B12*B20)	92.18 kJ/C-s
B22	=B16*1000/(B21)	358.0 C
C3	=c2+273.15	418.9
D3	=d2+273.15	810.9
E3	=e2+273.15	681.1
E11	=b11/b12	1.144
E21	=B21/(PI*E16*E17*e18)	0.2393 kJ/s-m2-C

SPREADSHEET

	A	B	C	D
1		Air, In *	Air, Out *	Na, In *
2	Temperature (C) *	32.22 C *	145.7 C *	537.8 C *
3	Temperature (K) *	305.4 *	418.9 *	810.9 *
4	Pressure (kPa) *	104.1 kPa *	101.3 kPa *	752.4 kPa *
5	Cp (kJ/kg*K) *	1.014 kJ/kg-K *	1.037 kJ/kg-K *	1.364 kJ/kg-K *
6	Density (kg/m3) *	1.183 kg/m3 *	0.8392 kg/m3 *	816.9 kg/m3 *
7	Enthalpy (kJ/kg) *	7.024 kJ/kg *	123.4 kJ/kg *	701.1 kJ/kg *
8	Entropy (kJ/kg*K) *	5.274 kJ/kg-K *	5.606 kJ/kg-K *	1.446 kJ/kg-K *
9	Mass Flow Rate (kg/s) *	283.5 kg/s *	283.5 kg/s *	186.5 kg/s *
10				
11	Ccold *	290.7 *		Cr *
12	Chot *	254.2 *		
13	Cp Cold *	1.025 *		
14	Cp Hot *	1.363 *		
15	HX Information *			
16	HX Duty Cold Side (MW) *	33.00 MW *		Length of Pipes *
17	HX Duty Hot Side (MW) *	-33.00 MW *		Diameter of pipes *
18	Maximum Duty (MW) *	128.5 MW *	<empty> *	
19	Effectiveness *	0.2569 *		

* Specified by user.

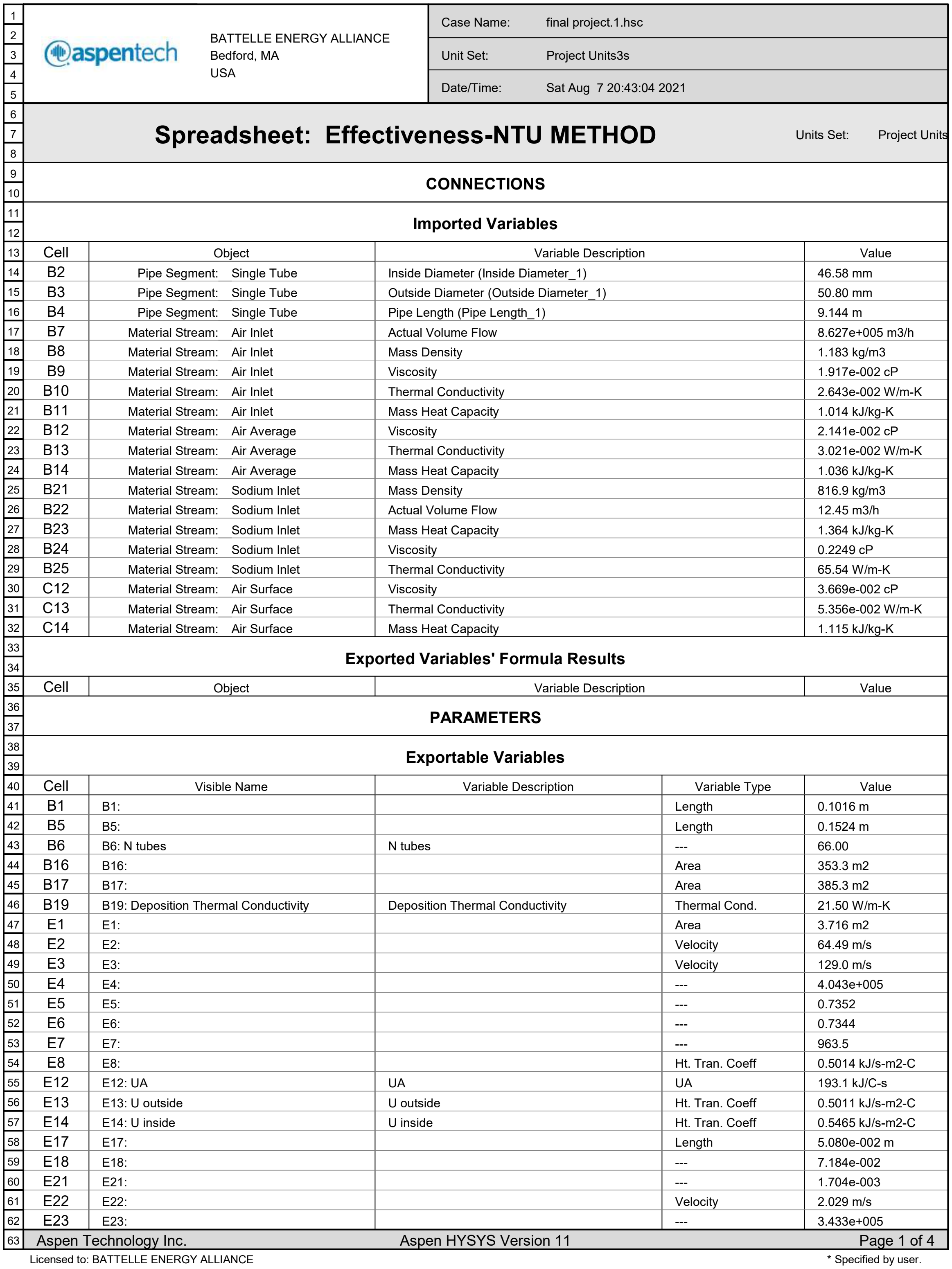
Spreadsheet: DumpHX Control (continued)

Units Set: Project Units

SPREADSHEET

20	NTU *	0.3626 *		
21	UA actual *	92.18 kJ/C-s *		U *
22	LMTD actual *	358.0 C *		
23				
	E			
1	Na, Out *			
2	407.9 C *			
3	681.1 *			
4	730.8 kPa *			
5	1.362 kJ/kg-K *			
6	841.6 kg/m3 *			
7	524.1 kJ/kg *			
8	1.208 kJ/kg-K *			
9	186.5 kg/s *			
10				
11	1.144 *			
12				
13				
14				
15				
16	36.58 m *			
17	5.080e-002 m *			
18	66.00 *			
19				
20				
21	0.2393 kJ/s-m2-C *			
22				
23				

* Specified by user.



BATTELLE ENERGY ALLIANCE
Bedford, MA
USA

Case Name:	final project.1.hsc
Unit Set:	Project Units3s
Date/Time:	Sat Aug 7 20:43:04 2021

Spreadsheet: Effectiveness-NTU METHOD

Units Set: Project Units

CONNECTIONS

Imported Variables

Cell	Object		Variable Description	Value
B2	Pipe Segment:	Single Tube	Inside Diameter (Inside Diameter_1)	46.58 mm
B3	Pipe Segment:	Single Tube	Outside Diameter (Outside Diameter_1)	50.80 mm
B4	Pipe Segment:	Single Tube	Pipe Length (Pipe Length_1)	9.144 m
B7	Material Stream:	Air Inlet	Actual Volume Flow	8.627e+005 m3/h
B8	Material Stream:	Air Inlet	Mass Density	1.183 kg/m3
B9	Material Stream:	Air Inlet	Viscosity	1.917e-002 cP
B10	Material Stream:	Air Inlet	Thermal Conductivity	2.643e-002 W/m-K
B11	Material Stream:	Air Inlet	Mass Heat Capacity	1.014 kJ/kg-K
B12	Material Stream:	Air Average	Viscosity	2.141e-002 cP
B13	Material Stream:	Air Average	Thermal Conductivity	3.021e-002 W/m-K
B14	Material Stream:	Air Average	Mass Heat Capacity	1.036 kJ/kg-K
B21	Material Stream:	Sodium Inlet	Mass Density	816.9 kg/m3
B22	Material Stream:	Sodium Inlet	Actual Volume Flow	12.45 m3/h
B23	Material Stream:	Sodium Inlet	Mass Heat Capacity	1.364 kJ/kg-K
B24	Material Stream:	Sodium Inlet	Viscosity	0.2249 cP
B25	Material Stream:	Sodium Inlet	Thermal Conductivity	65.54 W/m-K
C12	Material Stream:	Air Surface	Viscosity	3.669e-002 cP
C13	Material Stream:	Air Surface	Thermal Conductivity	5.356e-002 W/m-K
C14	Material Stream:	Air Surface	Mass Heat Capacity	1.115 kJ/kg-K

