An Investigation of Steam-Powered Turbine Operation at Steady-State

Leah Gaeta
ME 304: Energy & Thermodynamics

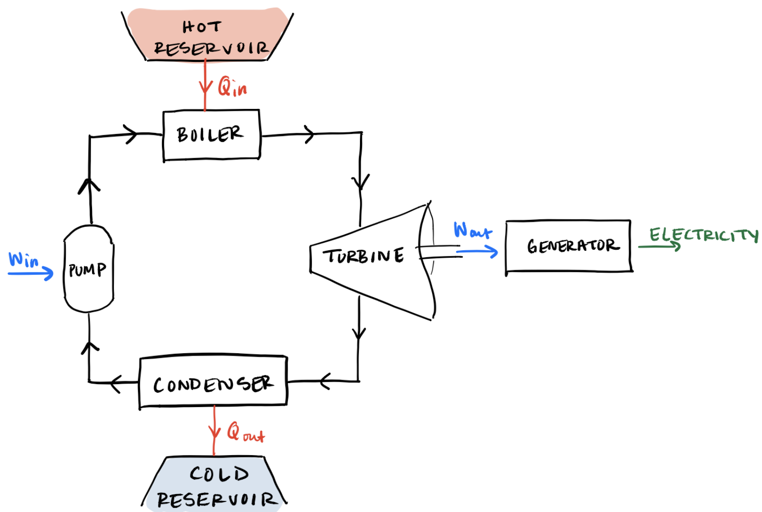
ltgaeta@bu.edu

April 15, 2020

Contents

1 Pre-lab

A. In order for a turbine to produce work in an open power plant system, multiple components must be factored in for the turbine to be successful. Firstly, for a steam-turbine there must be superheated water vapor at a higher pressure entering the turbine and then pass through blades on a rotating shaft to a lower pressure. The rotating shaft is then connected to a generator that will convert the power developed from the shaft into electricity for use. In order for steam to enter the turbine however, another component must be considered: the boiler. The boiler acts to change liquid water from its saturated liquid phase to vapor isobarically and in order for this to happen, heat must be added by some Q_H from a hot reservoir. The boiler receives the liquid water from a pump that will take an input work W_{in} to convert a liquid-vapor mixture into liquid adiabatically. Finally, the pump receives this two-phase mixture from a condenser which releases heat isobarically by some Q_{out} to cold reservoir after receiving steam from the turbine. The integration of these components of an open power plant system are illustrated in the accompanying figure below. It's important to note that the turbine also produces work adiabatically; that is, there is no heat transfer as it produces work and generates power.



B. A rheostat is a device that is capable of providing variable resistance. It is a form of potentiometer which can measure voltage/potential differences. Since the rheostat is able to provide variable resistance, it can be used to control electrical current, and in the case of a turbine it can then be used to control shaft rotation speed and therefore power output of the turbine.

C. It can be difficult to make steady-state assumptions during a transient analysis of turbine operation since the work output rate could vary with time. In order to bring this system to "steady-state" conditions, it is imperative to define a control volume in which the mass flow rates in and out satisfy conservation of mass. In addition, the intensive properties within the control volume, such as the specific volume and specific internal energy, must be constant in order to conduct steady-state analysis. This also means that the state of the steam entering the turbine must be constant with time and the state of the steam leaving the turbine must also be constant with time and in equilibrium. The states of the steam could be measured by analyzing the quality x of the vapor entering and exiting. If there are differences in the qualities measured, then it can be inferred that the turbine is not operating at steady-state.

2 Introduction

In the field of thermodynamics and energy analysis, Engineers are constantly seeking to improve upon inefficiencies within the systems that people interact with frequently. An example of such is the steam power plant that produces much of our electrical power used in everyday life. Often, the engineer wants to know how long a system will last under particular conditions, how its efficiency changes with time, and how power is generated, among many other items of importance.

Detailed in this report is the study of a laboratory-sized steam-powered turbine integrated within a system to generate electrical power, for the ultimate goal of gaining a broader understanding of the actualities of larger-scale power production systems. This was accomplished by using a RankineCycler™ at Boston University to gather data on the steady-state operation of this particular steam-powered system.

