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ES211: Project Report

Water: From the thermodynamical perspective

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Introduction:

Our group has chosen to study the thermodynamic properties of water at different temperatures through the study of its applications in the Rankine cycle, and analysing various relations between Pressure, Temperature, specific entropy, specific enthalpy and specific volume.

Problem Statement:

To study the behavior of a pure substance near its liquid-vapor region and relate it to its real-life applications in industries.
To write MATLAB codes for the 3D graphs for PsT, PhT, and Pvt values for the pure substance and use additive/subtractive manufacturing to print the PsT graph.
To explain the industrial applications of the substance.

Familiarization to Water:

Our entire lives depend on water and particularly, in the context of this project, industries cannot function without water. Water is used in chemical reactions, as a coolant, as a means of transportation and fabrication, cleaning, etc. From a chemical point of view, the study of water is very interesting. Water has more than 60 anomalies with respect to its chemical properties like decrease in density on decreasing temperature etc.

Water as a working fluid in Rankine Cycle:

Why water?

1. Cheap.
2. Easily available
3. Could be deployed in large quantities as per the need of large machinery.
4. Posses good thermal transport properties which make it suitable as a heat pipe working fluid
5. Could be re-utilized.

What is a Rankine Cycle?

The Rankine cycle is a thermodynamic cycle describing the process by which heat engines, such as steam turbines or reciprocating steam engines, allow mechanical work to be extracted from a fluid as it moves between a heat source and heat sink. The Rankine cycle is named after William John Macquorn Rankine, a Scottish polymath professor at Glasgow University.

Components of Rankine Cycle:

1 Pump:

Fig: A typical pump

The pump compresses the fluid from low pressure to high pressure. This does require work done.

2 Boiler:

Fig: A typical steam boiler used in Industries

The compressed fluid is heated to the final temperature (which is at boiling point), therefore, a phase change occurs—from liquid to vapor.

3 Turbine:

Fig: A typical Turbine

Expansion of the vapor takes place in the turbine. The turbine then produces useful work.

4 Condenser:

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Fig: A typical condenser

Condensation of the vapor in the condenser takes place. The non-useful heat goes to the final heat sink. The heat sink is generally the atmosphere or a large body of water eg. a lake or river.

Working of Rankine Cycle:

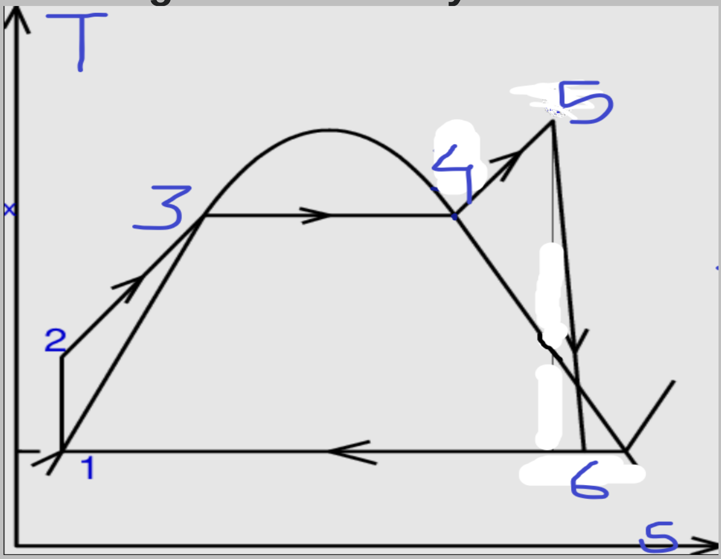


Fig: Temperature vs specific Entropy graph (Rankine Cycle)

The various states are as follows:

1: Subcooled liquid
2:Subcooled liquid
3: Saturated liquid
4: Saturated vapor
5: Superheated vapor
6: Either saturated vapor or saturated vapor-liquid mixture

Generally, Rankine Cycle is classified into four processes for understanding its working. The states are marked as 1, 2, 3, 4, 5, 6 in the figure.