Exported Variables' Formula Results

Cell	Object	Variable Description	Value

PARAMETERS

Exportable Variables

Cell	Visible Name	Variable Description	Variable Type	Value
B1	B1:		Length	0.1016 m
B5	B5:		Length	0.1524 m
B6	B6: N tubes	N tubes	---	66.00
B16	B16:		Area	353.3 m2
B17	B17:		Area	385.3 m2
B19	B19: Deposition Thermal Conductivity	Deposition Thermal Conductivity	Thermal Cond.	21.50 W/m-K
E1	E1:		Area	3.716 m2
E2	E2:		Velocity	64.49 m/s
E3	E3:		Velocity	129.0 m/s
E4	E4:		---	4.043e+005
E5	E5:		---	0.7352
E6	E6:		---	0.7344
E7	E7:		---	963.5
E8	E8:		Ht. Tran. Coeff	0.5014 kJ/s-m2-C
E12	E12: UA	UA	UA	193.1 kJ/C-s
E13	E13: U outside	U outside	Ht. Tran. Coeff	0.5011 kJ/s-m2-C
E14	E14: U inside	U inside	Ht. Tran. Coeff	0.5465 kJ/s-m2-C
E17	E17:		Length	5.080e-002 m
E18	E18:		---	7.184e-002
E21	E21:		---	1.704e-003
E22	E22:		Velocity	2.029 m/s
E23	E23:		---	3.433e+005

* Specified by user.

BATTELLE ENERGY ALLIANCE
Bedford, MA
USA

Case Name: final project.1.hsc
Unit Set: Project Units3s
Date/Time: Sat Aug 7 20:43:04 2021

Spreadsheet: Effectiveness-NTU METHOD (continuec

Units Set: Project Units

PARAMETERS

Exportable Variables

Cell	Visible Name	Variable Description	Variable Type	Value
E24	E24:		---	4.681e-003
E25	E25:		---	1607
E26	E26:		---	13.14
E27	E27:		Ht. Tran. Coeff	18.49 kJ/s-m2-C
F3	F3:		Velocity	64.49 m/s
F4	F4:		---	2.021e+005
F5	F5:		---	0.7344
F6	F6:		---	0.7638
F7	F7:		---	558.0
F8	F8:		Ht. Tran. Coeff	0.2903 kJ/s-m2-C
F12	F12: UA - Staggered	UA - Staggered	UA	111.8 kJ/C-s
F13	F13: U Outside - Staggered	U Outside - Staggered	Ht. Tran. Coeff	0.2903 kJ/s-m2-C
F14	F14: U Inside - Staggered	U Inside - Staggered	Ht. Tran. Coeff	0.3165 kJ/s-m2-C
F18	F18:		---	7.620e-002

User Variables

FORMULAS

Cell	Formula	Result
B16	=PI*(b2/1000)*4*b4*b6	353.3 m2
B17	=PI*(b3/1000)*4*b4*b6	385.3 m2
E1	=b4*4*b5-(b3/1000)*4*b4	3.716 m2
E2	=b7/3600/e1	64.49 m/s
E3	=b1/(b1-b3/1000)*e2	129.0 m/s
E4	=b8*e3*(b3/1000)/(b9/1000)	4.043e+005
E5	=(b9/1000)*(b11*1000)/b10	0.7352
E6	=(b12/1000)*(b14*1000)/b13	0.7344
E7	=0.021*e4^0.84*e5^0.36*(e5/e6)^0.25	963.5
E8	=e7*b10/(b3/1000)*1/1000	0.5014 kJ/s-m2-C
E12	=(1/(e27*b16)*@ln(b3/b2)/(2*PI*b19/1000*4*b4)+1/(e8*b17))^(-1)	193.1 kJ/C-s
E13	=e12/b17	0.5011 kJ/s-m2-C
E14	=e12/b16	0.5465 kJ/s-m2-C
E17	=1/2*b1	5.080e-002 m
E18	=(e17^2+(b1/2)^2)^0.5	7.184e-002
E21	=PI/4*(b2/1000)^2	1.704e-003
E22	=(b22/3600)/e21	2.029 m/s
E23	=b21*e22*(b2/1000)/(b24/1000)	3.433e+005
E24	=(b24/1000)*(b23*1000)/b25	4.681e-003
E25	=e23*e24	1607
E26	=4.85+0.0185*e25^0.827	13.14
E27	=e26*b25/(b2/1000)/1000	18.49 kJ/s-m2-C
F3	=b1/(2*(2*e17-b3/1000))*e2	64.49 m/s
F4	=b8*f3*(b3/1000)/(b9/1000)	2.021e+005
F5	=(b12/1000)*(b14*1000)/b13	0.7344
F6	=(c12/1000)*(c14*1000)/c13	0.7638
F7	=0.022*f4^0.84*f5^0.36*(f5/f6)^0.25	558.0
F8	=f7*b10/(b3/1000)*1/1000	0.2903 kJ/s-m2-C
F12	=(1/(e27*b16)*@ln(b3/b2)/(2*PI*b19/1000*4*b4)+1/(f8*b17))^(-1)	111.8 kJ/C-s
F13	=f12/b17	0.2903 kJ/s-m2-C

* Specified by user.

BATTELLE ENERGY ALLIANCE
Bedford, MA
USA

Case Name:	final project.1.hsc
Unit Set:	Project Units3s
Date/Time:	Sat Aug 7 20:43:04 2021

Spreadsheet: Effectiveness-NTU METHOD (continuec

Units Set: Project Units

FORMULAS

Cell	Formula	Result
F14	=f12/b16	0.3165 kJ/s-m2-C
F18	=(b1+b3/1000)/2	7.620e-002

SPREADSHEET

	A	B	C	D
1	S_T *	0.1016 m *	<empty> *	HX Area *
2	Dinside *	46.58 mm *		Velocity *
3	Doutside *	50.80 mm *		Max Velocity *
4	Pass Length of straight section *	9.144 m *		Re_D Max *
5	Height of Area Section *	0.1524 m *		Pr *
6	N of Tubes *	66.00 *		Pr_s *
7	Air Volume Flow *	8.627e+005 m3/h *		Ave Nu_D *
8	Air Density *	1.183 kg/m3 *		h outside *
9	Air Viscosity *	1.917e-002 cP *		
10	Air Thermal Conductivity *	2.643e-002 W/m-K *		
11	Air Mass Heat Capacity *	1.014 kJ/kg-K *		
12	Ave Air Viscosity *	2.141e-002 cP *	3.669e-002 cP *	UA *
13	Ave Air Thermal Cond *	3.021e-002 W/m-K *	5.356e-002 W/m-K *	U outside *
14	Ave Air Mass Heat Cp *	1.036 kJ/kg-K *	1.115 kJ/kg-K *	Uinside *
15				
16	Inside Area *	353.3 m2 *		
17	Outside Area *	385.3 m2 *	<empty> *	S_L *
18		<empty> *	<empty> *	S_D *
19	Thermal Cond Pipe *	21.50 W/m-K *	<empty> *	
20		<empty> *	<empty> *	
21	Sodium mass density *	816.9 kg/m3 *	<empty> *	XArea *
22	Sodium Volume Flow *	12.45 m3/h *	<empty> *	Velocity *
23	Sodium mass heat Cp *	1.364 kJ/kg-K *	<empty> *	Reynolds Number *
24	Sodium Viscosity *	0.2249 cP *	<empty> *	Pr *
25	Sodium Thermal Cond *	65.54 W/m-K *	<empty> *	Pe *
26		<empty> *	<empty> *	NU_D *
27		<empty> *	<empty> *	hinside *

	E	F		
1	3.716 m2 *			
2	64.49 m/s *			
3	129.0 m/s *	64.49 m/s *		
4	4.043e+005 *	2.021e+005 *		
5	0.7352 *	0.7344 *		
6	0.7344 *	0.7638 *		
7	963.5 *	558.0 *		
8	0.5014 kJ/s-m2-C *	0.2903 kJ/s-m2-C *		
9				
10	<empty> *	<empty> *		
11				
12	193.1 kJ/C-s *	111.8 kJ/C-s *		
13	0.5011 kJ/s-m2-C *	0.2903 kJ/s-m2-C *		
14	0.5465 kJ/s-m2-C *	0.3165 kJ/s-m2-C *		
15				
16				
17	5.080e-002 m *			
18	7.184e-002 *	7.620e-002 *		