3 Materials & Methods

The RankineCycler™ apparatus includes a boiler, throttling valve, turbine, and condenser all connected in series with each other. The boiler provides heat input into the system to create steam, Q_{in}, and is fueled by propane gas. The steam travels from the boiler through the throttling valve, which is used to adjust the flow of steam, to the turbine. The turbine then produces mechanical work from this superheated steam, and the generator that is connected to the turbine will take this work and convert it into electrical power. Finally, the condenser then receives the steam from the turbine's outlet and vapor escapes to the atmosphere, meaning there is mass loss to the surroundings. The water therefore does not circulate back to the boiler. A general schematic of this system can be seen in Figure 1 below.

The pressures and temperatures were recorded for the boiler as well as the turbine inputs and outputs throughout this system's time in steady-state. In addition, the flow rate of propane and the voltage, current, and electrical power data from the generator were also collected. The data obtained is analyzed in the proceeding section.

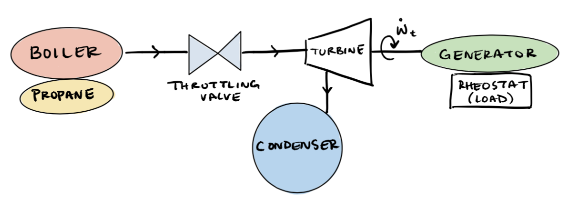


Figure 1: General schematic of the apparatus studied.

In order to study this integrated system under steady-state conditions, it first underwent a transient phase that composed of the start-up. This included opening the throttling valve to release any air within the system prior to the experiment, filling the boiler with 5500 ml of distilled water, then closing the valve once all of the water was in. The propane burner for the boiler was then turned on and once the pressure had reached 120 psi, the steam throttling valve was opened again, though very slowly so that the boiler pressure fell to about 50 psi and the turbine speed was not too fast. The valve was then closed again and the boiler pressure raised to 120 psi to conclude the start-up process.

Steady-state operation then proceeded by slowly opening the throttling valve again and adjusting the rheostat (or load knob) until the generator was outputting about 9 volts and the boiler pressure was consistently near 120 psi. Once the boiler pressure fell about 10%, steady-state was terminated by beginning the next transient phase of shutdown. Everything was turned off, the throttling valve slowly opened to vent and release all of the boiler pressure until reaching the atmospheric value, and the final volume of water from the condenser tower was measured.

4 Analysis

To study the steady-state operation of this power production system, one must start with the energy equation developed from the first law of thermodynamics (Eq. 1), in which $\frac{dE}{dt}$ is the change in energy over time, $\dot{Q}_{cv}$ is the net heat transfer rate, $\dot{W}_{cv}$ is the net power, $\dot{m}$ the mass flow rate, h the specific enthalpy, V the velocity, g the gravitational acceleration, and z the vertical position. In this equation, i is represents the values at the inlet while e represents the values at the exits, and cv simply stands for control volume. At steady-state, there is no change in energy over time so $\frac{dE}{dt}$ is equal to zero. This equation can be applied specifically to the throttling device, in which there is no work, heat transfer, or gravitational potential effects, and kinetic energy is negligible (assuming ideality). Therefore, the specific enthalpies at the inlet and outlet of the throttling device must be equal under steady-state conditions, as seen in Eq. 2. From the collected data, the specific enthalpy was found by taking the pressures and the average temperature at the boiler and the turbine inlet, looking up published specific enthalpies for the minimum and maximum pressures at their respective average temperatures, and applying linear interpolation to find specific enthalpies for each time point. This was all done in MATLAB and specific enthalpies were also obtained in the same manner for the turbine outlet: finding the average temperature, the range of the pressure values, and using tabulated data from https://www.spiraxsarco.com/ for superheated steam to linearly interpolate specific enthalpy values.

$$\frac{dE}{dt} = \dot{Q}_{cv} - \dot{W}_{cv} + \dot{m}[(h_i - h_e) + \frac{V_i^2 - V_e^2}{2} + g(z_i - z_e)] \tag{1}$$