Process 1–2: The working fluid is pumped from low to high pressure. As the fluid is a liquid at this stage, the pump requires little input energy. *Process 1-2 is isentropic compression.*

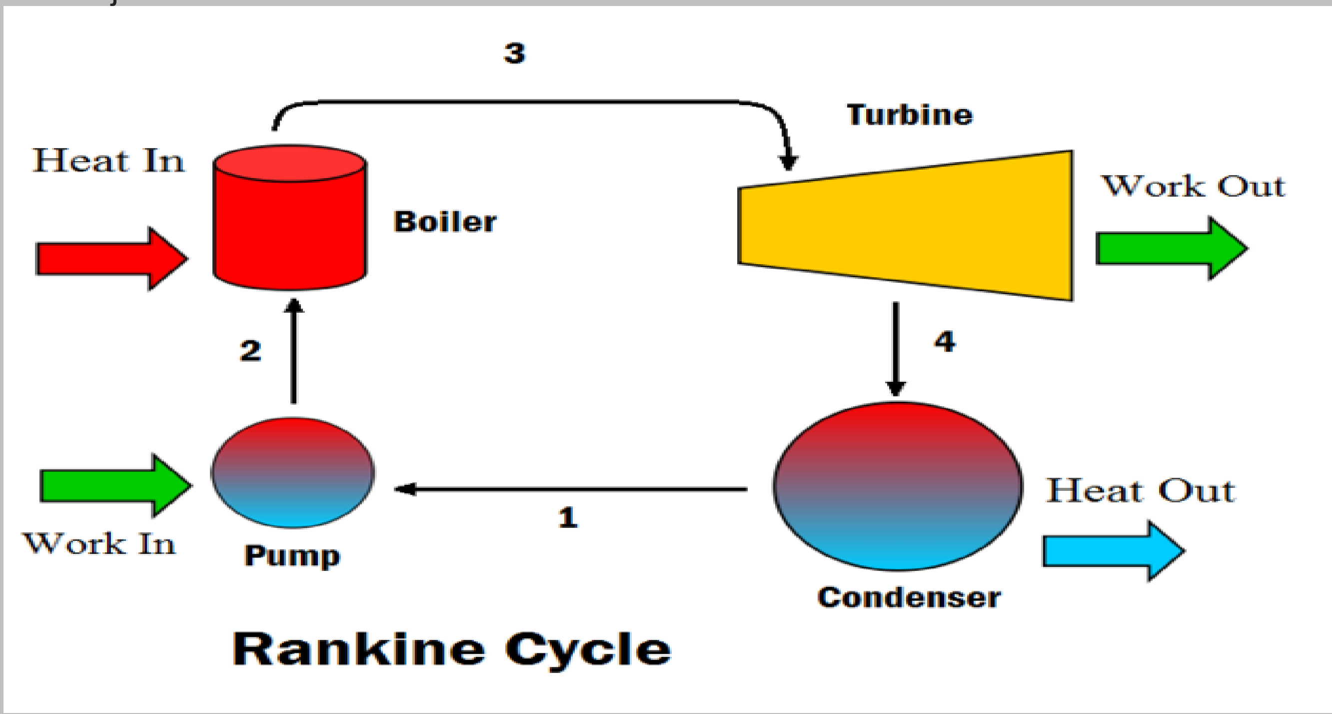
Process 2–3: *The high-pressure liquid comes into the boiler after being pumped. Heat addition takes place which manifests in the form of sensible heating.* Process 2-3 is constant pressure heat addition in the boiler.

Process 3–4: This is a constant temperature process. Water transits from saturated liquid to saturated vapor consuming the *Latent heat of vaporization*. Since it is a phase change process, so the temperature remains constant.

Process 4-5: Heat addition takes place in form of sensible heating, and the temperature continuously rises.

Process 5-6: *Work output* is being produced by the turbine, accompanied by the expansion of the vapor. The temperature of the steam decreases. This process is *Isentropic* i.e. the entropy of the fluid remains constant.

Process 6-1: The wet vapor then enters a condenser, where it is condensed at a *constant pressure* to become a saturated liquid. Process 6-1 is constant pressure heat rejection in the condenser.