* Specified by user.

aspentech

BATTELLE ENERGY ALLIANCE
Bedford, MA
USA

Case Name:	final project.1.hsc
Unit Set:	Project Units3s
Date/Time:	Sat Aug 7 20:43:04 2021

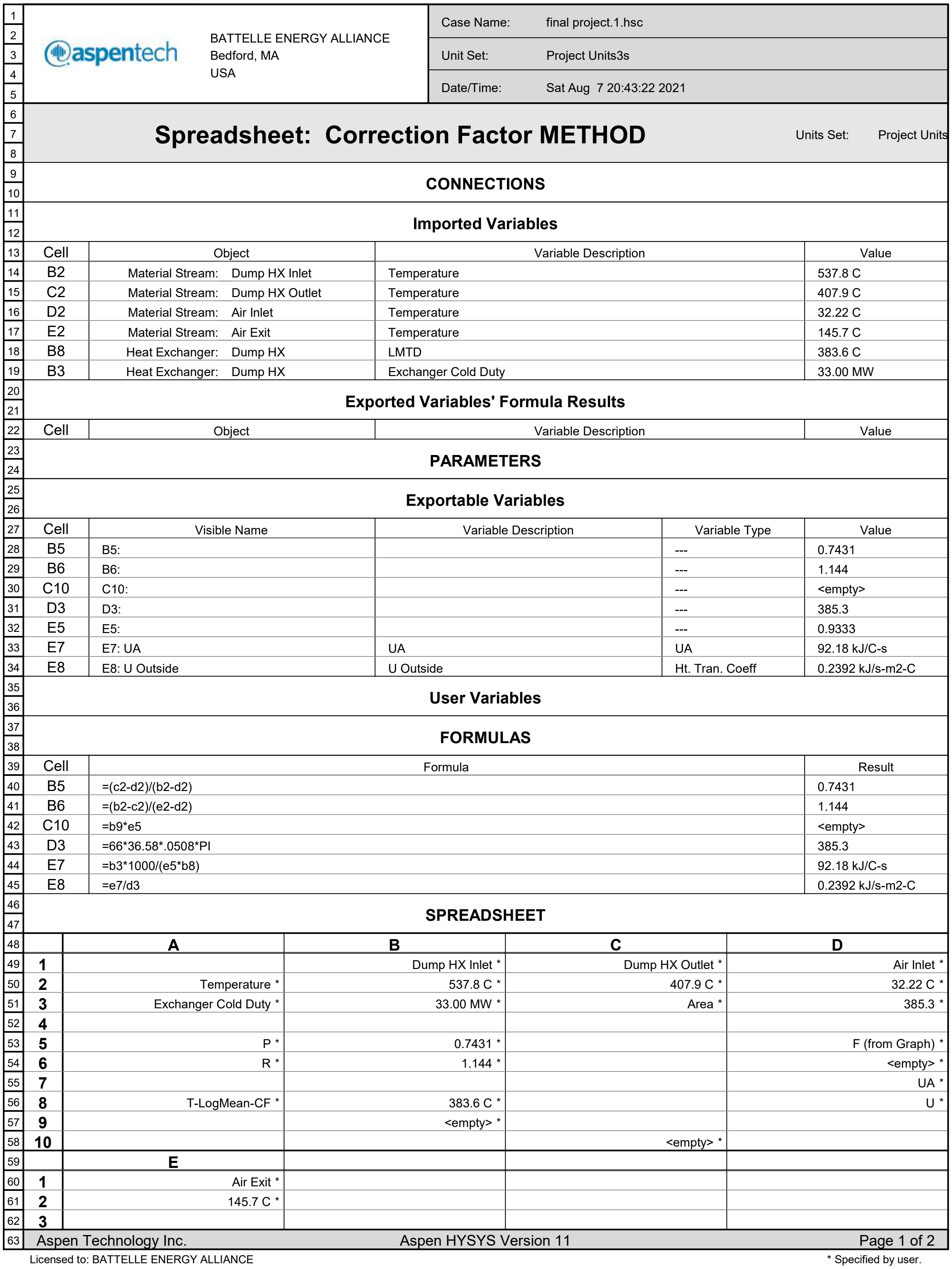
Spreadsheet: Effectiveness-NTU METHOD (continuec

Units Set: Project Units

SPREADSHEET

19				
20				
21	1.704e-003 *			
22	2.029 m/s *			
23	3.433e+005 *			
24	4.681e-003 *			
25	1607 *			
26	13.14 *			
27	18.49 kJ/s-m2-C *			

* Specified by user.



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BATTELLE ENERGY ALLIANCE
Bedford, MA
USA

Case Name:	final project.1.hsc
Unit Set:	Project Units3s
Date/Time:	Sat Aug 7 20:43:22 2021

Spreadsheet: Correction Factor METHOD

Units Set: Project Units

CONNECTIONS

Imported Variables

Cell	Object	Variable Description	Value
B2	Material Stream: Dump HX Inlet	Temperature	537.8 C
C2	Material Stream: Dump HX Outlet	Temperature	407.9 C
D2	Material Stream: Air Inlet	Temperature	32.22 C
E2	Material Stream: Air Exit	Temperature	145.7 C
B8	Heat Exchanger: Dump HX	LMTD	383.6 C
B3	Heat Exchanger: Dump HX	Exchanger Cold Duty	33.00 MW

Exported Variables' Formula Results

Cell	Object	Variable Description	Value

PARAMETERS

Exportable Variables

Cell	Visible Name	Variable Description	Variable Type	Value
B5	B5:		---	0.7431
B6	B6:		---	1.144
C10	C10:		---	<empty>
D3	D3:		---	385.3
E5	E5:		---	0.9333
E7	E7: UA	UA	UA	92.18 kJ/C-s
E8	E8: U Outside	U Outside	Ht. Tran. Coeff	0.2392 kJ/s-m2-C

User Variables

FORMULAS

Cell	Formula	Result
B5	=(c2-d2)/(b2-d2)	0.7431
B6	=(b2-c2)/(e2-d2)	1.144
C10	=b9*e5	<empty>
D3	=66*36.58*.0508*PI	385.3
E7	=b3*1000/(e5*b8)	92.18 kJ/C-s
E8	=e7/d3	0.2392 kJ/s-m2-C

SPREADSHEET

	A	B	C	D
1		Dump HX Inlet *	Dump HX Outlet *	Air Inlet *
2	Temperature *	537.8 C *	407.9 C *	32.22 C *
3	Exchanger Cold Duty *	33.00 MW *	Area *	385.3 *
4				
5	P *	0.7431 *		F (from Graph) *
6	R *	1.144 *		<empty> *
7				UA *
8	T-LogMean-CF *	383.6 C *		U *
9		<empty> *		
10			<empty> *	

	E
1	Air Exit *
2	145.7 C *
3	

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* Specified by user.

Spreadsheet: Correction Factor METHOD (continued)

Units Set: Project Units

SPREADSHEET

4				
5	0.9333 *			
6	<empty> *			
7	92.18 kJ/C-s *			
8	0.2392 kJ/s-m2-C *			
9				
10				

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BATTELLE ENERGY ALLIANCE
Bedford, MA
USA

Case Name:	final project.1.hsc
Unit Set:	Project Units3s
Date/Time:	Sat Aug 7 20:43:40 2021

Spreadsheet: Humidity

Units Set: ProjectUnits

CONNECTIONS

Imported Variables

Cell	Object	Variable Description	Value
B6	Material Stream: Water Vapor @TPL1	Mass Flow	0.0000 kg/s
B5	Material Stream: Dry Air @TPL1	Mass Flow	283.5 kg/s
B2	Material Stream: Saturated Air @TPL1	Master Comp Mole Frac (H2O)	0.0393
B1	Material Stream: Humid Air @TPL1	Master Comp Mole Frac (H2O)	0.0000

Exported Variables' Formula Results

Cell	Object	Variable Description	Value

PARAMETERS

Exportable Variables

Cell	Visible Name	Variable Description	Variable Type	Value
B3	B3: Relative Humidity	Relative Humidity	---	0.0000
B4	B4: Desired Humidity	Desired Humidity	---	0.0000
B7	B7:		---	0.0000

User Variables

FORMULAS

Cell	Formula	Result
B3	=b1/b2	0.0000
B7	=b6/b5	0.0000

SPREADSHEET

	A	B	C	D
1	Mole Fraction of H2O in Humid Air *	0.0000 *		
2	Mole Fraction of H2O in Saturated Air *	0.0393 *		
3	Relative Humidity *	0.0000 *		
4	Desired Humidity *	0.0000 *		
5	Mass Flow of Dry Air *	283.5 kg/s *		
6	Mass Flow of Water Vapor *	0.0000 kg/s *		
7	Specific Humidity *	0.0000 *		
8				
9				
10				

* Specified by user.