$$0 = \dot{m}(h_i - h_e) \tag{2}$$

One can also analyze the isentropic efficiency of the turbine within this system from the data collected. The isentropic efficiency of the turbine is defined in Eq. 3 below, where the numerator is the actual turbine power output and the denominator is the theoretical turbine power output, or where h_3 is the actual specific enthalpy found at the outlet of the turbine and h_{3s} is the hypothetical specific enthalpy at the outlet while h_2 is the specific enthalpy at the turbine inlet. (The integer 3 represents the outlet of the turbine, while 2 represents the inlet.) One value for h_{3s} was found by finding the average specific entropy at the turbine inlet (s_2) and equating it to s_{3s}, then using the average temperature at the turbine outlet to find the hypothetical specific enthalpy, or h_{3s}. The average specific entropy was found to be $s_2 = 7.21361 \ \frac{kj}{kg*k}$, and since $s_2 = s_{3s}$ and the average temperature at the turbine outlet equals 112.7 degrees C, superheated steam tables were then used to find that $h_{3s} = 2694.84 \ \frac{kj}{k}$. Using the single h_{3s} value found, isentropic efficiencies for the turbine were again found for every time point using linear interpolation and MATLAB.

$$\eta_t = \frac{\dot{W}_t/\dot{m}_s}{(\dot{W}_t)_s/\dot{m}_s} = \frac{h_2 - h_3}{h_2 - h_{3s}} \tag{3}$$

In addition, applying the first law equation to just the turbine and the generator, reduces to Eq. 4 below and the efficiency of the two elements together e_{TG} is defined in Eq. 5. If there is no heat transfer, then the efficiency must be equal to one. The efficiency of the turbine and generator were found for every time stamp using the electrical power data, the actual enthalpies previously calculated, and the mass flow rate of the steam. The mass flow rate of the steam, $\dot{m}_s$, was found by taking the average specific volume from the published average temperature and pressure values at the turbine outlet, and taking into account that 1900 ml of steam flowed through the turbine during the steady-state time period. The average specific volume was found to be $1.388105 \ \frac{m^3}{kg}$ and an example calculation of the mass flow rate over the total period of 426.0720 seconds can be seen in Eq. 6.

$$0 = \dot{Q} - \dot{W}_e + \dot{m}_s(h_2 - h_3) \tag{4}$$

$$e_{TG} = \frac{\dot{W}_e}{\dot{m}_s(h_2 - h_3)} \tag{5}$$

$$\dot{m}_s = \frac{1900ml}{426.07s} \cdot \frac{1L}{1000ml} \cdot \frac{0.001m^3}{1L} \cdot \frac{1kg}{1.3881m^3} = 3.2125 \cdot 10^{-6} \frac{kg}{s} \tag{6}$$

Finally, knowing the heating value of propane q_p to be equal to 19,950 $\frac{Btu}{lbm}$ and the density of propane ($\rho_{propane} = 493 \ \frac{kg}{m^3}$), the overall efficiency e for electrical power production is defined in Eq. 7 and was also found for each time point using the flow rate of propane $\dot{m}_p$, the heating value, and the electrical power output $\dot{W}_e$.

$$e = \frac{\dot{W}_e}{\dot{m}_p q_p} \tag{7}$$

Example calculations for all of these equations for an arbitrarily picked timepoint can be seen in the appendix of this report. In addition, the averages of these values over the steady-state time period are tabulated in the following section.

5 Results

Average values from the application of the previously mentioned equations for this steady-state data, as well as average pressure, temperature, and power output can be found in Tables 1 & 2.

Table 1: Average Pressures, Temperatures, and Power.

Component	Pressure (psig)	Temperature (C)	Power (Watts)
Boiler	103.75	189.76	
Turbine Inlet	12.53	128.38	
Turbine Outlet	3.79	112.70	
Generator			3.53

Table 2: Calculated enthalpies and efficiencies of the system at steady-state.

Boiler Specific Enthalpy ($\frac{kj}{kg}$)	Turbine$_i$ Specific Enthalpy ($\frac{kj}{kg}$)	Turbine$_e$ Specific Enthalpy ($\frac{kj}{kg}$)	h$_{3s}$ ($\frac{kj}{kg}$)	Average Isentropic Efficiency (η_t)	Average T & G Efficiency (e_{TG})	Average Overall Efficiency (e)
2814.3	2724.3	2698.2	2694.8	0.8876	42.04	1.84 x 10^{-6}

To further explore the behavior of this steam-powered electrical production system, the changes in isentropic turbine efficiency, power generated, efficiency of the turbine and generator, and overall efficiency were examined over the steady-state time period. These can be seen in the following plots and will be discussed in depth in the Discussion.