Non-ideal Rankine Cycle:

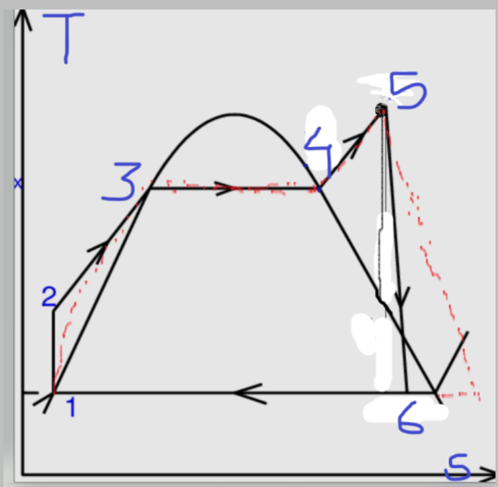


Fig: The path shown by the red dotted line corresponds to a real power plant cycle

In a real power-plant cycle (in fact, the name "Rankine" cycle is used only for the ideal cycle), the compression (process 1-2) by the pump and the expansion (process 5-6) in the turbine is not isentropic.

In other words, these processes are non-reversible, and entropy is increased during the two processes. This somewhat increases the power required by the pump and decreases the power generated by the turbine.

The problem in Ideal Rankine Cycle:

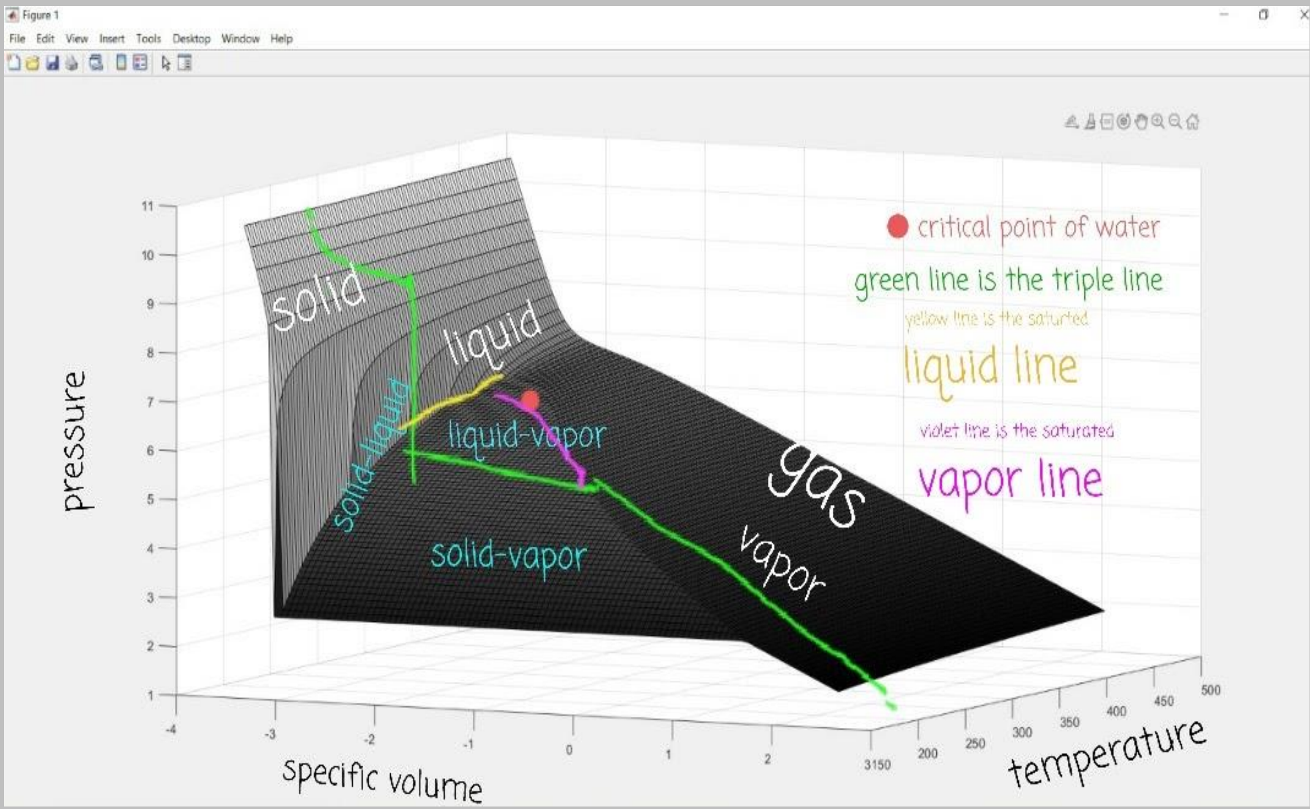
In a practical case, the efficiency of the steam turbine is affected by the formation of water droplets.