BATTELLE ENERGY ALLIANCE
Bedford, MA
USA

Case Name:	final project.1.hsc
Unit Set:	Project Units3s
Date/Time:	Sat Aug 7 20:42:39 2021

Spreadsheet: IHX Effectiveness

Units Set: ProjectUnits

CONNECTIONS

Imported Variables

Cell	Object	Variable Description	Value
B2	Material Stream: 1	Temperature	595.8 C
B3	Material Stream: 1	Mass Heat Capacity	1.368 kJ/kg-K
B4	Material Stream: 1	Mass Flow	742.4 kg/s
C2	Material Stream: 2	Temperature	565.6 C
C3	Material Stream: 2	Mass Heat Capacity	1.366 kJ/kg-K
C4	Material Stream: 2	Mass Flow	742.4 kg/s
D2	Material Stream: 6	Temperature	415.1 C
D3	Material Stream: 6	Mass Heat Capacity	1.362 kJ/kg-K
D4	Material Stream: 6	Mass Flow	186.5 kg/s
E2	Material Stream: Dump HX Inlet	Temperature	537.8 C
E3	Material Stream: Dump HX Inlet	Mass Heat Capacity	1.364 kJ/kg-K
E4	Material Stream: Dump HX Inlet	Mass Flow	186.5 kg/s

Exported Variables' Formula Results

Cell	Object	Variable Description	Value

PARAMETERS

Exportable Variables

Cell	Visible Name	Variable Description	Variable Type	Value
B6	B6: IHX Effectiveness	IHX Effectiveness	---	0.6788
C5	C5:		---	1015
E5	E5:		---	254.2

User Variables

FORMULAS

Cell	Formula	Result
B6	=@if(c5<e5,(b2-c2)/(b2-d2),(e2-d2)/(b2-d2))	0.6788
C5	=b4*(b3+c3)/2	1015
E5	=d4*(d3+e3)/2	254.2

SPREADSHEET

	A	B	C	D
1		Inlet 1 *	Outlet 2 *	Inlet 6 *
2	Temperature (C) *	595.8 C *	565.6 C *	415.1 C *
3	Cp *	1.368 kJ/kg-K *	1.366 kJ/kg-K *	1.362 kJ/kg-K *
4	Mass Flow *	742.4 kg/s *	742.4 kg/s *	186.5 kg/s *
5		mdot Cp Hot *	1015 *	mdot Cp Cold *
6	Effectiveness *	0.6788 *		
7				
8				
9				
10				

	E
1	Outlet 4 *
2	537.8 C *
3	1.364 kJ/kg-K *
4	186.5 kg/s *

* Specified by user.

Spreadsheet: IHX Effectiveness (continued)

Units Set: ProjectUnits

SPREADSHEET

5	254.2 *			
6				
7				
8				
9				
10				

* Specified by user.

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BATTELLE ENERGY ALLIANCE
Bedford, MA
USA

Case Name: final project.1.hsc
Unit Set: Project Units3s
Date/Time: Sat Aug 7 20:41:58 2021

Workbook: Humidity Calculator (TPL1)

Material Streams

Fluid Pkg: All

Name	Water Vapor	Dry Air	Humid Air	Water 2	Air 2
Vapour Fraction	---	1.0000	1.0000	---	---
Temperature (C)	---	28.97	28.97	---	---
Pressure (kPa)	101.3	101.3	101.3	101.3	101.3
Molar Flow (kgmole/h)	0.0000	3.538e+004	3.538e+004	1.998e+004	1.248e+004
Mass Flow (kg/s)	0.0000 *	283.5	283.5	100.0 *	100.0 *
Liquid Volume Flow (m3/s)	0.0000	0.3277	0.3277	0.1002	0.1156
Heat Flow (MW)	---	1.059	1.059	---	---
Name	1	Saturated Air	Liquid Water		
Vapour Fraction	0.4001	1.0000	0.0000		
Temperature (C)	28.97	28.97	28.97		
Pressure (kPa)	101.3	101.3	101.3		
Molar Flow (kgmole/h)	3.246e+004	1.299e+004	1.947e+004		
Mass Flow (kg/s)	200.0	102.6	97.45		
Liquid Volume Flow (m3/s)	0.2158	0.1182	9.764e-002		
Heat Flow (MW)	-1580	-33.92	-1547		

Compositions

Fluid Pkg: All

Name	Water Vapor	Dry Air	Humid Air	Water 2	Air 2
Comp Mole Frac (Sodium*)	***	***	***	***	***
Comp Mole Frac (Nitrogen)	0.0000 *	0.7900 *	0.7900	0.0000 *	0.7900 *
Comp Mole Frac (Oxygen)	0.0000 *	0.2100 *	0.2100	0.0000 *	0.2100 *
Comp Mole Frac (H2O)	1.0000 *	0.0000 *	0.0000	1.0000 *	0.0000 *
Comp Mole Frac (Sodium)	***	***	***	***	***
Name	1	Saturated Air	Liquid Water		
Comp Mole Frac (Sodium*)	***	***	***		
Comp Mole Frac (Nitrogen)	0.3037	0.7589	0.0000		
Comp Mole Frac (Oxygen)	0.0807	0.2017	0.0000		
Comp Mole Frac (H2O)	0.6156	0.0393	1.0000		
Comp Mole Frac (Sodium)	***	***	***		

Energy Streams

Fluid Pkg: All

Name					
Heat Flow (MW)					

Unit Ops

Operation Name	Operation Type	Feeds	Products	Ignored	Calc Level
MIX-100	Mixer	Water Vapor Dry Air	Humid Air	No	500.0 *
MIX-101	Mixer	Water 2 Air 2	1	No	500.0 *
Set Temp	Set			No	500.0 *
Set Pressure	Set			No	500.0 *
V-100	Separator	1	Liquid Water Saturated Air	No	500.0 *
ADJ-1	Adjust			No	3500 *

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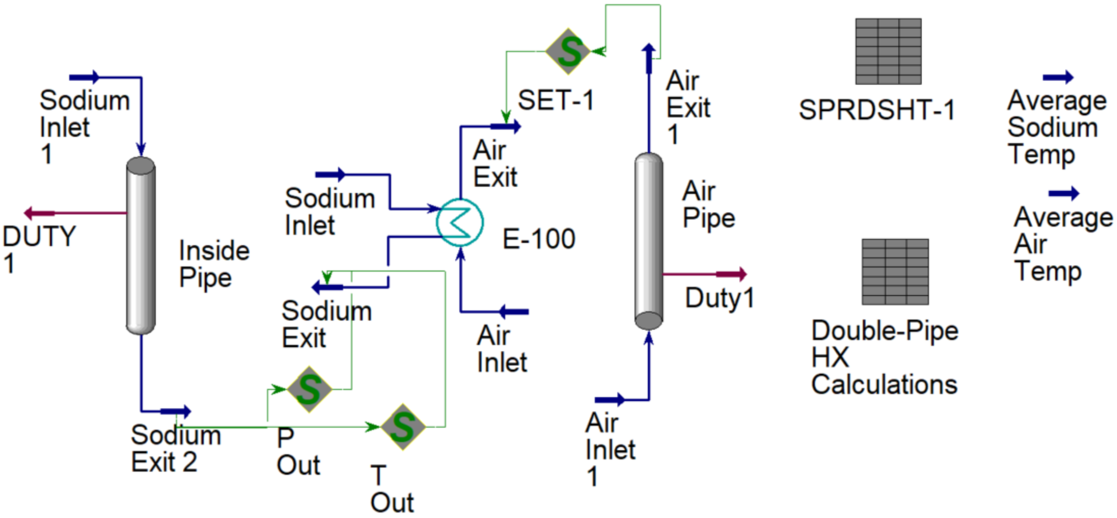

Figure B.2: Annulus Heat Exchanger model designed in HYSYS for 25 tubes

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BATTELLE ENERGY ALLIANCE
Bedford, MA
USA

Case Name:	Annulus HX.25Tube.hsc
Unit Set:	Project Units3i
Date/Time:	Sat Aug 7 18:59:34 2021

Workbook: Case (Main)