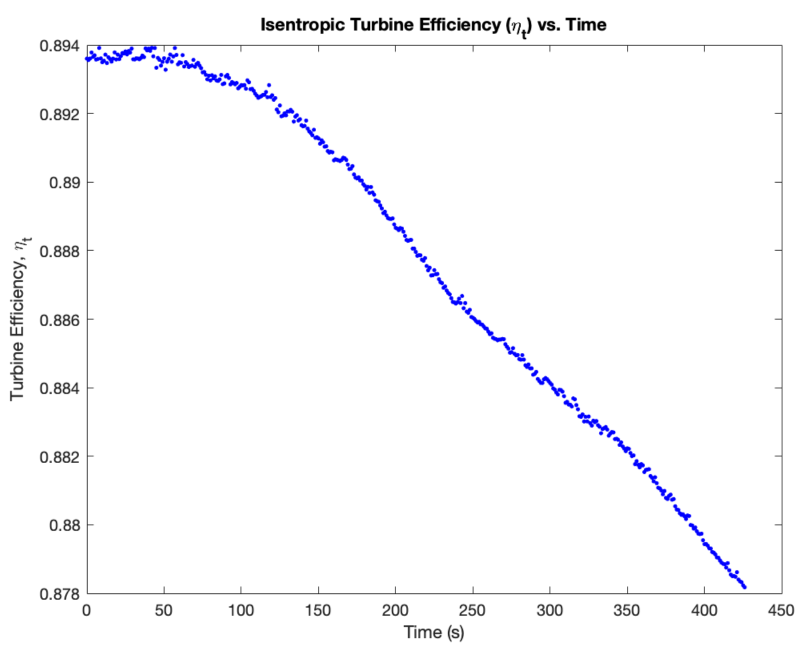


Figure 2: Isentropic turbine efficiency over time.

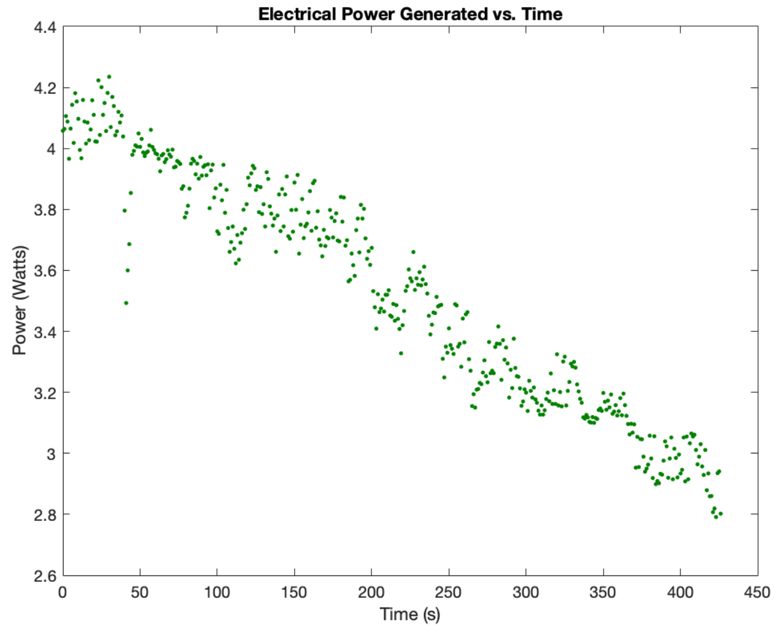


Figure 3: Power (watts) generated over time.