Since water condenses while passing through the turbine, they cause pitting and erosion, and therefore leading to decreased efficiency of turbine blades and thus decreased output efficiency.

Proposed Solution:

One way to overcome this problem is by superheating the steam. On the T–s diagram above, state 4 is at a border of the two-phase region of steam and water, therefore after expansion(from the turbine), the steam will be very wet.
By superheating, state 4 will move to the right (and up) in the diagram and hence produce drier steam after expansion.

Explaining the 3D Curves for Water:



Note: This figure is being generated by the Matlab code written by the team and all the markings have been manually done.

The areas marked as solid, liquid and gas indicate the p,v and t values of different equilibrium states when the state of the water substance is purely solid, purely liquid or purely gas. The important thing to note is that above the red point, the liquid region and gaseous region are not easily distinguishable indicating that at pressures above the critical point, the distinction between liquid and gas greatly reduces.

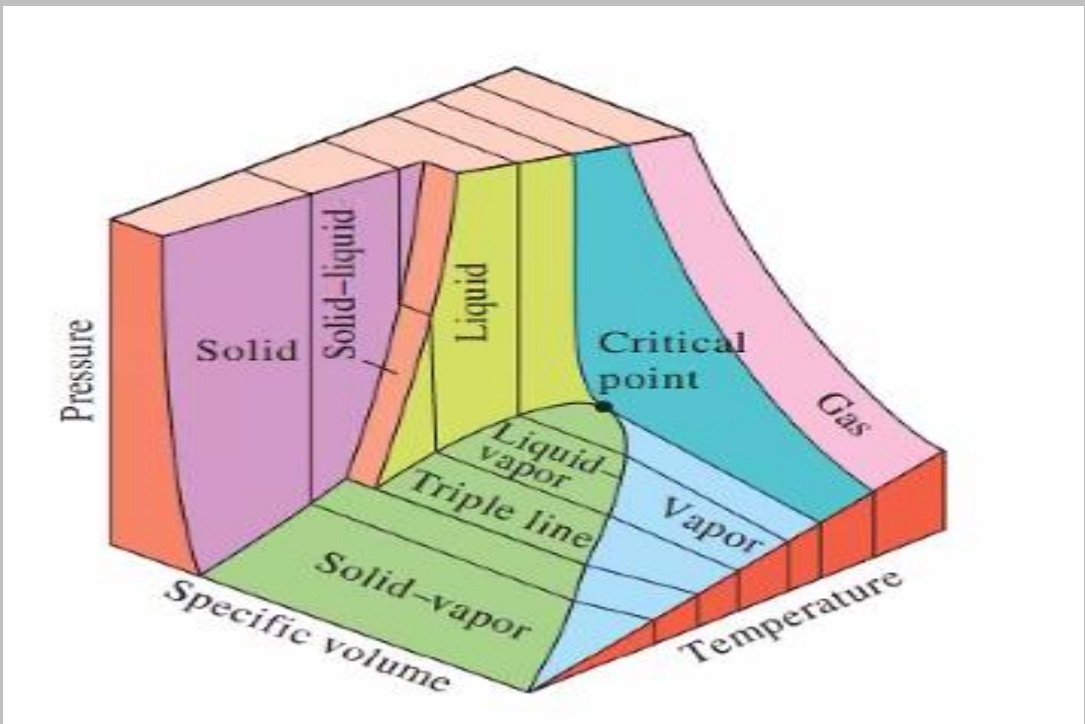
The boundary between gas and vapor is also not very precise as gas is just superheated vapor.

The vertical lines on the graph like the triple line are isotherms.

Now consider an isotherm in the gas region. The isotherm passing through the critical point is called the critical isotherm.

The triple point in 2D temperature-pressure graphs is now a triple line as specific volume can change in any way.

At the critical point, the phase boundaries between liquid and gaseous phase cease to exist. The critical point of water occurs at 647.096 K. The pressure there is 217.75 atm according to the graph. The entropy value at that point according to cantera is 1.4813e+04 $J \cdot K^{-1}$



This is the graph showing the behaviour of water at different combinations of temperature, pressure and specific volume.