Material Streams

Fluid Pkg: All

Name		Sodium Inlet	Sodium Exit	Air Inlet	Air Exit	Sodium Inlet 1
Vapour Fraction		0.0000	0.0000	1.0000	1.0000	0.0000
Temperature	(C)	537.8 *	462.4	32.22 *	148.0	537.8 *
Pressure	(kPa)	752.2 *	679.2	109.6 *	52.15	752.2 *
Molar Flow	(kgmole/h)	3.962e+004	3.962e+004	3.525e+004	3.525e+004	584.1
Mass Flow	(kg/s)	253.0 *	253.0	283.5 *	283.5	3.730 *
Liquid Volume Flow	(m3/s)	0.2692	0.2692	0.3223	0.3223	3.970e-003
Heat Flow	(MW)	238.6	205.6	1.947	34.95	3.518
Name		**Sodium Exit 2**	**Air Exit 1**	**Air Inlet 1**	**Average Sodium Tem**	**Average Air Temp**
Vapour Fraction		0.0000	1.0000	1.0000	0.0000	1.0000
Temperature	(C)	435.4	148.1	32.22 *	434.9 *	147.9 *
Pressure	(kPa)	751.5	109.6	109.6 *	752.2 *	109.6 *
Molar Flow	(kgmole/h)	584.1	705.1	705.1	2.920e+004	3.525e+004
Mass Flow	(kg/s)	3.730	5.670	5.670 *	186.5 *	283.5 *
Liquid Volume Flow	(m3/s)	3.970e-003	6.446e-003	6.446e-003	0.1985	0.3223
Heat Flow	(MW)	2.858	0.6989	3.895e-002	142.7	34.89

Compositions

Fluid Pkg: All

Name	Sodium Inlet	Sodium Exit	Air Inlet	Air Exit	Sodium Inlet 1
Comp Mole Frac (Sodium)	1.0000 *	1.0000	***	***	1.0000 *
Comp Mole Frac (Air)	***	***	1.0000 *	1.0000	***
Name	**Sodium Exit 2**	**Air Exit 1**	**Air Inlet 1**	**Average Sodium Tem**	**Average Air Temp**
Comp Mole Frac (Sodium)	1.0000	***	***	1.0000 *	***
Comp Mole Frac (Air)	***	1.0000	1.0000 *	***	1.0000 *

Energy Streams

Fluid Pkg: All

Name		DUTY 1	Duty1			
Heat Flow	(MW)	0.6600 *	-0.6600 *			

Unit Ops

Operation Name	Operation Type	Feeds	Products	Ignored	Calc Level
E-100	Heat Exchanger	Sodium Inlet Air Inlet	Sodium Exit Air Exit	No	500.0 *
Inside Pipe	Pipe Segment	Sodium Inlet 1	Sodium Exit 2 DUTY 1	No	500.0 *
Air Pipe	Pipe Segment	Air Inlet 1	Air Exit 1 Duty1	No	500.0 *
P Out	Set			Yes	500.0 *
SET-1	Set			Yes	500.0 *
T Out	Set			Yes	500.0 *
SPRDSHT-1	Spreadsheet			No	500.0 *
Double-Pipe HX Calculations	Spreadsheet			No	500.0 *

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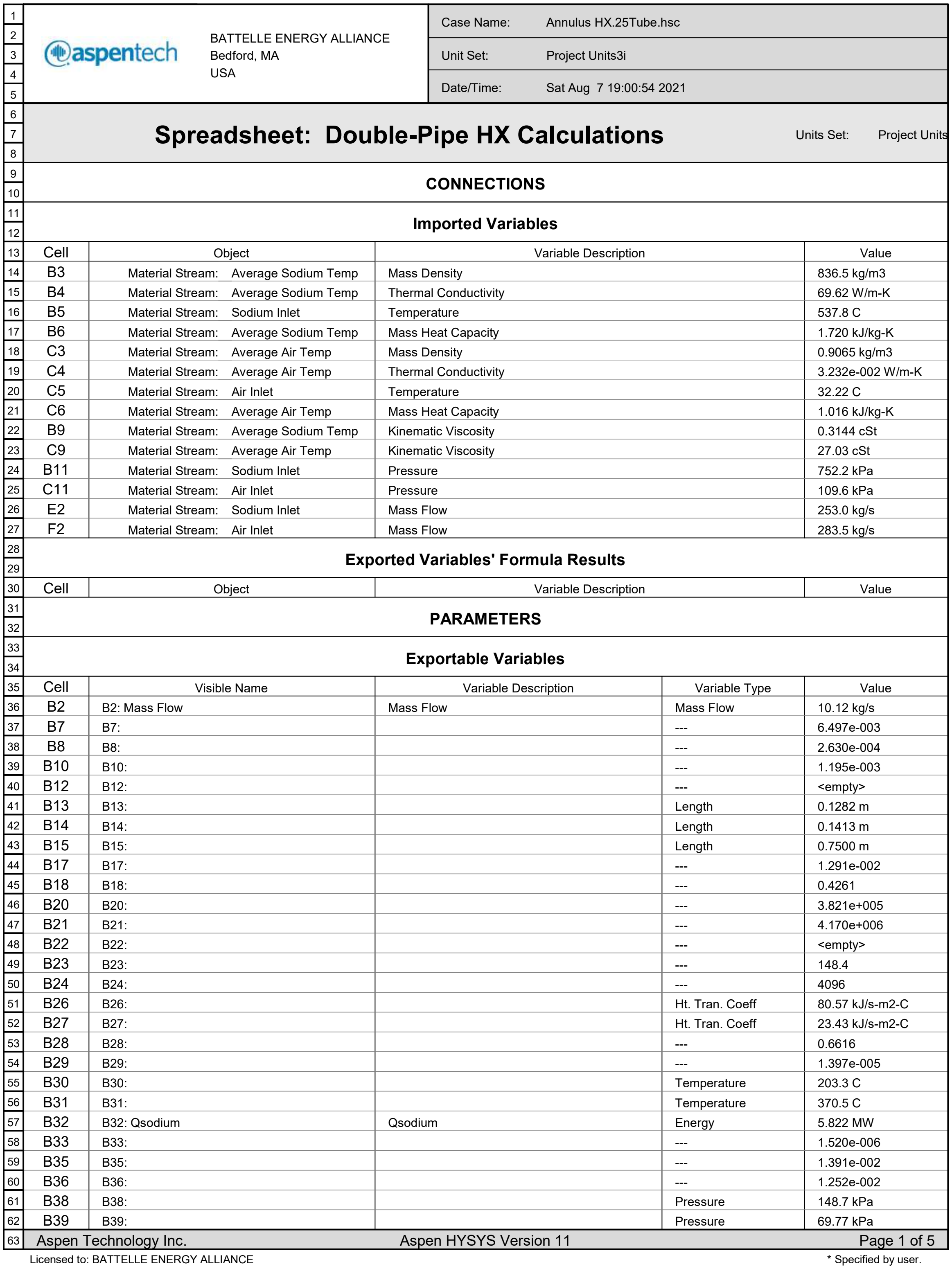

BATTELLE ENERGY ALLIANCE
Bedford, MA
USA

Case Name:	Annulus HX.25Tube.hsc
Unit Set:	Project Units3i
Date/Time:	Sat Aug 7 19:00:54 2021

Spreadsheet: Double-Pipe HX Calculations

Units Set: Project Units

CONNECTIONS

Imported Variables

Cell	Object	Variable Description	Value
B3	Material Stream: Average Sodium Temp	Mass Density	836.5 kg/m3
B4	Material Stream: Average Sodium Temp	Thermal Conductivity	69.62 W/m-K
B5	Material Stream: Sodium Inlet	Temperature	537.8 C
B6	Material Stream: Average Sodium Temp	Mass Heat Capacity	1.720 kJ/kg-K
C3	Material Stream: Average Air Temp	Mass Density	0.9065 kg/m3
C4	Material Stream: Average Air Temp	Thermal Conductivity	3.232e-002 W/m-K
C5	Material Stream: Air Inlet	Temperature	32.22 C
C6	Material Stream: Average Air Temp	Mass Heat Capacity	1.016 kJ/kg-K
B9	Material Stream: Average Sodium Temp	Kinematic Viscosity	0.3144 cSt
C9	Material Stream: Average Air Temp	Kinematic Viscosity	27.03 cSt
B11	Material Stream: Sodium Inlet	Pressure	752.2 kPa
C11	Material Stream: Air Inlet	Pressure	109.6 kPa
E2	Material Stream: Sodium Inlet	Mass Flow	253.0 kg/s
F2	Material Stream: Air Inlet	Mass Flow	283.5 kg/s