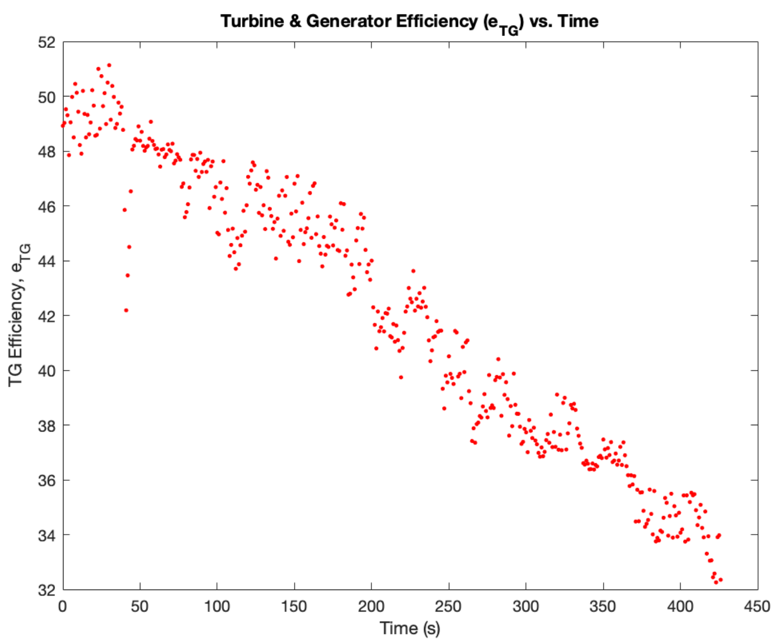


Figure 4: Efficiency of the turbine & generator over time.

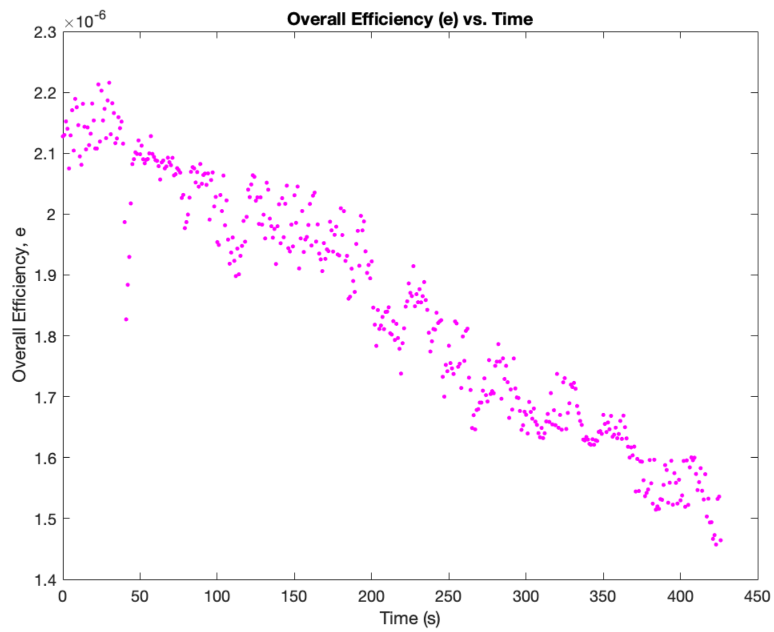


Figure 5: Overall efficiency of electrical power production over time.

6 Discussion

The results from the previous calculations provide significant insights into the processes that comprise this power production system using superheated steam. Purely based on average specific enthalpy values obtained, there was clearly heat loss at the throttling valve. The throttling valve was positioned between the boiler and the turbine, meaning that the average specific enthalpy of the boiler (2814.3 $\frac{kj}{kg}$) and the average specific enthalpy at the inlet of the turbine (2724.3 $\frac{kj}{kg}$) are equal to the specific enthalpies of the throttling valve inlet and exit, respectively. Theoretically, the valve is adiabatic, does no work, and has negligible potential and kinetic energy effects, so the specific enthalpy should remain unchanged as the steam passes through. However, subtracting the inlet from the outlet specific enthalpy results in -90.01 $\frac{kj}{kg}$, suggesting that there was in fact some heat loss to the surroundings as the enthalpy of the steam decreased.

In addition, the average isentropic efficiency of the turbine was found to be 0.8876, or 88.76%, which is close to what was expected. It's interesting to note the trend of this efficiency over time, as displayed in Figure 2. Clearly, the efficiency is at its highest at the beginning of steady-state operation but then decreases about a third of the time in, though only by about 2%. This suggests that while high efficiencies can be achieved, there are more implications that must be considered to maintain such high efficiencies over longer periods of time. For example, one may want to put more turbines in series with each other to increase the efficiency though this would be more costly to obtain such materials. Ultimately this depends on the goals of the system. As seen in Figure 3, which is a plot of the raw data of the power generated over time, the wattage produced also decreases, but more drastically than the turbine efficiency (almost by a third from the beginning). If the goal of a power production system such as this is to only produce this finite amount of power, then the efficiency of the turbine is satisfactory. However, for greater scale power production systems in which electric power is expected to be constantly generated, clearly this system studied would not suffice. As mentioned, putting several turbines in series with one another could greatly improve the isentropic efficiency of this portion of the power production system.