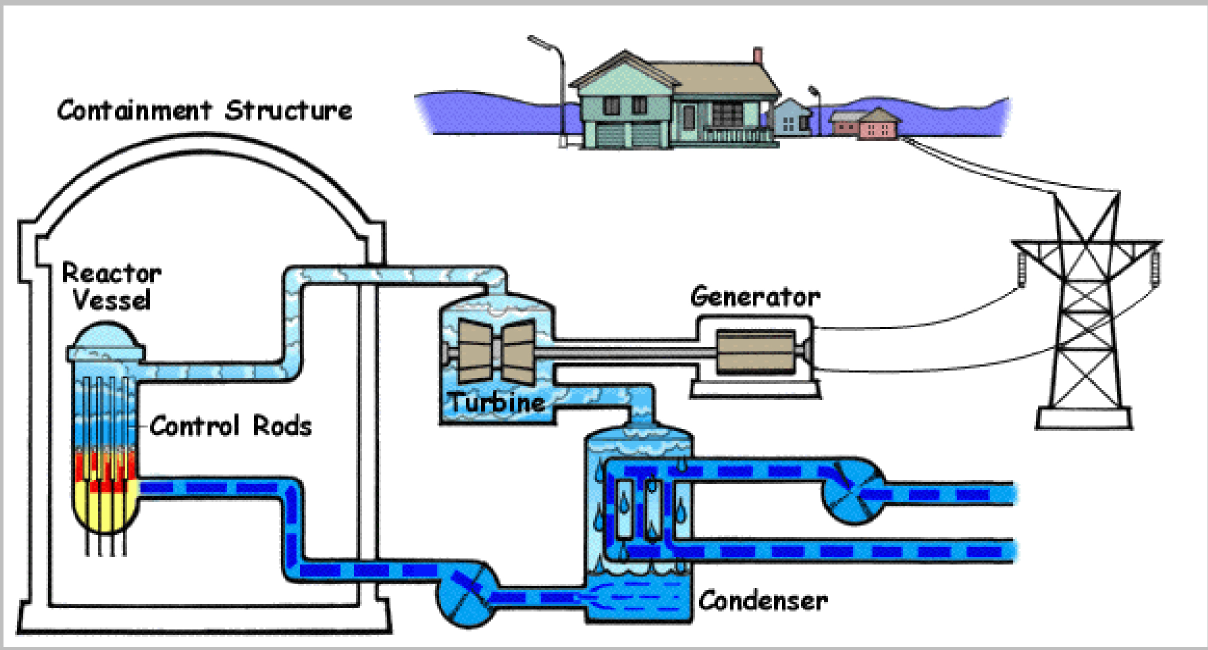


Fig: Rankine cycle being used in a Nuclear Power Plant

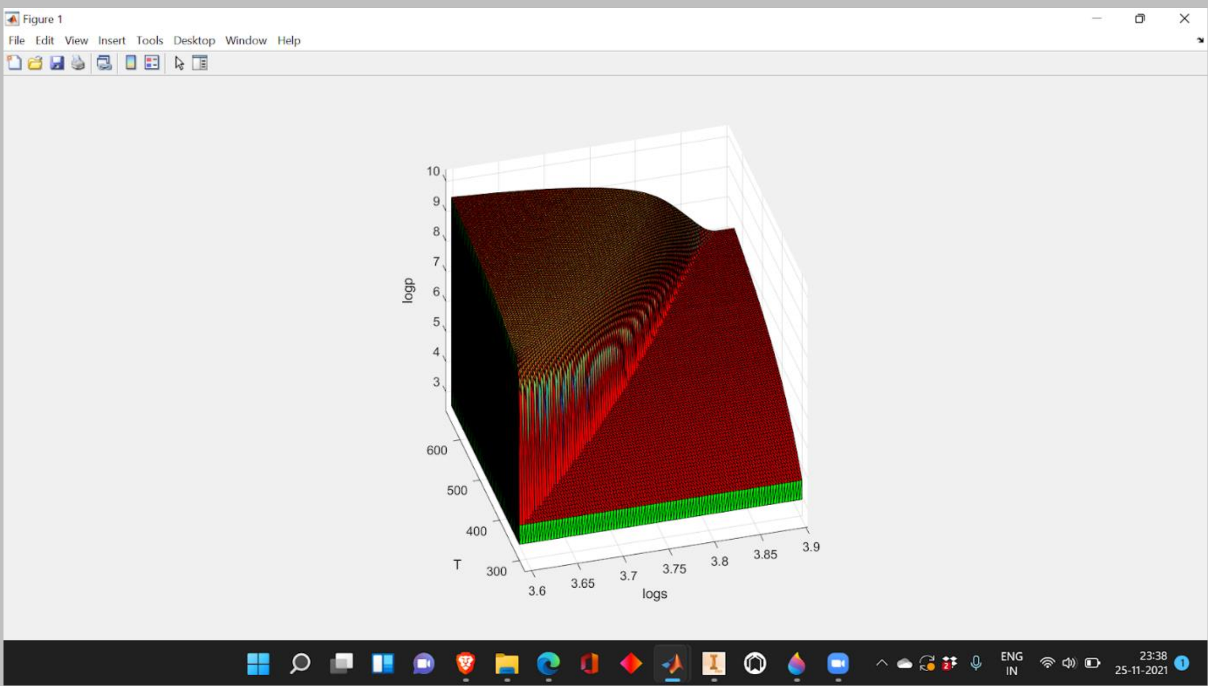