Exported Variables' Formula Results

Cell	Object	Variable Description	Value

PARAMETERS

Exportable Variables

Cell	Visible Name	Variable Description	Variable Type	Value
B2	B2: Mass Flow	Mass Flow	Mass Flow	10.12 kg/s
B7	B7:		---	6.497e-003
B8	B8:		---	2.630e-004
B10	B10:		---	1.195e-003
B12	B12:		---	<empty>
B13	B13:		Length	0.1282 m
B14	B14:		Length	0.1413 m
B15	B15:		Length	0.7500 m
B17	B17:		---	1.291e-002
B18	B18:		---	0.4261
B20	B20:		---	3.821e+005
B21	B21:		---	4.170e+006
B22	B22:		---	<empty>
B23	B23:		---	148.4
B24	B24:		---	4096
B26	B26:		Ht. Tran. Coeff	80.57 kJ/s-m2-C
B27	B27:		Ht. Tran. Coeff	23.43 kJ/s-m2-C
B28	B28:		---	0.6616
B29	B29:		---	1.397e-005
B30	B30:		Temperature	203.3 C
B31	B31:		Temperature	370.5 C
B32	B32: Qsodium	Qsodium	Energy	5.822 MW
B33	B33:		---	1.520e-006
B35	B35:		---	1.391e-002
B36	B36:		---	1.252e-002
B38	B38:		Pressure	148.7 kPa
B39	B39:		Pressure	69.77 kPa

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Spreadsheet: Double-Pipe HX Calculations (continue

Units Set: Project Units

PARAMETERS

Exportable Variables

Cell	Visible Name	Variable Description	Variable Type	Value
C2	C2: Mass Flow	Mass Flow	Mass Flow	11.34 kg/s
C7	C7:		---	0.7698
C8	C8:		---	2.450e-005
C10	C10:		---	1.103
C31	C31:		Temperature	285.0 C
C32	C32: Q	Q	Energy	5.822 MW
D17	D17:		Velocity	0.9373 m/s
D18	D18:		Velocity	29.36 m/s
D26	D26:		Ht. Tran. Coeff	73.10 kJ/s-m2-C
D29	D29:		---	<empty>
D30	D30:		Temperature	537.8 C
E3	E3:		---	25.00
E27	E27:		Length	36.58 m
E28	E28:		---	16.24
E34	E34:		---	1.196e+022
E35	E35:		---	7.488e-017
E36	E36:		---	3.821e+005
F12	F12:		---	<empty>
F13	F13:		Length	0.6087 m
F14	F14:		Length	3.840 m
F17	F17:		---	784.0
F18	F18:		---	26.61
F26	F26:		Thermal Cond.	34.49 W/m-K
F32	F32:		Power	145.5 MW
F34	F34:		---	2.787e+022
F35	F35:		---	1.164e-020
F36	F36:		---	6.611e+005

User Variables

FORMULAS

Cell	Formula	Result
B2	=e2/e3	10.12 kg/s
B7	=B8*B6*1000/B4	6.497e-003
B8	=B9/1000000*B3	2.630e-004
B10	=1/b3	1.195e-003
B17	=PI*B13^2/4	1.291e-002
B18	=PI*(B15^2-B14^2)/4	0.4261
B20	=D17*B13/(B9/1000000)	3.821e+005
B21	=D18*F14/(C9/1000000)	4.170e+006
B23	=0.023*B20^(4/5)*B7^0.3	148.4
B24	=0.023*B21^(4/5)*C7^0.4	4096
B26	=B23*B4/1000/B13	80.57 kJ/s-m2-C
B27	=1/(1/D26+1/F26)	23.43 kJ/s-m2-C
B28	=c2*c6/(b2*b6)	0.6616
B29	=@EXP(B27*E28*(B28-1)/(C2*C6))	1.397e-005
B30	=(B5*(B28-1)-B28*C5*(1-B29))/(B28*B29-1)	203.3 C
B31	=(B5+B30)/2	370.5 C
B32	=B2*B6*(B5-B30)/1000	5.822 MW

* Specified by user.

BATTELLE ENERGY ALLIANCE
Bedford, MA
USA

Case Name:	Annulus HX.25Tube.hsc
Unit Set:	Project Units3i
Date/Time:	Sat Aug 7 19:00:54 2021

Spreadsheet: Double-Pipe HX Calculations (continue

Units Set: Project Units

FORMULAS

Cell	Formula	Result
B35	=8*((8/e36)^12+1/(E34+E35)^1.5)^(1/12)	1.391e-002
B36	=8*((8/f36)^12+1/((F34+F35)^1.5))^(1/12)	1.252e-002
B38	=B35*E27/B13*b3*(d17^2)/(2*9.81)	148.7 kPa
B39	=(b36*e27/f13+1)*c3*d18^2/(2*9.81)	69.77 kPa
C2	=f2/e3	11.34 kg/s
C7	=C8*C6*1000/C4	0.7698
C8	=C9/1000000*C3	2.450e-005
C10	=1/c3	1.103
C31	=(C5+D30)/2	285.0 C
C32	=C2*C6*(D30-C5)/1000	5.822 MW
D17	=B2/B3/B17	0.9373 m/s
D18	=C2/C3/B18	29.36 m/s
D26	=B26*B13/B14	73.10 kJ/s-m2-C
D30	=C5+(B5-B30)/B28	537.8 C
E28	=PI*B14*E27	16.24
E34	=(2.457*@LN(1/((7/e36)^0.9+(0.27*B33/B13))))^16	1.196e+022
E35	=(37530/e36)^16	7.488e-017
E36	=d17*b13/(b9/1000000)	3.821e+005
F13	=B15-B14	0.6087 m
F14	=(B15^2-B14^2)/B14	3.840 m
F17	=B2/B17	784.0
F18	=C2/B18	26.61
F26	=B24*C4/F14	34.49 W/m-K
F32	=b32*e3	145.5 MW
F34	=(2.457*@LN(1/((7/f36)^0.9+(0.27*B33/F13))))^16	2.787e+022
F35	=(37530/f36)^16	1.164e-020
F36	=d18*f13/(c9/1000000)	6.611e+005

SPREADSHEET

	A	B	C	D
1		Hot Fluid *	Cold Fluid *	
2	mass flow *	10.12 kg/s *	11.34 kg/s *	Mass Flow *
3	density *	836.5 kg/m3 *	0.9065 kg/m3 *	number of tubes *
4	thermal conductivity *	69.62 W/m-K *	3.232e-002 W/m-K *	
5	Inlet Temperature *	537.8 C *	32.22 C *	
6	Cp *	1.720 kJ/kg-K *	1.016 kJ/kg-K *	
7	Pr *	6.497e-003 *	0.7698 *	
8	Dynamic Viscosity *	2.630e-004 *	2.450e-005 *	
9	kinetic viscosity *	0.3144 cSt *	27.03 cSt *	
10	specific volume *	1.195e-003 *	1.103 *	
11	Pressure *	752.2 kPa *	109.6 kPa *	
12		<empty> *		
13	ID of pipe *	0.1282 m *	<empty> *	
14	OD of pipe *	0.1413 m *	<empty> *	
15	ID of Annulus *	0.7500 m *		
16				
17	Area Pipe *	1.291e-002 *	Velocity Pipe *	0.9373 m/s *
18	Area Annulus *	0.4261 *	Velocity Annulus *	29.36 m/s *
19				
20	Re pipe *	3.821e+005 *		
21	Re Annulus *	4.170e+006 *		

* Specified by user.