Along the same lines, the efficiency of the turbine and generator also decreases over time during these steady-state conditions, as seen in Figure 4. This is also assuming however, that the process is completely adiabatic and it's likely there was some heat transfer to the surroundings. The average e_{TG} was found to be 42.04 while a value of 1 would have been considered completely adiabatic. The fact that the average efficiency of the turbine and generator was of much greater magnitude than 1 clearly suggests that the turbine and generator were not operating adiabatically, as well other errors that may have risen from data collection and/or the experiment itself. One would typically expect this value to be less than 1.

In addition, the overall efficiency e was found to have an average value of $1.8447 \cdot 10^{-6}$, or $1.8447 \cdot 10^{-4}\%$. The overall efficiency calculations involved values of the propane fuel used at the boiler and the results also have a decreasing trend as displayed in Figure 5. Related to the previous argument, this suggests that this isn't a very productive or efficient system for large-scale electricity production. However, it is interesting to quantify what is actually happening during steady-state to help better understand the thinking and innovation that must go into creating power production systems for everyday use.

One aspect of this experiment that would have been interesting to investigate but was not touched on in this report, is the mass loss and rate of mass loss of steam from the condenser over time. Findings related to this could also help engineers better understand these systems and their components.

7 Conclusion

In conclusion, the goal of this laboratory exercise was to discover and analyze the details of a simple electricity power production system. While the experiment was done virtually, this report serves as the analysis of a system operating at steady-state. From the findings, one can observe that many aspects of the system did not operate adiabatically and that the efficiency decreased with time, shedding light on how these processes are unlikely to operate in a completely ideal manner in reality. While unable to perform the experiment in person, the analysis itself was very interesting and gave great perspective on the amount of work and research that contributes to improving efficiencies of power production plants.

8 Appendix

1. Enthalpy at Throttle: timedata 1st point

min boiler press: 96.281 psig   AVE TEMP: 189.7602 °C
max boiler press: 108.281 psig

min turbine_i press: 11.070 psig   AVE TEMP: 120.3814 °C
max turbine_e press: 13.311 psig

→ using these ranges for pressure, the average of temperatures measured, and superheated steam tables, linear interpolation gives
$h_1 = 2812.5 \frac{kJ}{kg} = h_{i,throttle} = h_{boiler}$
$h_2 = 2723.7 \frac{kJ}{kg} = h_{e,throttle} = h_{turbine,i}$
at the first time pt.

2. $\eta_t = \frac{h_2 - h_3}{h_2 - h_{3s}}$ using linear interpolation for pressure ranges at at turbine inlet (2) and outlet (3), and average temperatures measured there, $s_2 = 7.21361 \frac{kJ}{kgK}$

$s_2 = s_{3s} = 7.21361 \frac{kJ}{kgK}$ → then working backwards and using linear interpolation at the average temp of turbine,e
$\Rightarrow h_{3s} = 2694.84 \frac{kJ}{kg}$

∴ at the first time pt:
$$\eta_t = \frac{2723.7 \frac{kJ}{kg} - 2697.9 \frac{kJ}{kg}}{2723.7 \frac{kJ}{kg} - 2694.84 \frac{kJ}{kg}} = 0.8940$$

3. calculation for $\dot{m}_s$ in report

$$e_{TG} = \frac{\dot{W}_e}{\dot{m}_s(h_2 - h_3)}$$ for 1st time pt.

$$\Rightarrow e_{TG} = \frac{4.0580 \text{ watt}}{\left(3.2125(10^{-4})\frac{kg}{s}\right)\left(2723.7\frac{kJ}{kg} - 2697.9\frac{kJ}{kg}\right)\left(\frac{watt}{1\,J/s}\right)\left(\frac{1000\,J}{kJ}\right)} \quad 48.9609$$

4. $$e = \frac{4.0580 \text{ watt}}{\left(5.0020\frac{L}{min}\right)\left(19950\frac{Btu}{lbm}\right)\left(2.326\,{}^{kJ/kg}/_{Btu/lbm}\right)\left({}^{1\,min}/_{60\,s}\right)\left({}^{1\,kW}/_{(kJ/s)}\right)\left(\frac{1000\,watt}{kW}\right)\left(493\frac{kg}{m^3}\right)\left(.001\frac{m^3}{L}\right)}$$

$\rho_{propane}$

$e = 2.1277(10^{-6})$ for first time pt