Fig: 3D PsT graph as generated in Matlab by the code

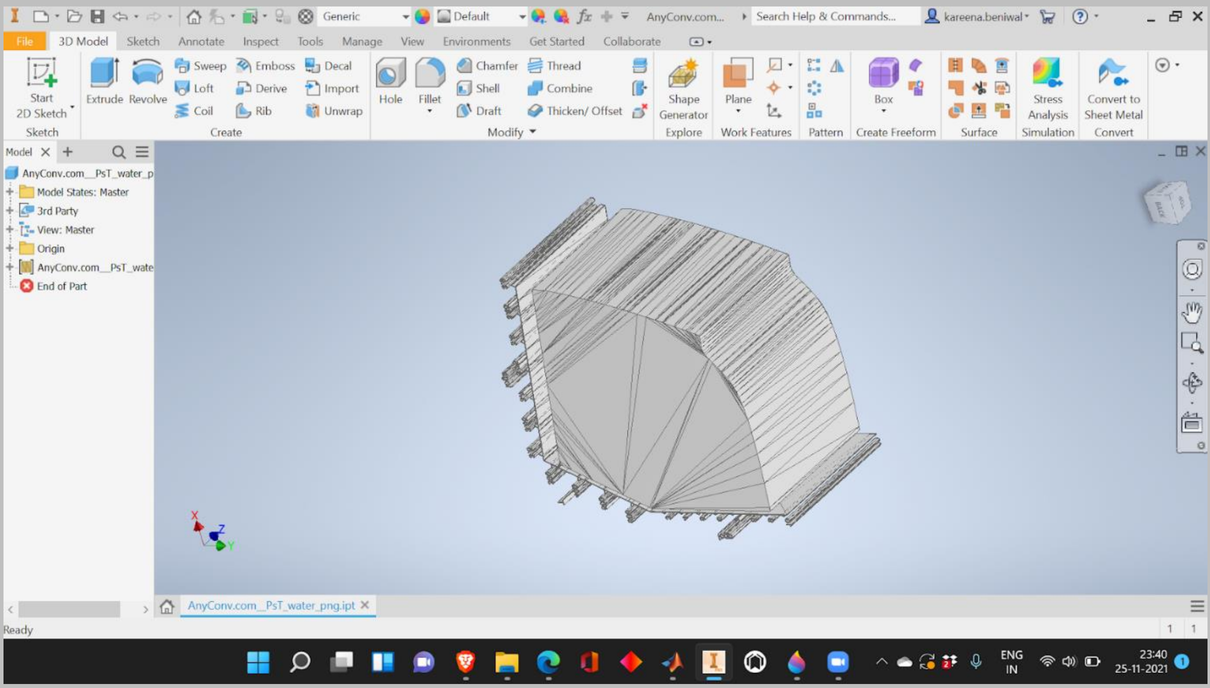


Fig: PsT CAD file (.stl file) as generated from .m file