Spreadsheet: Double-Pipe HX Calculations (continue

Units Set: Project Units

SPREADSHEET

22		<empty> *		
23	Nu pipe *	148.4 *		
24	Nu annulus *	4096 *		
25				
26	hi *	80.57 kJ/s-m2-C *	hp *	73.10 kJ/s-m2-C *
27	Uo *	23.43 kJ/s-m2-C *		L *
28	R *	0.6616 *		A0 *
29	Ecounter *	1.397e-005 *		<empty> *
30	T2 *	203.3 C *	t2 *	537.8 C *
31	Avg Temp *	370.5 C *	285.0 C *	
32	q *	5.822 MW *	5.822 MW *	<empty> *
33	Epsilon *	1.520e-006 *		
34				b *
35	friction factor pipe *	1.391e-002 *		c *
36	friction factor annulus *	1.252e-002 *		Re *
37				
38	Pressure Drop pipe *	148.7 kPa *		
39	Pressure Drop Annulus *	69.77 kPa *		
40				
	E	**F**		
1	Sodium *	Air *		
2	253.0 kg/s *	283.5 kg/s *		
3	25.00 *			
4				
5				
6				
7				
8	<empty> *			
9				
10				
11				
12		<empty> *		
13	Dh *	0.6087 m *		
14	De *	3.840 m *		
15				
16				
17	G pipe *	784.0 *		
18	G Annulus *	26.61 *		
19				
20				
21				
22				
23				
24				
25				
26	ha *	34.49 W/m-K *		
27	36.58 m *			
28	16.24 *			
29				
30				
31				
32	True Q *	145.5 MW *		

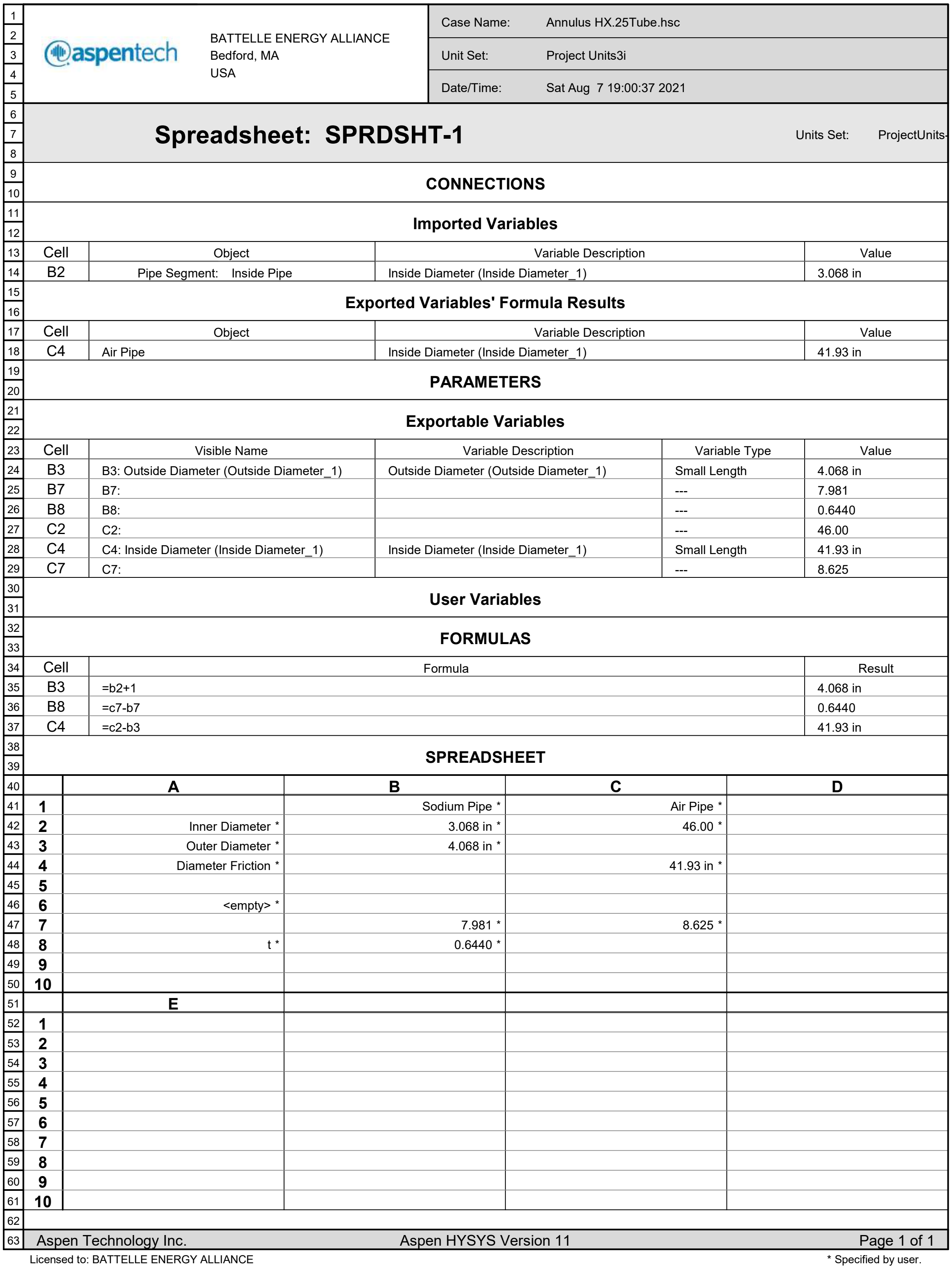
* Specified by user.

Spreadsheet: Double-Pipe HX Calculations (continue

Units Set: Project Units

SPREADSHEET

33	pipe *	anulus *		
34	1.196e+022 *	2.787e+022 *		
35	7.488e-017 *	1.164e-020 *		
36	3.821e+005 *	6.611e+005 *		
37				
38				
39				
40				



BATTELLE ENERGY ALLIANCE Bedford, MA USA	Case Name:	Annulus HX.25Tube.hsc	
	Unit Set:	Project Units3i	
	Date/Time:	Sat Aug 7 19:00:37 2021	

Spreadsheet: SPRDSHT-1

Units Set: ProjectUnits

CONNECTIONS

Imported Variables

Cell	Object	Variable Description	Value
B2	Pipe Segment: Inside Pipe	Inside Diameter (Inside Diameter_1)	3.068 in

Exported Variables' Formula Results

Cell	Object	Variable Description	Value
C4	Air Pipe	Inside Diameter (Inside Diameter_1)	41.93 in

PARAMETERS

Exportable Variables

Cell	Visible Name	Variable Description	Variable Type	Value
B3	B3: Outside Diameter (Outside Diameter_1)	Outside Diameter (Outside Diameter_1)	Small Length	4.068 in
B7	B7:		---	7.981
B8	B8:		---	0.6440
C2	C2:		---	46.00
C4	C4: Inside Diameter (Inside Diameter_1)	Inside Diameter (Inside Diameter_1)	Small Length	41.93 in
C7	C7:		---	8.625

User Variables

FORMULAS

Cell	Formula	Result
B3	=b2+1	4.068 in
B8	=c7-b7	0.6440
C4	=c2-b3	41.93 in

SPREADSHEET

	A	B	C	D
1		Sodium Pipe *	Air Pipe *	
2	Inner Diameter *	3.068 in *	46.00 *	
3	Outer Diameter *	4.068 in *		
4	Diameter Friction *		41.93 in *	
5				
6	<empty> *			
7		7.981 *	8.625 *	
8	t *	0.6440 *		
9				
10				

	E			
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				

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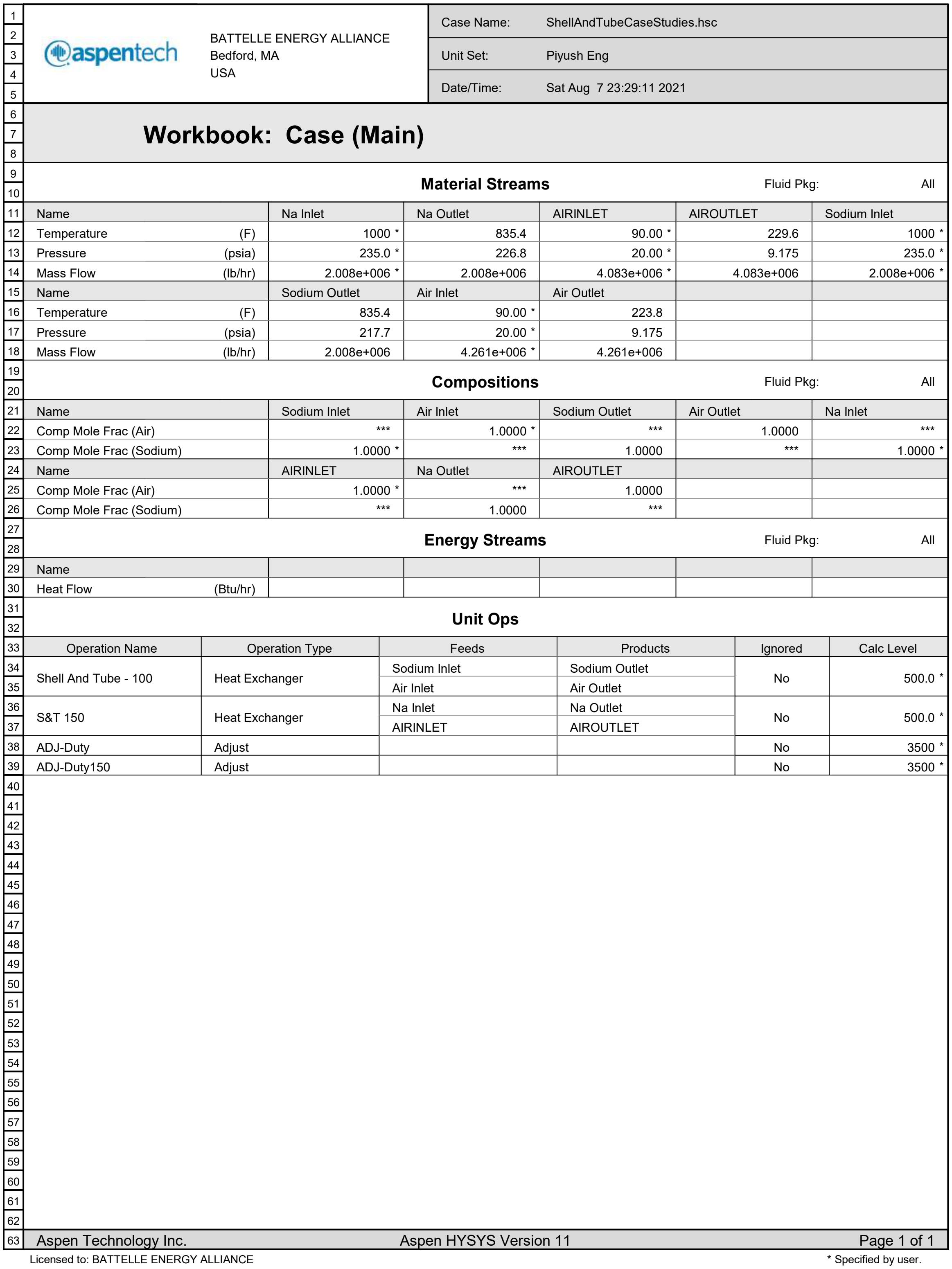