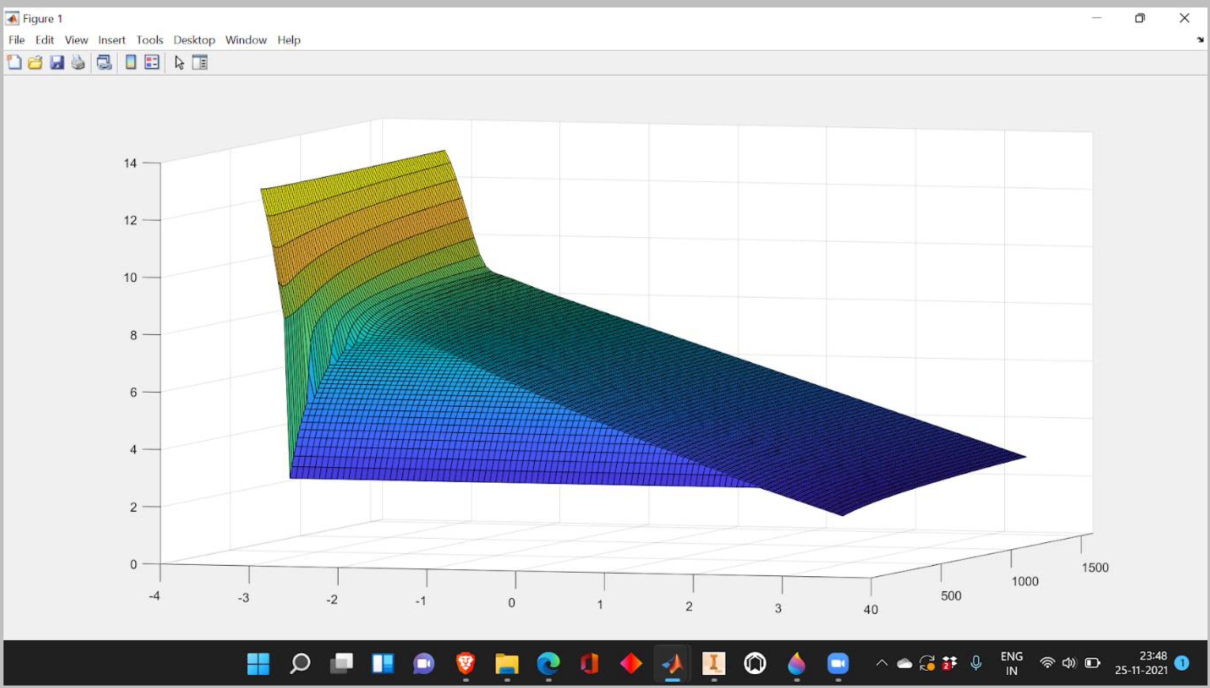


Fig: 3D PvT graph as generated in Matlab by the code (without availing surf2 solid function)