BATTELLE ENERGY ALLIANCE
Bedford, MA
USA

Case Name: ShellAndTubeCaseStudies.hsc
Unit Set: Piyush Eng
Date/Time: Sat Aug 7 23:29:11 2021

Workbook: Case (Main)

Material Streams

Fluid Pkg: All

Name		Na Inlet	Na Outlet	AIRINLET	AIROUTLET	Sodium Inlet
Temperature	(F)	1000 *	835.4	90.00 *	229.6	1000 *
Pressure	(psia)	235.0 *	226.8	20.00 *	9.175	235.0 *
Mass Flow	(lb/hr)	2.008e+006 *	2.008e+006	4.083e+006 *	4.083e+006	2.008e+006 *
Name		Sodium Outlet	Air Inlet	Air Outlet		
Temperature	(F)	835.4	90.00 *	223.8		
Pressure	(psia)	217.7	20.00 *	9.175		
Mass Flow	(lb/hr)	2.008e+006	4.261e+006 *	4.261e+006		

Compositions

Fluid Pkg: All

Name	Sodium Inlet	Air Inlet	Sodium Outlet	Air Outlet	Na Inlet
Comp Mole Frac (Air)	***	1.0000 *	***	1.0000	***
Comp Mole Frac (Sodium)	1.0000 *	***	1.0000	***	1.0000 *
Name	AIRINLET	Na Outlet	AIROUTLET		
Comp Mole Frac (Air)	1.0000 *	***	1.0000		
Comp Mole Frac (Sodium)	***	1.0000	***		

Energy Streams

Fluid Pkg: All

Name						
Heat Flow	(Btu/hr)					

Unit Ops

Operation Name	Operation Type	Feeds	Products	Ignored	Calc Level
Shell And Tube - 100	Heat Exchanger	Sodium Inlet Air Inlet	Sodium Outlet Air Outlet	No	500.0 *
S&T 150	Heat Exchanger	Na Inlet AIRINLET	Na Outlet AIROUTLET	No	500.0 *
ADJ-Duty	Adjust			No	3500 *
ADJ-Duty150	Adjust			No	3500 *

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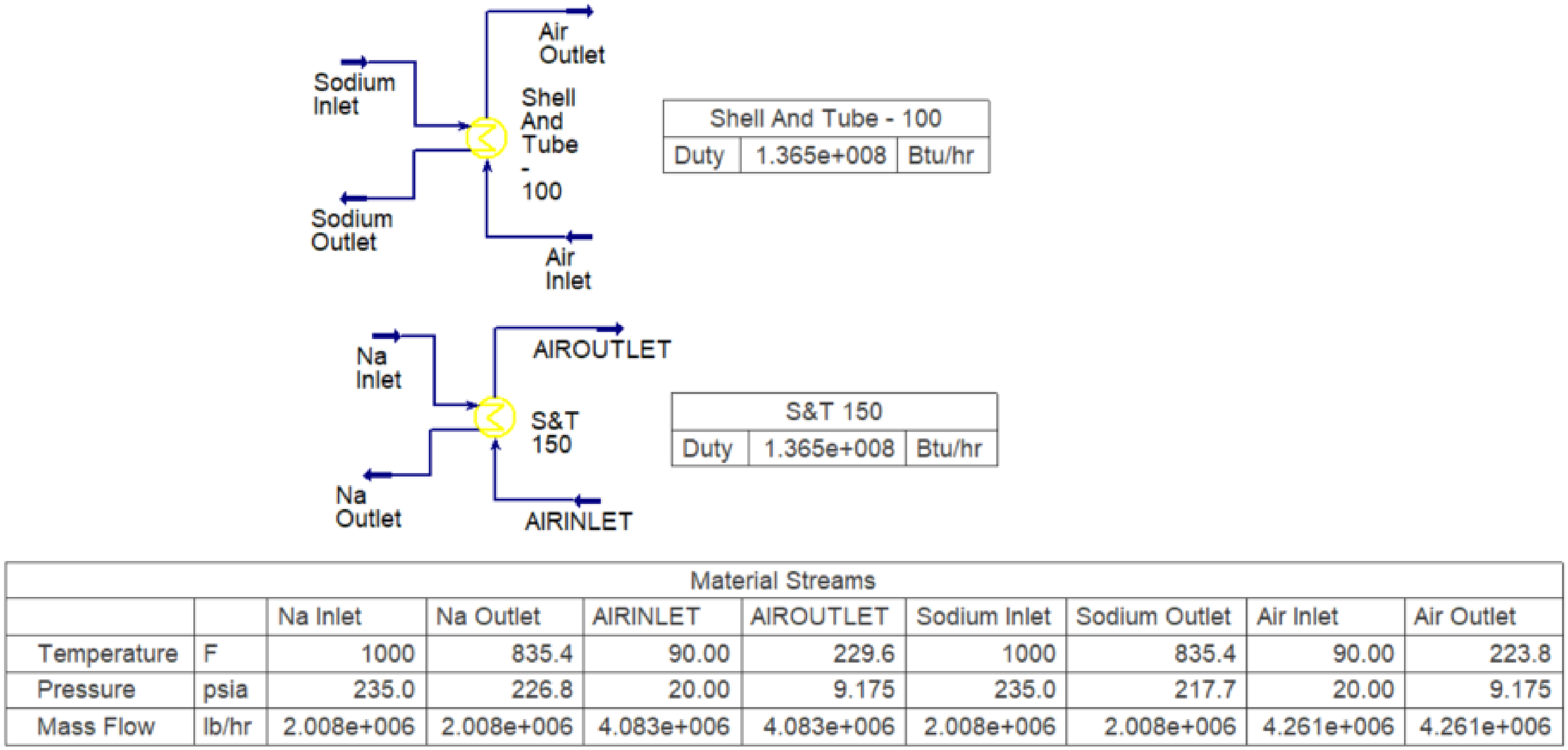
* Specified by user.



Shell And Tube - 100		
Duty	1.365e+008	Btu/hr

S&T 150		
Duty	1.365e+008	Btu/hr

Material Streams									
		Na Inlet	Na Outlet	AIRINLET	AIROUTLET	Sodium Inlet	Sodium Outlet	Air Inlet	Air Outlet
Temperature	F	1000	835.4	90.00	229.6	1000	835.4	90.00	223.8
Pressure	psia	235.0	226.8	20.00	9.175	235.0	217.7	20.00	9.175
Mass Flow	lb/hr	2.008e+006	2.008e+006	4.083e+006	4.083e+006	2.008e+006	2.008e+006	4.261e+006	4.261e+006

Figure B.3: Shell and Tube heat exchanger models in HYSYS