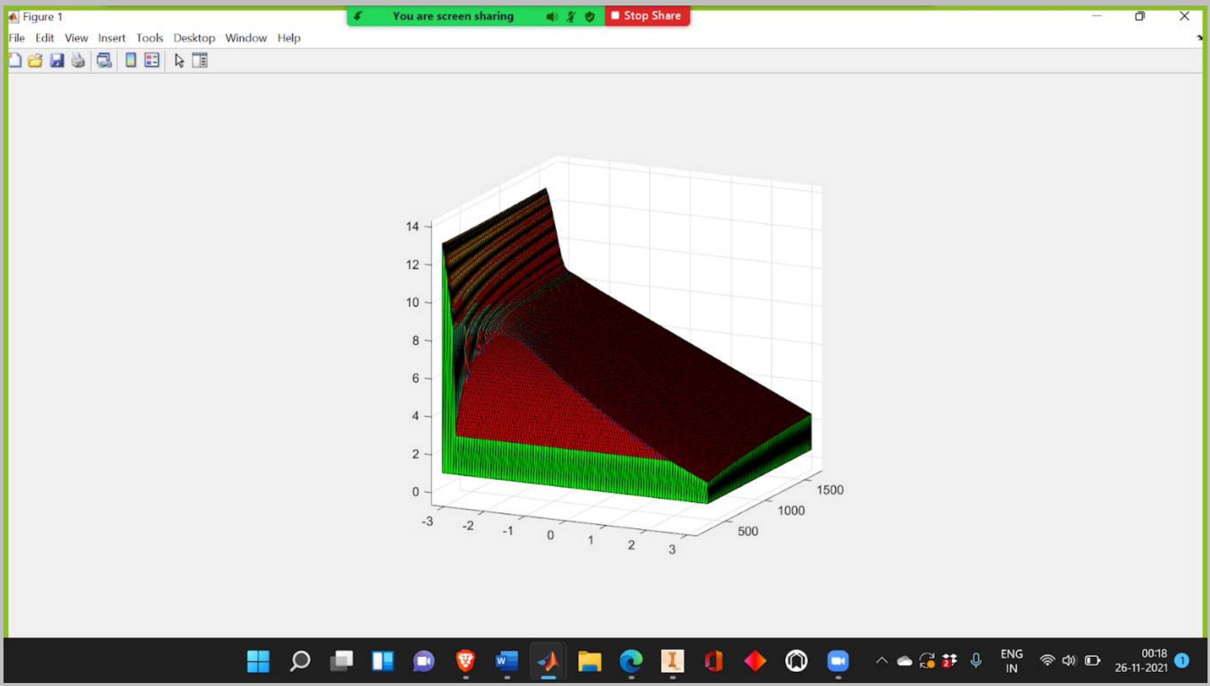


Fig: 3D PvT graph as generated in Matlab by the code (availing surf2 solid function)

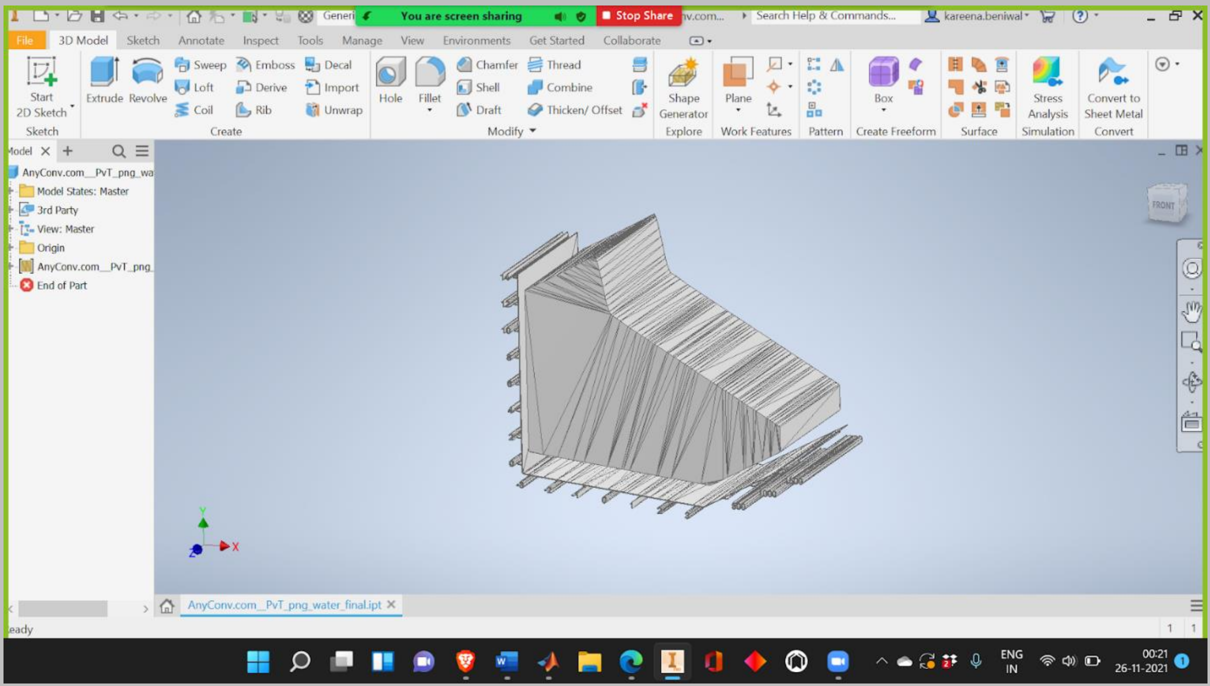


Fig: PvT CAD image (.stl file) as generated from .m file